HIGH FREQUENCY RADIO
AUTOMATIC LINK ESTABLISHMENT (ALE)
APPLICATION HANDBOOK

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HF RADIO ALE APPLICATION HANDBOOK

PREFACE

High frequency (HF) communications has been an essential part of worldwide information transmission since the advent of radio and has advanced nearly in step with information technology. Today, advanced thinkers in the field envision HF radio technology as embracing and supporting such technological advances as HF e-mail and compressed multimedia voice and data services. A guide has long been needed that brings together into one concise user's handbook all of the working knowledge of HF Automatic Link Establishment (ALE) radio technology. Many publications exist that deal with one or more aspects of this technology—sometimes in great detail. This guide, which is general in scope, provides a broad approach. It is a tutorial for explaining the basics of this HF ALE technology and for passing along working knowledge for hands-on operation of HF ALE systems. This guide is the product of many authors who have combined their considerable expertise. This document was edited by the Institute for Telecommunication Sciences (ITS), Boulder, Colorado. Technical contributions were received from Dr. John Goodman of TCI/BR Communications, from Harris Corporation, from Dr. Eric Johnson of New Mexico State University, and from Rockwell International. The editors secured written permission from the holders of the copyright when any copyrighted material was used herein.

In the United States, both the federal and military communities have produced standards to define the details necessary for interoperation among radios of different manufacture. Such interoperability is especially important in order (a) to fulfill specialized or cooperative missions, often one branch of the military service must communicate with a second branch, and (b) government agencies have a tradition of purchasing from only one manufacturer for reasons of familiarity. This standardization has been very important in the growth of HF ALE radio technologies: without standardization, inter-service communications over long distances might not be possible. But this standardization is burdened by the proliferation of special features which, when incorporated into the standard, result in bulky, unwieldy documents that are awkward to use because of their size. To address this problem of size, the authors of current standards are making a conscious effort to remove tutorial text from their documents. Hence the need for a handbook with tutorial material that is easy for the layman to read and that contains sufficient details for a basic understanding of HF ALE radio technology. This *HF Radio ALE User's Guide* addresses that need.

This guide begins with a brief introduction to the propagation properties that make HF radio work. That introduction sets the stage for later discussion about the propagation and physical media of HF radio. The introductory chapter identifies the ways in which HF ALE radio technology relieves the operator of much of the work associated with maintaining information on propagation conditions, tracking the stations with which communications are possible, and noting the frequencies that can be used for those communications. The introductory chapter also discusses the terms *automatic* and *adaptive*, which are an integral part of any discussion of HF ALE radio technology. The scope and definition of adaptive systems are identified to define the user's requirements that must be met despite the difficult propagation environment. The introduction also presents a brief historical perspective of HF radio to date, outlining its impact on the HF communication systems engineer. The introduction also identifies the automation and adaptive concepts described in detail later in the handbook. Finally, the introduction introduces the organization of the handbook.

PART I. USER'S GUIDE

CHAPTER 1
INTRODUCTION

1.1 Purpose

Radio frequency (rf) transmission between 3 and 30 MHz by ITU convention is called high frequency (HF) or "shortwave" radio. HF is the widely used communication band for long distances. The use of HF radio transmissions has been experiencing a renewal of interest and investment because of the realization that satellite and terrestrial communication modes are vulnerable to electronic countermeasures and physical destruction. HF radio transmissions, although of much lower overall reliability and limited data bandwidth than other communication bands, allow communication over long distances and can be expected to function throughout a global conflict, and even to recover more rapidly from the effects of nuclear detonations [Bennett *et al.,* 1987]. This level of survival and recovery may not be the case for satellite and terrestrial communication modes.

The ionosphere is a key element of HF skywave communications. Transmitted HF radio waves hitting the ionosphere are bent or refracted. When they are bent sufficiently, the waves are returned to earth at a distant location. Often at the distant location they are reflected to the sky again, only to be returned to earth yet again, even farther from the transmitter. This HF skywave hopping or skipping (*i.e.,* transmitter-to-ionosphere-and back to receiver on the ground) can increase communication to very long distances (1 hop: <4000 km, 2 hops: 4000 to 7000 km, 3 hops: 7000 to 12000 km). This propagation phenomenon is such that many amateur radio operators ("hams") at certain times carry out satisfactory communication at distances greater than halfway around the world with 1 W to 2 W of radiated power. In fact, if the medium were noiseless and there were no interference, the required power could even be less [Freeman, 1997].

Unfortunately the HF environment is not noiseless and interference does exist; additionally, other details of the HF propagation environment are also constantly changing. Optimum HF propagation can vary by location, frequency, season, time of day; can have cyclic variations; and can be affected by unexpected ionospheric disturbances. This handbook's Annex 1, "The Communications Media," describes in detail the HF propagation medium and how these variations and disturbances will affect it. The amount of bending or refraction of the HF signal is frequency dependent. During certain periods of the day or night, one frequency might propagate well but perhaps during other periods of day or night propagation might be poor or non-existent. A generalization might be: *the high-end frequencies are best during the day, low-end frequencies are best during night,* but even this generalization is not an accurate descriptor all of the time.

1.2 Scope and definition of adaptive systems

How, then, can we use this medium for reliable communication? A few years ago, communication in the HF band relied on the tracking of propagation variations by using computer propagation modeling programs to interpolate variations, and by relying on the skills of the operators to listen to noisy channels for communication links. The characteristics of this communication mode might include:

1. the mode requires very labor-intensive operator duties,
2. the propagation is variable in nature,
3. the mode is vulnerable to jamming, and
4. blackouts are possible in an ionized atmosphere such as a nuclear explosion.

To rectify at least some of these problems, technology has now provided an improved adaptive radio and other improvement schemes to simplify the lives of HF communicators. A new class of radio, under microprocessor control, has a more robust modulation/demodulation scheme, includes error coding, and includes rapidly switching antenna tuners and couplers. The new class of radio has also added automation features such as frequency selection/management, link establishment, link maintenance, and networking protocols to relieve the operator of these duties.

1.3 Historical perspectives and background

To insure that this new technology would not develop completely unchecked with a number of manufacturers all producing incompatible radio systems, the development cycle also included the development of HF radio standards. The United States has produced Federal Standards and military Standards defining all the protocols that comprise Automatic Link Establishment (ALE) radio operations [Young *et al.*, 1994]. Corresponding international standards are in the process of being produced. The cooperation in the standards process between government agencies and industry manufacturers has worked so well that the HF communications systems designer can concentrate on the system-level details of the design, using a document agreed upon by industry leaders.

1.4 Organization of this handbook

This handbook describes the requirements and attributes of automatic and adaptive HF radio systems. Within the chapters, the HF ionospheric channel and communications propagation medium are discussed, as are the details of how automatic and adaptive equipment can be used to track the variations in the HF communication medium. Automatic Link Establishment is discussed, as are advanced HF modems and networks. The handbook contains an Implementer's/System Engineer's handbook which can be used by a system designer to design and implement an HF ALE system. A Network Manager's handbook shows the details associated with designing and implementing a network of HF ALE radio equipment. Annexes to this handbook describe:

- the communications media [Annex 1],
- propagation-prediction systems [Annex 2],
- elements in an HF radio system [Annex 3],
- examples of typical HF radio systems and networks [Annex 4],
- linking protection for HF ALE radio networks [Annex 5],
- HF e-mail [Annex 6],
- HF Internet access [Annex 7].

Other annexes provide:

- a common glossary for HF radio [Annex 8],
- a bibliography/list of references for this handbook [Annex 9].

1.5 Product Disclaimer

Certain commercial equipment, instruments, services, and materials are identified in this handbook to specify adequately the technical aspects discussed herein. In no case does such identification imply recommendation or endorsement by the U.S. Department of Commerce or by the National Telecommunications and Information Administration, nor does it imply that the material or equipment identified is necessarily the best available for the purpose.

CHAPTER 2
REQUIREMENTS FOR AUTOMATIC AND ADAPTIVE HF RADIO

2.1 Automatic and adaptive HF radio

The introduction (Chapter 1) introduced HF radio transmission as a communications medium. This introductory chapter gives us the first look at some of the problems associated with HF radio communication, and it introduces us to the concepts of automation and adaptivity. These features have been added to make HF radio a more reliable communications medium and less prone to problems.

In Chapter 2, we explain why the automatic and adaptive techniques have improved HF radio. In later chapters we will show how these techniques advance as the technology advances from generation to generation. The approach used in this chapter is to describe the radio system in terms of layering. The lowest level is the transmission level, which is responsible for physically moving the message from point to point. Table 2.1 shows how this layer is related to other layers. Above this layer is the link level where the heart of the radio transceiver resides. It is in this layer that the concepts of Automatic Link Establishment (ALE) are primarily added. Above this layer is the network layer, which is responsible for bringing a series of radios together into a network. The uppermost layer is the operator or the higher level system function responsible for generating and receiving the messages or data traffic. Using this concept of layers, the fundamentals of taking a basic radio and adding the features and functions of automation and adaptivity can more easily be understood.

HF radio has been used for decades for long-distance communications. HF radio communication has a number of positive characteristics that can be enhanced—and drawbacks that can be minimized—through the use of automatic and adaptive techniques. The positive attributes for communication in the HF band include long-distance transmissions and the potential for better recovery from ionized effects in a nuclear environment [Galanos, *et al.*, 1987]. The negative aspects include: labor-intensive operation, variable propagation, much lower overall reliability and limited data bandwidth. Communicating in the HF radio band requires the optimization of conditions to make it reasonably reliable. The reliability of HF radio transmissions is dependent on a large number of factors such as:

a. operating frequency,
b. the degree of ionization of the ionosphere,
c. the distance between stations (number of hops),
d. overhead procedures (*i.e.*, error checking, handshaking, *etc.*)

In manual operation—a procedure used until recent years to optimize HF radio communication between points—the operator must adjust the parameters of the system for maximum performance. He/she must monitor the conditions of the ionosphere, track the variable propagation conditions, and select the operating conditions (*i.e.*, frequency) that will allow the signal to propagate best. Because of the intensive labor required, HF radio communication was an easy target for justifying adding automation and adaptive techniques. Present-day, automation techniques reduce the burden on the operator by adding subsystems for frequency management, link establishment, link maintenance, etc. These techniques can be used to reduce the skill-level demands and duty requirements of the HF radio operator or communicator. Typically, automation can be added to make the radio appear to be "push-to-talk on the best channel," while actually the radio is a multichannel communication device performing many underlying functions.

Beyond these automation techniques are the "adaptive" techniques, which also can reduce the burden on the operator while making the radio more responsive to changing HF radio propagation conditions. The definition of adaptivity might be: *the process associated with automatically altering operating parameters and/or system configuration in response to changes in the time-varying channel propagation conditions and external noise.*

The functional parts of the radio system can be represented using the model of the International Organization for Standardization (ISO) called the Open System Interconnection—Reference Model (OSI—RM). Adaptivity techniques exist that can be added to various levels of the radio system (see Table 2.1). At the *transmission level*, adaptive characteristics might include: data rate, waveform, error coding, power, and antenna type and pattern procedures as well as performance assessment characteristics unique to the transmission level. At the *link level*, adaptive characteristics might include frequency management, ionospheric sounding, channel probing, and occupancy/congestion monitoring in addition to performance-assessment details. At the *network level*, adaptive characteristics might include: adaptive routing, flow control, protocol management, data exchange, and network reconfiguration, as well as performance-assessment details. At the *system level*, adaptive characteristics might include: system-level system management, system-level frequency management and control, in addition to performance assessment details.

TABLE 2.1
Adaptivity techniques and associated levels

Level	Adaptivity technique that can be added
System Level	System-level frequency management and control
Network Level	Adaptive routing Flow control Handshaking Data exchange
Link Level	Frequency management and control
Transmission level	Data rate Waveform Error coding Power Antenna type Antenna pattern

2.1.1 Transmission adaptivity level

The lowest level of adaptivity (see Table 2.2) is concerned with the characteristics associated with a communication over a single transmission path at one or more frequencies. Such characteristics include data rate, transmission waveform, coding scheme, transmitted power, antenna pattern, and performance assessment [Goodman, 1992].

Data Rate

It may be possible to boost the communication data rate to the maximum rate that the ionospheric channel will support. However, when unfavorable conditions exist, the data rate will necessarily be adjusted to a lower rate. Adaptive systems can be conceived that will try communication at the maximum rate, then if the bit error ratio becomes excessive, the system will try a lower rate in an attempt to complete the transmission sequence.

Adaptive Transmission Waveform

The choice of modulation format is critical with HF communication because of the precarious nature of the propagation channel [Goodman, 1992]. The transmission waveform should be chosen that will give the system maximum throughput while maintaining acceptable error characteristics.

Adaptive Coding Schemes

Error detection and correcting coding methods provide varying degrees of protection for data integrity and transmission security. It seems only natural, therefore, to visualize the development of coding schemes which are adaptive in nature. Use of the adaptive schemes can be selectable depending on the state of the channel. Some schemes are more robust in the face of channel disturbance but they carry with them a significant overhead burden. Other methods require less burden and can be relatively fast, provided the channel is only moderately disturbed, but may fail under conditions of virulent disturbance.

Adaptive Power Control

Adaptive power control is a very important control technique. Adaptive power control concepts can assure that adequate power is used to achieve maximum range without creating interference beyond the desired coverage area. Adaptive power control is also useful to the military when use of minimum power is desired to prevent detection of critical communications.

TABLE 2.2

HF communications adaptivity levels

Level	**Function**
System Adaptivity Level - (Multi-Media)	Higher level system management System level frequency management Stress environment assessment Performance assessment—System
Network Adaptivity Level - (Multi-Mode)	Message routing schemes Adaptive routing Flow control Protocol management Data exchange Network reconfiguration Performance assessment—Network
Link Adaptivity Level - (Point-to-point)	Frequency management procedures Ionospheric sounding Channel probing Occupancy/Congestion monitoring Performance assessment—Link
Transmission Adaptivity Level - (Fixed Frequency)	Data rate Adaptive transmission waveform Adaptive coding schemes Adaptive power control Adaptive null-steering Performance assessment—Transmission

Adaptive null-steering

An antenna system that is controllable is also an important adaptive technique. In antennas, a lobe is a direction of strength or good reception. A null is an absence of good signal transmission or reception. Adaptive antennas use null-steering techniques which might position a major lobe in the direction of the desired signal (beam-steered array) and/or deep nulls in the direction of the noise sources (null-steered array). One technique for reducing noise effects might be to steer the nulls within the pattern toward unwanted signals to reduce harmful effects. Other uses might arise in directing the pattern toward or away from certain areas such as in the auroral zone or a nuclear disturbance [Goodman, 1992].

Performance assessment - limited real-time channel evaluation (RTCE)

RTCE is the process of measuring appropriate parameters of a set of communication channels in real time and using the data thus obtained to describe quantitatively the states of those channels and hence the capabilities for passing a given class, or classes, of communication traffic [Maslin, 1987]. The transmission adaptivity level uses a *subset* of the full RTCE set of characteristic information for making determinations associated with level (see Section 2.1.5 for a discussion of RTCE).

2.1.2 Link adaptivity level

The link adaptivity level is relevant to point-to-point communications. The characteristics at this level include various frequency management and control functions, vertical and oblique sounding, channel probing, and spectrum monitoring.

Frequency management procedures

The concept of HF frequency management implementation has been discussed in CCIR Report 899-1 [CCIR, 1986]. This report suggests that the three stages for implementation of HF frequency management are: long-term forecasting, short-term forecasting, and immediate conditions. Adaptive frequency management deals with the issues that might be used to adjust frequency use, based on network conditions. At the link-adaptive level, the primary consideration is with immediate conditions and the choice of frequency to use for a particular message. The transceiver must keep track of propagating frequencies/channels based on the results of an analysis of real-time-channel-evaluation (RTCE) information to determine the best choice for message transmission. RTCE information gathering is an automatic technique that allows the receiver to adjust the frequency scanning according to information accumulated through passive or active techniques of traffic monitoring, sounding, polling, *etc.*. Once a list of propagating channels is determined, a channel ranking can be performed by taking into account the effects of the following characteristics:

- path loss,
- noise,
- interference
- multipath,
- fading,

- dispersion,
- Doppler shift, and
- user requirements. [Ripley *et al.*, 1996].

Also see Section 2.14 for system-level frequency management considerations.

Ionospheric sounding

Sounding is the process of testing the transmission medium for short-term propagation information. Soundings provide up-to-date indications of propagation characteristics over vertical (directly overhead) paths and oblique paths (along the actual communication route direction). It is not practical to sound all possible paths in a large communication network, but some benefits from sounding may still be achieved if selected paths are probed and the results are extrapolated to geographically nearby paths [Goodman, 1992].

Sounding can be divided into three subgroups for purposes of distinguishing the significance of each type. The sub-groups consist of:

- Ionospheric Pulse Sounding,
- Linear Sweep Sounding, and
- Channel Evaluation Sounding [Maslin, 1987].

Ionospheric pulse sounding

Ionospheric Pulse Sounding is used to test the propagation medium characteristics for such things as channel unit impulse response, signal propagation delay, and signal amplitude [Maslin, 1987]. Pulse sounding consists of emitting a pulse sweep over a portion or all of the HF band for a period of a few seconds to several minutes. The received signal is then analyzed. The sounding sweep over the link will indicate to the user or equipment the range of frequencies that will propagate. The transmitted energy can be focused either vertically or obliquely.

Vertical-incidence-sounder (VIS)

The Soundings would be emitted vertically and the reflected returns are received by the receiver as returns from the ionosphere.

Oblique-incidence-sounder (OIS)

The sounding would be emitted in the direction of the actual communications path, and the receiver is located at the remote location.

Oblique incidence backscatter sounding

The Soundings would be emitted in the direction of the actual communication, and the reflected returns are gathered by a co-located receiver very near the transmitter.

Linear sweep sounding (chirpsounding)
Linear FM modulation or chirpsounding consists of sending a low power 2- to-30 MHz linear FM/cw test signal over the communication path [Maslin, 1987]. This method can be used over either a vertical or an oblique path. The data received from the chirpsounding equipment is similar to the pulse sounding equipment, but has the advantage of causing less interference to nearby equipment.

Channel evaluation sounding
Channel evaluation sounding consists of probing only frequencies that are allocated to this system, rather than a broadband approach of the other two methods. Channel evaluation provides information used in evaluation of signal-to-noise performance such as: data error rate, speech intelligibility, and noise levels [Maslin, 1987].

Channel probing

A wideband HF channel probe can be used to collect data over a single-hop polar path using the F layer [Goodman, 1992]. The collected data shows a scattering function when the doppler frequency is plotted against delay.

Occupancy/congestion monitoring

The channel is monitored for occupancy, congestion, and a "full" condition to determine if message traffic is possible. If the channel is busy, a backoff algorithm or continual monitoring can be used to determine when message traffic is possible.

Performance assessment - full RTCE complement

The link adaptivity level uses the full RTCE complete set of characteristic information for making determinations associated with level. (See section 2.1.5 for a discussion of RTCE.)

2.1.3 Network adaptivity level

At the network level of adaptivity, multinode networks are involved, so the characteristics of routing, adaptive routing, flow control, protocol handling, and data exchange become issues of importance.

Message routing schemes

Routing is defined as the process of determining the transmission path of the message through the network to enable the message to reach its destination node [Vijay, 1982]. The two major types of routing algorithms are deterministic and adaptive. Deterministic or fixed routing algorithms establish message routes based on network topology, average message delays, or both. Adaptive routing strategies use centralized or distributed schemes to forward messages based on some criterion that is usually not fixed over time. The message route is determined during message transmission to adapt to the current network traffic or conditions, such as node or link failures. The routing decision may come from the sender, may be dynamic with each node making routing decisions, or may be routed based on instructions issued by a centralized point such as a network control station.

Route selection is a Network-layer function that uses connectivity information, path information, and channel information to select the best route to get a message through the network. This information is constantly being updated through passive or active collection, by polling commands issued by the network controller, or by the use of one of the routing strategies. Using indirect routing techniques, the connectivity and path information will include possible links through transfer stations or relay stations. This will give the station increased connectivity, fewer delays, and, in general, better throughput. The possible routing-strategies support will be of both the fixed and adaptive type, using source, query, flood, hierarchical, or other routing techniques.

When a station cannot be directly linked with a desired destination, other stations may be used to assist in getting the message to its destination. When this assistance is done by station operators it is termed *indirect calling*. If it is done automatically by radio equipment, it is termed *relaying.*

Adaptive routing

Adaptive routing is the process of routing calls based on network conditions. The routing decision may come from the sender, may be dynamic with each node making routing decisions, or may be based on instructions issued by a centralized point such as a network control station (NCS). The sender may not have up-to-date information, so this node may not be able to direct traffic for maximum efficiency. In some cases, a centralized scheme may be desirable, but the central node may not have the latest information. The individual node in the process of relaying will probably have the best information for at least one hop. However, unless information is distributed or relayed throughout the system, this node may not be able to see beyond a single hop with any degree of efficiency.

Flow control

An unrestricted flow of messages into a network may lead to congestion. A network is considered to be *congested* when messages experience longer than expected delays. Network congestion can lead to a deadlock in which no message flow occurs. An unexpectedly high rate of message arrivals into the network can lead to congestion. If no remedy is applied, network congestion can eventually result in a buffer deadlock, thereby blocking all message movement [Vijay, 1982].

Flow control is a mechanism for preventing congestion in networks. Congestion arises when the nodes that are sending messages to a particular receiving node exceed the receiving node's capacity to process, or forward, messages. Thus, the problem reduces to one of providing each node with mechanisms to control the rate at which it receives the messages from other nodes. As such, flow control is the process of regulating the rate at which a sender generates messages so that the receiver can process them. From a network user's perspective, flow control is a mechanism that prevents entrance into the network those messages that cannot be delivered in a predefined time [Vijay, 1982].

Network flow control is a mechanism for distributing the traffic equally among network nodes. As such, flow control can reduce message delays during normal network operations and prevent any part of the network from becoming overloaded relative to the rest of the network as a whole [Vijay, 1982].

Protocol management

The primary purpose of a protocol is to establish orderly information exchange among processes, and to manage network resources efficiently. The general approach to describing the establishment of rules to manage the network is the concept of layering. Through a process of characterizing functions into a series of layers, the functionality of the network can be described. Each layer in a node supports its own protocols to communicate with the corresponding layer in another node. The protocols for layers that are relatively farther from the transmission link layer match the applications functions, while the protocols for layers closer to link layer contribute to the communication mechanism of the network [Vijay, 1982].

Network nodes exchange two types of messages: *control messages* and *data messages*. Data messages, or simply "messages," are units of information exchanged between network users, such as operators or application programs. Control messages are used to exchange information among the layers at different nodes to facilitate transmission of data messages. Compared to data messages, control messages are not known to the network user and are transmitted within the network [Vijay, 1982].

Some of the numerous functions served by network protocol [Vijay, 1982]:

1. Orderly exchange of data messages.
2. Management of priorities at both the network entry and transmission levels within the network.
3. Process synchronization.
4. Session establishment between network users.
5. Session termination between network users.
6. Means for protocol validation.
7. Routing establishment and assignment of message routes.
8. Flow control and congestion prevention.
9. Sequenced transmission and delivery of messages.
10. Addressing of network components and users.
11. Efficient network resource utilization.
12. Resource management, monitoring, and protection.
13. Layered transparency between network users and nodes.
14. Reliable message transmission, including error control and recovery.
15. Testing of network resources, such as links and routes.

16. Security and privacy.
17. Optional packet switching through message segmenting and pipelining.

The protocols used in the system may be fixed or adaptive in nature. It seems only natural therefore to visualize the development of protocol schemes which are adaptive in nature or are selected adaptively, depending on the state of the channel. The system would observe channel conditions and might change the relative timings to exchange messages and control information with other nodes. Also line management, message handling, and buffer management might all be functions of channel conditions.

Data exchange

If the radio system is also a data exchange network this function might be a paramount mission for this network. It might be beneficial to adjust some exchange techniques in order to maximize transfer efficiency. Techniques that are candidates for possible adjustment based on network conditions might include: message size, error correction, handshaking techniques, and buffer control techniques.

Network reconfiguration

The architecture of the network might be fixed or adaptive in nature. It seems only natural therefore to visualize the development of architecture schemes which are adaptive in nature or are selected adaptively, depending on the state of the channel. The system would observe channel conditions and might change the relative timings to exchange messages and control information with other nodes. Also, line management, message handling, and buffer management might all be functions of channel conditions.

Performance assessment - network-wide RTCE

The network adaptivity level uses a network-associated subset of the full RTCE set of characteristic information. [See Section 2.1.5 for a discussion of real-time channel evaluation (RTCE).]

2.1.4 System adaptivity level

The system level is concerned with those capabilities that allow multimedia communication. Characteristics include: higher level system management, system-level frequency management and control, stress assessment of the environment, and system-level performance assessment.

Higher level system management

The higher level system management functions include: operator interface, determination of routes, queuing messages, determining message priority, reestablishment of packet order, ultimate flow control, message store-and-forward control. Many of these functions have adaptive characteristics. The operator interface is able to change many of the system characteristics in response to changing conditions. Route determination, message queuing, and flow control all allow the message to be rerouted to the best message path. Message store and forward allow messages to be retained until conditions are more favorable.

System level frequency management and control

The concept of HF frequency management implementation has been discussed in CCIR Report 899-1 [CCIR, 1986]. That report suggests that the three stages for implementation of HF frequency management are: long-term forecasting, short-term forecasting, and RTCE. An example of long-term forecasting is described later in this report under the subject of computer propagation modeling. Short-term forecasting might be adjustments made to compensate for an unpredicted needed change. Both long-term and short-term adjustment would require the operator to manually adjust the frequencies used, the way the receiver scans the list, or other possible means to assure that the receiver scans the desired frequencies under some kind of priority direction. Real-Time-Channel-Evaluation (RTCE) is an automatic technique that allows the receiver to adjust the frequency scanning based on information accumulated through passive or active techniques of traffic monitoring, sounding, polling, *etc.*

Stress environment assessment

In a stress environment, such as after a nuclear event, HF is considered to be more vulnerable to nuclear effects than any other component of the suite of communication systems. Although this may be so, it is also true that the HF channel tends to repair itself over time. So there is an ultimate survivability, if not continuity, associated with the use of HF in a nuclear-disturbed environment [Goodman, 1992].

Performance assessment - system assessment

The System Adaptivity Level uses a higher level associated subset of the full RTCE set of characteristic information. This subset list includes the only real-time channel evaluation items that would be of concern to systems at the operator or higher level controlling system interface.

2.15 Real-time channel evaluation (RTCE)

The key to achieving significant benefits in the way that an operator or automated HF radio system controller uses the HF propagation medium for communication is to ensure that an adequate supply of real-time data is available for decision-making purposes. Off-line propagation analysis is the older time-proven method for getting this information. More recently automated and adaptive systems have turned to real-time collection of information to be used in propagation analysis. When a radio link is established with data or voice traffic passing across it, it is possible for a suitably equipped receiver to extract substantial RTCE information about the characteristics of the link. The data collected constitutes the HF communication channel parameters that are important for successful communication. Decisions on the message path, the channel to use, whether to use direct or indirect message handing, and how much noise and interference to expect are usually generated by some form of RTCE and frequency management routine. *RTCE is the process of measuring* *appropriate parameters from a set of communication channels in real time and using the data thus obtained to describe quantitatively the states of those channels and hence the capabilities for passing a given class, or classes, of communication traffic* [Darnell, 1975, 1982; Maslin, 1987].

The need for RTCE arises because of the variability in the total environment associated with the HF channel. In most cases, it is not necessary for the communicator to know what detailed fundamental physical principles create the distortions imposed by the ionospheric medium on a particular signal, only that it is possible to measure the characteristics of the available paths and, from this, to adapt the associated communications-link parameters for optimum information transfer [Galanos *et al.*, 1987]. The analysis, application, and ability to respond to RTCE information is integral to each adaptivity level, as shown in Sections 2.1.1 - 2.1.4. This implies automation (*i.e.*, microprocessor control) of the adaptive processes being used by the radio or controller system. Beyond automation, to be effective in reducing the data produced by the ionograms, the prediction programs, and the collected RTCE information, a comprehensive real-time frequency-management system should be used. The frequency-management system should have the following characteristics:

- take into account all the assigned operating frequencies,
- account for high and low power levels,
- account for the various antenna types,
- take into account the modem-specific and data-rate parameters,
- issue an automatic recommendation of the optimum operating frequency.

The system would be expected to operate continually, to measure the channel characteristics, and to make recommendations based on the system characteristics such as modem, antenna, *etc*.

2.2 User's requirements

HF radio is needed as a long-haul communication provider; it can be an alternative to satellite, microwave, or landline terrestrial communication systems. HF radio requires a frequency channel that is as clear as possible (*i.e.,* free of noise and interference). The attributes of the automated and adaptive HF radio communication link are that it will regularly monitor the operation of the varying HF medium to exploit the spectrum with the greatest efficiency possible [Ripley *et al.*, 1996]. Monitoring the HF environment was previously done by the operator in a very labor-intensive manner. Operators had to monitor noisy HF channels waiting for calls and making valuable judgement calls on procedures to make sure the communication was done with maximum efficiency. With the advent of automatic and adaptive HF systems, the radio can now remain muted until a valid call is received or transmitted.

Users' requirements include the basic function of using the radio to communicate on a specific channel with other users and with networks of users. The very basic requirement might be said to be the ability to key the mike to communicate with other users on some common frequencies and networks without knob tuning and adjusting. If automation and adaptive features are added to the basic radio, together with the advantage of long-range propagation offered by HF, this combination makes a communication mechanism that is ideally suited to quick, short messages by an operator who may have other pressing tasks and a heavy workload.

It is the work of the radio to maximize the abilities of the operator by automating the selection of the clearest and best path to the intended message receiver. The features of sounding, polling, connectivity path tracking, and indirect addressing all go to satisfy the needs of the operator to communicate over the greatest distance and to maximize the number of users possible on the channels provided. As the capabilities of the radio increase, so will the user's requirements, since as a feature is introduced to the operating users, it soon will become one of their necessities. New features and refinements such as those shown in the list below will rapidly become user requirements of next generation radios:

- frequency flexibility and agility,
- network topologies/configurations,
- alternate routing and message relaying,
- robust waveform,
- mobility,
- compatibility with other designs and other radios, and
- minimum operator intervention.

2.3 Impact of requirements for automatic/adaptive HF on systems design

HF radio system designers must be aware of the drawbacks as well as the benefits of automatic and adaptive HF radios. As the radios become more capable they also become more expensive, more bulky, draw more input current, and may even require larger antennas. It is the responsibility of the radio designer to make the necessary tradeoffs between adding a feature and keeping the size and cost minimized. It is responsibility of the system designer to require manufacturers to include the functions and features needed for network-capable operation at the same time that they offer a low-cost, small size, automatic, and adaptive radio for the individual user.

2.4 Principles and components of automatic/adaptive HF radio systems

Specific items attributed to automation and adaptivity might include:

- selective calling,
- multi-channel frequency scanning
- real-time channel evaluation,
- real-time path sounding
- link quality analysis

- automatic link establishment (ALE)
- automatic relaying
- power control, and
- frequency hopping.

Selective calling
This feature allows for the linking and selective conversation between two individual stations on a single specified HF channel. The radio performs its functions of scanning and handshaking until it has linked with the second party. After linkup is achieved, the speakers are unmuted for two-way communication.

Multi-channel frequency scanning
This feature allows for automatic operation of frequency selection. One of the most important elements in HF radio operation is the operating frequency. As stated above, HF radio propagation is dependent on the chosen operating frequency, and this choice will vary during different parts of the day. If there were a way to have a group of frequencies, have them spread across the frequency range from 3 to 30 MHz, and then to have automatic hardware to scan the range automatically, then this would constitute an automated system. *Scanning* is the procedure where, under computer control, the receiver goes from frequency to frequency, pausing momentarily on each channel to check for traffic, specifically traffic for this station. Channel frequency scanning is a very important part of automating a radio system.

Real-time channel evaluation
This feature allows the radio to measure the appropriate parameters of a set of communications channels in real time and using the data thus obtained to describe quantitatively the states of those channels, and hence their relative capabilities for passing a class (or classes), of communication traffic [CCIR, 1986].

Real-time path sounding
This technique is the process where, either automatically (as a timed event) or manually, a short beacon-like identifying broadcast, on a selected channel, is issued to provide information on the connectivity, propagation, and availability of available channels; and to select known working channels for possible later use for communication. The broadcast benefits both the sender and the receiver as the information may be utilized by both the sender and all of the receiving parties.

Link quality analysis
This feature concerns the automatic measurement of the quality of the signal on links between stations. As communication messages are passed between stations, error, noise, and multipath-spread information about the path is stored to support a later decision about which channel might be adequate or "best" for use at a later time. The information is stored at each

receiver but may also be transferred to other stations such as a net control station.

Automatic Link Establishment (ALE)
This feature allows for the simplification of HF radio operation. It is a combination of selective calling, and/or link quality analysis to provide automatic connectivity. ALE improves the performance of connectivity and allows for quiet or muted operation.

Automatic Relaying
This feature allows for the automatic retransmission of a message to a different receiver. This feature drastically improves connectivity, since messages can be rerouted around areas with no connectivity.

Frequency hopping
This technique is the transmission of the same information or packet on different frequencies at different times. This feature provides a degree of anti-jam protection and it lowers power densities while offering a degree of covertness.

Power control
This feature allows for the control of the transmitted power to achieve acceptable range without over-burdening the HF environment.

2.5 Conclusion

As the family of HF ALE radios evolves, their design is constantly being updated with new features and functions that continually make them more helpful and desirable to individual and network users. These features can be broadly grouped into features added to increase the level of automation and those that will serve to increase the radio's ability to adapt to changing HF propagation conditions. A fully adaptive HF system typically operates under microprocessor control, incorporates automation for most operator-intensive functions, and is capable—through a marriage of a variety of diversity schemes with a set of channel intelligence functions—of automatically establishing and maintaining links in an adaptive manner in response to time-varying channel propagation, external noise, and electromagnetic-compatibility (EMC) conditions.

Some of the described features will be added to the present second generation radios and some will be features that will have to wait to be incorporated into third generation radios, which are coming soon.

CHAPTER 3
AUTOMATIC LINK ESTABLISHMENT

3.1 Introduction and overview of automatic link establishment systems

The United States has developed a series of HF radio standards that characterize and specify protocols and parameters for automatic link establishment (ALE), networking, linking protection, high-speed data modems, and basic HF radio parameters.

Automatic link establishment is a robust, adaptive HF radio method for automatically establishing communications over HF single sideband (SSB) links. Using ALE, an operator or computer-initiated control signal can automatically initiate point-to-point or point-to-multipoint calls. The ALE controller can be programmed to scan one or more frequencies, pick the best frequency for operation, and switch to voice or data operation immediately upon link establishment. The ALE system initiates calls on selected channels, which are rank ordered, through an internally programmed link quality analysis (LQA) algorithm. This permits the link establishment process to have the most likely chance of success on its initial trial using previously measured LQA numerical channel scores that are stored in the system's memory. The identities of the calling and called stations are exchanged between stations, along with call sign designators to distinguish the calling from the called station.

Optional features include linking protection, which uses security methods to prevent unauthorized network entry, transmission and reception of user data, and over-the-air reprogramming (OTAR).

The ALE link-establishment and link-management functions are performed by reliably conveying the ALE link information over HF channels between station pairs. This high reliability is obtained by triple redundancy transmission of the ALE data, by interleaving, and by using Golay forward error correction.

An adaptive HF radio system block diagram is shown in Figure 3.1. The ALE controller provides the automation of the linking process. ALE networking functions and linking protection functions can also be incorporated into the ALE controller. After the link is established, data or voice communications can be initiated by switching a high speed data modem into the circuit.

ALE is designed to be modular in nature, and uses audio tones and serial data signals to interface the ALE controller with HF-SSB radios. It can be embedded as a low-cost, integral part of modern HF-SSB radios using digital signal processing (DSP), either as a standard or optional module. It can also be added to many existing HF-SSB radios as an external appliqué, either as a stand-alone component, or as a personal-computer (PC) compatible kit of hardware and software. Also available are tools such as calibration and test signals on audio compact discs (CD), which permit the development and interoperability testing of ALE products without costly channel simulators.

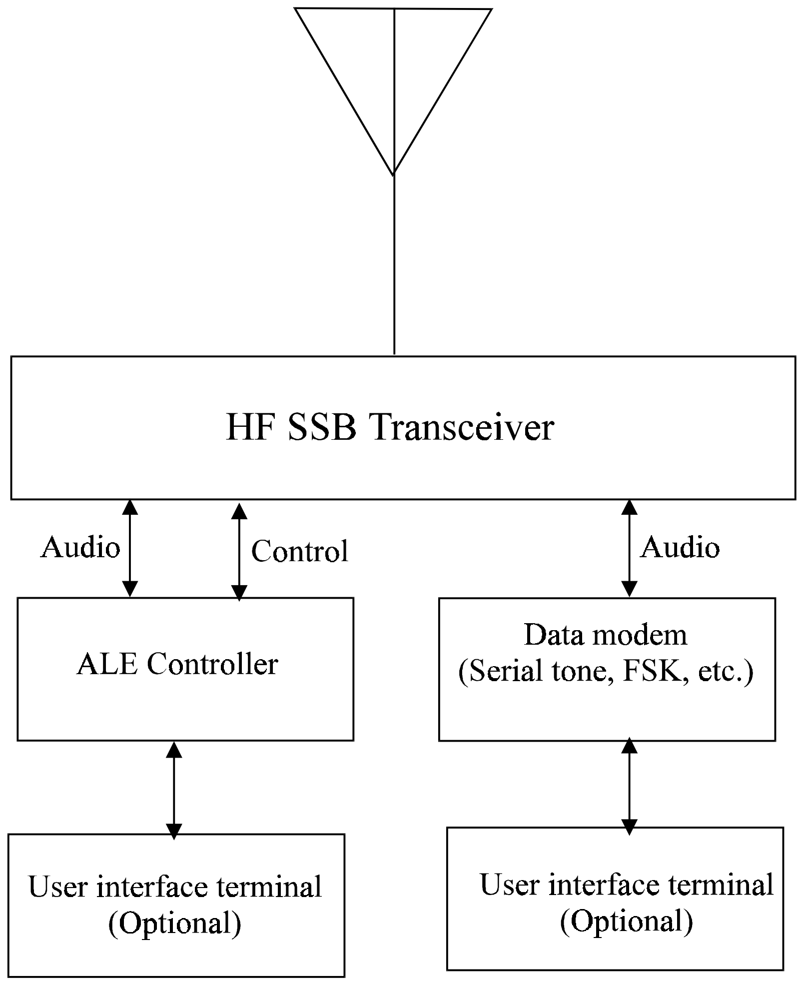

FIGURE 3.1
Adaptive HF radio system block diagram

3.2 ALE transmissions and word format

The ALE waveform is designed to pass through the audio passband of conventional SSB radio equipment. The waveform is an 8-ary frequency shift keying (FSK) modulation with eight orthogonal tones. Each tone is 8 milliseconds in duration and ranges in frequency from 750 Hz to 2500 Hz with 250 Hz separation between adjacent tones. Each tone represents three bits of data, resulting in an over-the-air data rate of 375 bits per second (b/s).

The ALE standard word consists of 24 bits which are separated into a 3-bit preamble field followed by three 7-bit ASCII character fields. The function of each transmitted ALE word, as designated by the preamble code, is related to the basic ALE capabilities. There are eight word types: TO, THIS IS, THIS WAS, DATA, REPEAT, THRU, COMMAND, and FROM. Each 7-bit ASCII character field is used to specify an individual address character or as ASCII text, depending on the preamble.

3.3 Protocols

3.3.1 Scanning

All ALE stations, when operational and not otherwise committed, continually scan a preselected set of channels, or "scan set," listening for calls and ready to respond. The minimum dwell time on each channel is the reciprocal of the scan rate, and the channels in the scan set are repeatedly scanned in the same order. ALE receivers scan channels at either 2 or 5 channels per second resulting in a dwell time of 200 ms or 500 ms. When a transmitter wishes to "capture" a scanning receiver, it will transmit a signal that will be recognized by the scanning receiver. The duration of this "scanning call" must be sufficient to ensure that if the receiver is indeed scanning for calls, it will land on the channel carrying the scanning call before the transmitter ceases emitting.

3.3.2 Selective calling

Selective calling in an ALE system involves the exchange of ALE frames among stations. This selective calling capability supports all higher level ALE functions, including link establishment and data transfer. The general structure of an ALE frame consists of one or more destination addresses, an optional message section, and a frame conclusion which contains the address of the station sending the frame.

The fundamental ALE operation of establishing a link between two stations proceeds as follows:

1) The calling station addresses and sends a call frame to the called station.
2) If the called station "hears" the call, it sends a response frame addressed to the calling station.
3) If the calling station receives the response, it now "knows" that a bilateral link has been established with the called station. However, the called station does not yet know this, so the calling station sends an acknowledgement frame addressed to the called station. At the conclusion of this three-way handshake, a link has

been established, and the stations may commence voice or data communications, or drop the link.

3.3.3 Individual calling

Systems for HF automatic link establishment have a protocol suite for both single channel and multiple channel linking. All ALE stations, when not otherwise committed, continuously listen for calls. The protocol consists of three parts: an individual call, a response, and an acknowledgement.

3.3.4 Sounding

A sound is a unidirectional broadcast of ALE signaling by a station to assist other stations in measuring channel quality. The broadcast is not addressed to any station or collection of stations, but merely carries the identification of the station sending the sound.

3.3.5 Multiple station operations

A net call is addressed to a single address that implicitly names all members of a pre-arranged collection of stations (a "net"). All stations belonging to the net that hear the net call send their response frames in prearranged time slots. The calling station then completes the handshake by sending an acknowledgement frame as usual.

A group call works similarly, except that an arbitrary collection of stations is named in the call. Because no pre-arranged net address has been set up, each station must be individually named. Called stations respond in slots, determining their slot positions by reversing the order that stations were named in the call. The calling station sends an acknowledgement as usual.

3.4 Orderwire messages

In addition to automatically establishing links, ALE stations have the capability to transfer information within the orderwire, or message, section of the frame. Orderwire messages include automatic message display (AMD), data text message (DTM), and data block mode (DBM) modes. These functions enable stations to communicate short orderwire messages or prearranged codes to any selected station(s). This permits station operators to send and receive simple ASCII text messages by using only the ALE station equipment.

3.5 Link quality analysis (LQA)

ALE systems have the capability to support the exchange of LQA information among ALE stations. The LQA process measures the quality of a channel by placing a score on it, which incorporates three types of link analysis information: bit error ratio (BER), signal-plus-noise-plus-distortion to noise-plus-distortion ratio (SINAD), and optionally, a measure of multipath. The LQA scores are stored in memory for future use. ALE stations are capable of selecting the best channel to initiate a call to, or seek, a single station based on the values in the LQA memory, where the channel with the highest LQA score has the highest probability of being suitable for communication.

ALE radios obtain LQA scores by receiving sounds from other stations, resulting in a score on the received path from the sounding station to the receiving station. Another method of obtaining LQA scores is by initiating a bi-directional sound, a non-linking call designed to measure and transfer LQA scores. Bi-directional sounds produce LQA scores for the forward and reverse paths (in reference to the initiating station). A third method of obtaining LQA scores is during the linking process.

3.6 Network configurations

Multiple station operations are often required in HF networks where several types of network configurations, individual links, networks, and groups are encountered. The most simplistic configuration is a link that comprises only two stations and consists of a single path between the two. Star net and star group configurations consist of more than one link within the network.

Systems for HF radio automatic link establishment have a backup manual control capability.

3.6.1 Star net

A star net is a prearranged collection of stations that operates with a single hub station in a "one-to-many" configuration. In most cases it has the function of the net control station that manages and controls the functions of the network. The star net is usually organised with significant prior knowledge of the member stations so that so that operation of the network is optimized. By using a single net address for all of the net members, efficient contact with multiple stations is achieved.

3.6.2 Star group

A star group is a non-prearranged collection of stations where typically, little or nothing is known about the stations except their individual addresses and scanned frequencies. Like the star net it operates in a "one-to-many" configuration using a net control station. A star group call is performed from a sequence of the actual individual station addresses of the called stations. The stations respond in a manner specified by the sequence of call addresses.

3.7 Addressing

The ALE system deploys a digital addressing structure based upon the standard 24-bit (three-character) word and the Basic-38 character subset. ALE stations have the capability and flexibility to link or network with single stations or with prearranged or as-needed groups of stations.

The ALE system provides and supports three hierarchical sets of characters; the Basic-38 subset, the expanded-64 subset, and the full-128 set. The Basic-38 subset includes all capital alphabetics (A-Z) and all digits (0-9), plus designated utility and wildcard symbols "@" and "?". The expanded-64 subset consists of all ASCII characters whose two MSBs are 01 or 10, and includes all capital alphabetics, all digits (0-9), the utility symbols "@" and "?," plus 26 other commonly used symbols. The full-128 set includes all characters, symbols, and functions available within the ASCII code.

3.7.1 Individual station addresses

The fundamental address element in the ALE system is the single routing word, containing three characters, which forms the basic individual station address. This basic address word may be extended to multiple words for increased address capacity and flexibility for inter-net and general use. An address which is assigned to a single station is termed an "individual" address. If it consists of three characters or fewer, it is termed a "basic" size, while if it exceeds three characters it is termed an "extended" size. The three characters in the basic individual address provide a Basic-38-address capacity of 46,656 using only the 36 alphanumeric characters. Extended addresses provide address fields which are longer than three characters, up to a maximum system limit of 15 characters. This 15-character capacity enables Integrated Services Digital Network (ISDN) address capability.

3.7.2 Multiple station addresses

A common requirement in HF networks is to simultaneously (or nearly simultaneously) address and interoperate with multiple stations. A prearranged collection of stations with a common address is termed a "net," and the common address is a "net address." A non-prearranged collection of stations, *i.e.*, a collection of stations lacking a prearranged common address, is termed a "group."

3.7.2.1 Net addresses

As a prearranged collection of stations, a net is organized and managed with significant prior knowledge of the member stations, including their identities, capabilities, requirements, and in most cases, their locations and necessary connectivities. The purpose of a net call is to rapidly and efficiently establish contact with multiple prearranged stations by the use of a single net address, which is an address assigned to all net members in common in addition to their individual addresses. The net address structure is identical to that of individual station addresses, basic or extended, as necessary. At a net member's station, each assigned net address is associated with a response slot identifier to allow each station to respond to the net controller in a systematic manner.

3.7.2.2 Group addresses

Unlike a net, a group is not prearranged. In many cases, little or nothing is known about the stations except their individual addresses and scanned frequencies. The ALE group addressing mechanism provides a means to create a new group where none existed. This mechanism uses a standardized protocol that is compatible with virtually all automated stations, regardless of their individual, net, and other characteristics. The purpose of a group call is to establish contact with multiple non-prearranged stations rapidly and efficiently by the use of a compact combination of their own individual addresses. A group address is formed from a sequence of the actual individual station addresses of the called stations, in the manner directed by the specific standard protocol.

3.7.3 Special addressing modes

The special addressing modes include *Allcalls, Anycalls, Wildcards*, *Self-address*, and *Null* address. The ALE basic address structure is based on single words that, in themselves, provide multiples of three characters. The quantity of available addresses within the system, and the flexibility of assigning addresses, are significantly increased by the use of address character stuffing. This allows address lengths which are not multiples of three characters to be compatibly contained in the ALE system address fields by "stuffing" the empty trailing positions with the utility symbol “@”.

An “*Allcall*” is a general broadcast that does not request responses and does not designate any specific address. This mechanism is provided for emergencies, broadcast data exchanges, and propagation and connectivity tracking.

An “*Anycall*” is a general broadcast that requests responses without designating any specific addressee(s). It is required for emergencies, reconstitution of systems, and creation of new networks. An ALE station may use the “*Anycall*” to generate responses from essentially unspecified stations, and it thereby can identify new stations and connectivities. The selective *Anycall* is a selective general broadcast that is identical in structure, function, and protocol to the global anycall, except that it specifies the last single character of the addresses of the desired subset of receiving station (1/36 of all).

A caller may use the *Wildcard* character (“?”) to address multiple stations with a single wildcard address. Responses to a call containing an address with wildcard characters are generated in pseudorandom slots to avoid collisions.

For self-test, maintenance, and other purposes, stations should be capable of using and responding to their own *Self-Addresses*.

For test, maintenance, buffer times, and other purposes, stations may use a Null Address which is not directed to, accepted by, or responded to by any station.

CHAPTER 4
THIRD GENERATION HF MESSAGING PROTOCOL

4.1 Introduction

4.1.1 Summary

The United States Department of Defense is currently in the process of updating U.S. MIL-STD-188-141A, the automated HF radio standard commonly referred to as the ALE standard. Ratification of the new version, to be known as MIL-STD-188-141B, is planned for late 1998. Appendix C of the new version defines a unified third generation synchronous HF messaging protocol (3G-HF) that uses burst serial tone waveforms for link establishment and link maintenance, as well as improved data link engines for the faster transfer of data traffic. The third generation unified messaging protocol, henceforth named third generation HF, is intended for HF networks with intense voice and/or data message loading.

This paper begins with an overview of the layered architecture. This is followed by a brief overview of the constituent waveforms within the physical layer and an overview of the data link layer (DLL). The data link layer overview includes descriptions of the connection set-up (CSU) and traffic set-up (TSU) protocols, the high-rate and low-rate data link protocols, and the circuit link protocol. Finally, the paper discusses a framework for simulation of the entire HF messaging system.

4.1.2 Background

The need for a next-generation HF messaging protocol suite stems from the growing need for HF voice and data messaging systems offering high reliability and high capacity. HF continues to play a crucial role in military beyond-line-of-sight communications; however, this role is changing as more HF military users extend the internet into the battlefield. The use of standard internet applications (such as E-mail) over wireless transmission media (specifically HF) creates heightened technical challenges which are not met adequately by existing HF communications protocols. The existing protocols do not provide effective channel access mechanisms, and, as a result, tend to break down due to collisions and congestion under heavy network loads. The current ALE and data link standards use very different modulation formats (8-ary FSK vs. serial tone PSK), resulting in a performance mismatch between the linking subsystem and the message delivery subsystem. Current HF ARQ protocols require complicated methods for matching the waveform and/or data rate to the channel conditions. The 3G-HF system attempts to meet all of these challenges with simple but effective designs for:

- prioritized channel access and collision avoidance,
- a unified and scaleable burst waveform design used for connection set-up, traffic set-up, and traffic exchange,
- and an enhanced ARQ protocol that significantly increases throughput in all channel conditions, while simplifying the data rate adaptation algorithm.

A key element of any successful and widely implemented protocol is simplicity. One only has to look to the internet protocols to see that simple protocols thrive in the marketplace at the expense of more complex alternatives. While any interoperability standard requires correctness, completeness, conciseness, consistency, and clarity, the goal of simplicity must not be sacrificed to achieve the other goals. This is a major guiding principle applied in the definition of the 3G-HF protocols.

Figure 4.1 shows the concept architecture for 3G-HF. A specific architecture implementation is not required by 3G-HF; nor is the implementation of each service primitive. The protocol architecture and service primitives are provided within the standard for completeness and to aid in specifying the required over-the-air behavior in the form of exchanges of protocol data units (PDUs). In 3G-HF an HF subnet may have a network layer (NL), a data link layer (DLL), and a physical layer (PL). This does not preclude the existence of transport, session, presentation, and even application layers within the system. The 3G-HF specification pertains only to the DLL and PL. The DLL consists of a connection manager (CM), a traffic manager (TM), data link protocols (DLPs), and a circuit link protocol (CLP). Overviews of the PL and of each component of the DLL are provided in subsequent sections.

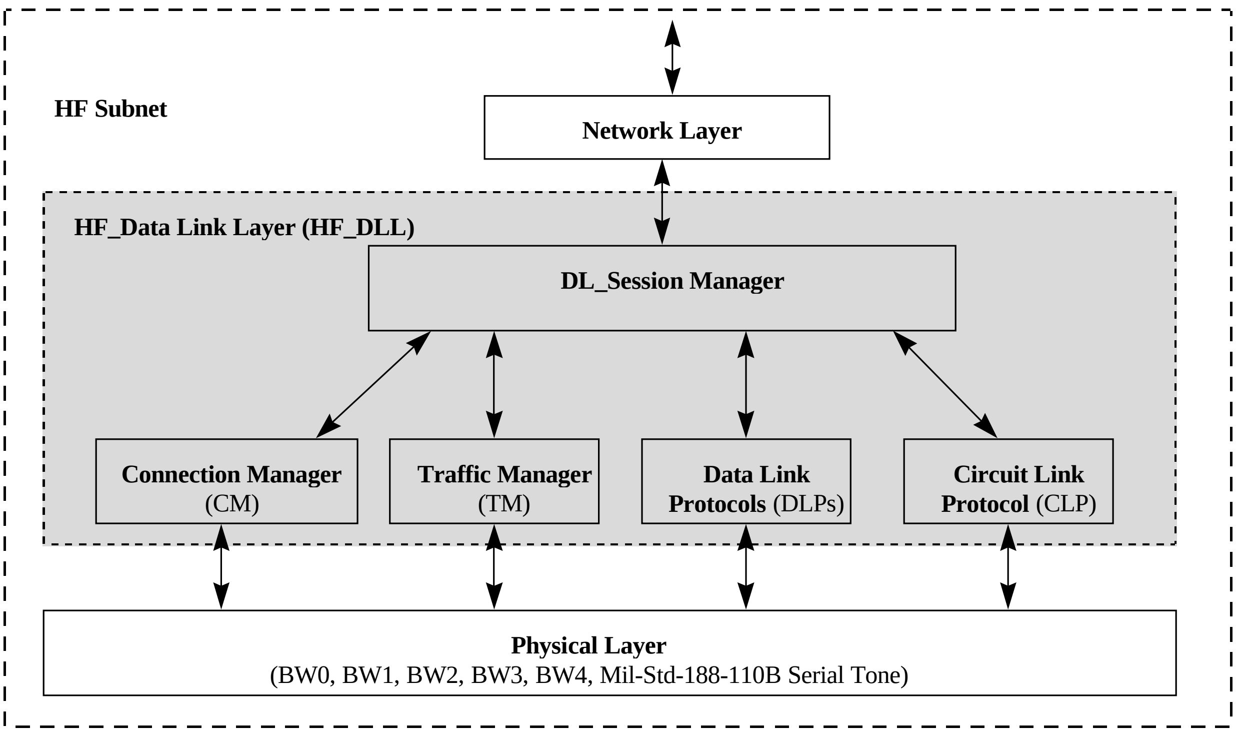

FIGURE 4.1

Conceptual view of the third generation architecture

It is important to note that Appendix C of MIL-STD-188-141B was still in preparation as this paper was being written; as a result, the protocol definitions and performance data presented here represent a ‘snapshot’ of 3G-HF taken at one moment in time, and may change by the time the standard is ratified. The paper is intended to provide a useful overview of the basic concepts and salient features of the 3G-HF protocols defined in Appendix C. Space limitations make it impossible to present many protocol details in this paper. These will, however, be presented in full in the published MIL-STD-188-141B specification.

4.2 Constituent waveforms

The 3G-HF system uses a family of scaleable burst waveform signaling formats for transmission of all control and data traffic signaling. Reference [1] provides a more detailed overview of these burst modems and their performance. Scaleable burst waveforms are defined for the various kinds of signaling required in the system, so as to meet their distinctive requirements as to payload, duration, time synchronization, and acquisition and demodulation performance in the presence of noise, fading, and multipath. All of the burst waveforms use the basic 8-ary PSK serial tone modulation at 2400 symbols per second that is also used in the MIL-STD-188-110A serial tone modem waveform. The low-level modulation and demodulation techniques required for the new system are similar to those of the 110A modems. TABLE 4.1 provides an overview of the characteristics of the various burst waveforms.

In contrast to the MIL-STD-188-110A waveform, the waveforms used in the 3G-HF system are designed to balance the potentially conflicting objectives of maximizing the time-diversity achieved through interleaving, and minimizing on-air time and link turn-around delay. The latter objective plays an important role in improving the performance of ALE and ARQ systems, which by their nature require a high level of agility.

TABLE 4.1

Waveform characteristics overview

Wave-form	used for	burst duration	pay load	preamble	FEC coding	inter-leaving	data format	effective code rate
BW0	Connection Set-Up (CSU) PDUs	613.33 ms 1472 PSK symbols	26 bits	160.00 ms 384 PSK symbols	rate = 1/2, k = 7 convolutional (no flush bits)	4x13 block	16-ary orthogonal Walsh function	1/96
BW1	Traffic Set-Up (TSU) PDUs; High-Rate Data Link acknow-ledgement PDUs	1.30667 sec 3136 PSK symbols	40 bits	240.00 ms 576 PSK symbols	rate = 1/3, k = 9 convolutional (8 flush bits)	16x9 block	16-ary orthogonal Walsh function	1/144
BW2	High-Rate Data Link traffic data PDUs	640 + (n*400) ms 1536 + (n*960) PSK symbols, n = 3, 6, 12, or 24	n*188 1 bits	26.67 ms 64 PSK symbols (for equalizer training)	rate = 1/4, k = 8 convolutional (7 flush bits)	none	32 unknown/ 16 known	variable: 1 / 1 to 1 / 4
BW3	Low-Rate Data Link traffic data PDUs	373.33 + (n*13.33) ms 32n + 896 PSK symbols, n = 64, 128, 256, or 512	8n+25 bits	266.67 ms 640 PSK symbols	rate = 1/2, k = 7 convolutional (7 flush bits)	24x24, 32x34, 44x48, or 64x65 convol-utional block	16-ary orthogonal Walsh function	variable: 1 / 12 to 1 / 24
BW4	Low-Rate Data Link acknow-ledgement PDUs	640.00 ms 1536 PSK symbols	2 bits	none	none	none	4-ary orthogonal Walsh function	1 / 1920

It is illuminating to compare the probability of linking under these conditions for the 3G-HF system vs. MIL-STD-188-141A ALE. A connection set-up (CSU) requires a two-way exchange of CSU PDUs conveyed using the BW0 waveform. As shown, the 3G-HF system is likely to achieve a probability of linking equivalent to that of 141A ALE, under conditions of roughly 5-7 dB lower signal-to-noise ratio (SNR).

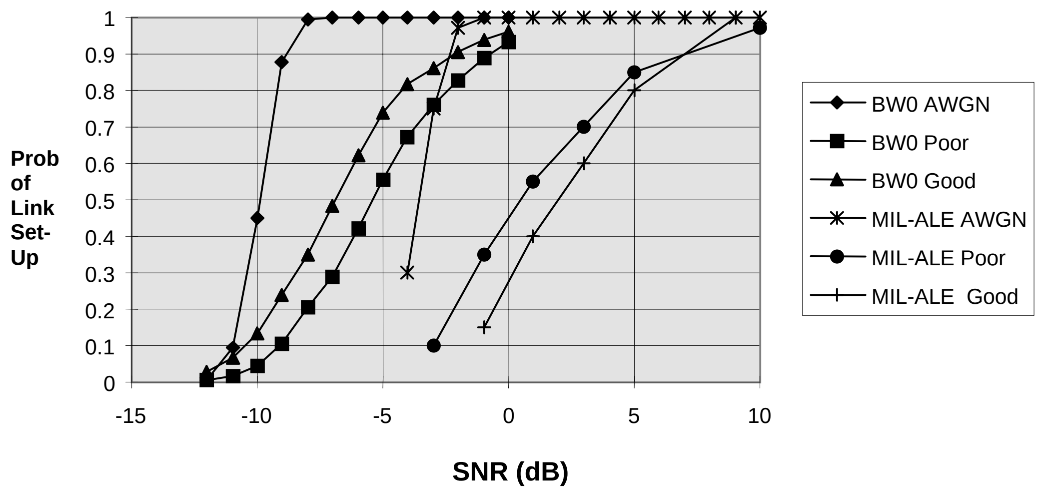

FIGURE 4.2

BW0 probability of linking vs. MIL-ALE

4.5 Connection manager

The connection manager is responsible for the connection set-up phase (otherwise known as ALE). Third-generation ALE (3G-ALE) is designed to quickly and efficiently establish one-to-one and one-to-many (both broadcast and multicast) links. It uses a specialized carrier-sense-multiple-access (CSMA) scheme to share *calling channels*, and monitors *traffic channels* prior to using them to avoid interference and collisions. Calling and traffic channels may share frequencies, but the system is likely to achieve better performance when they are separate. Each calling channel is assumed to be associated with one or more traffic channels that are sufficiently near in frequency to have similar propagation characteristics. The concept of associated control and traffic frequencies can be reduced to the case in which the control and traffic frequencies are identical.

4.6 Scanning

As in second-generation ALE (2G-ALE), 3G-HF receivers continuously scan an assigned list of calling channels, listening for 2G or 3G calls. However, 2G-ALE is an asynchronous system in the sense that a calling station makes no assumption about when a destination station will be listening to any particular channel. The 3G-HF system includes a similar asynchronous mode; however, synchronous operation is likely to provide superior performance under conditions of moderate to high network load.

When operating in synchronous mode, all scanning receivers in a 3G-ALE network change frequency at the same time (to within a relatively small timing uncertainty). It is not necessary that all stations monitor the same calling channel at the same time, however. By assigning groups of network members to monitor different channels in each scanning dwell, calls directed to network member stations will be distributed in time and/or frequency, which greatly reduces the probability of collisions among 3G-ALE calls. This is especially important under conditions of high traffic load. The set of stations that monitor the same channels at the same time is called a *dwell group*.

4.7 Addressing

One of the functions of the subnetwork layer is translation of upper-layer addresses (*e.g.*, IP addresses) into whatever peculiar addressing scheme the local subnet uses. The addresses used in 3G-ALE PDUs are 11-bit binary numbers. In a network operating in synchronous mode, these addresses are partitioned into a 5-bit dwell group number and a 6-bit member number within that dwell group. Up to 32 dwell groups of up to 60 members each are supported (1920 stations per net). Four additional reserved addresses in each group (1111xx) are available for use by stations calling into the network (see Figure 4.3).

When it is desired to be able to reach all network members with a single call, and traffic on the network is expected to be light, up to 60 network member stations may be assigned to the same dwell group. However, this arrangement is subject to calling channel congestion. To support heavier call volume than the single group scheme will support, the network members should be distributed into multiple dwell groups.

4.8 Synchronous dwell structure

The nominal duration of each synchronous dwell is 4 seconds. The timing structure within each synchronous dwell time is as follows.

Slot 0: Tune and Listen Time. During slot 0, radios are switched to the new receiving frequency, couplers are tuned as necessary, and so on. (A calling station will instead tune to the frequency on which it will handshake during that dwell.) Following tuning, every receiver samples a traffic frequency in the vicinity of the new calling channel, attempting to detect traffic. This provides recent traffic channel status before stations get involved in a handshake.

Calling Slots. The remainder of the dwell time is divided into 4 equal-length calling slots. These slots are used for the synchronous exchange of PDUs on calling channels. 800 ms per slot allows for a 26-bit PDU, 70 ms of propagation, and synchronization uncertainty of ± 50 ms.

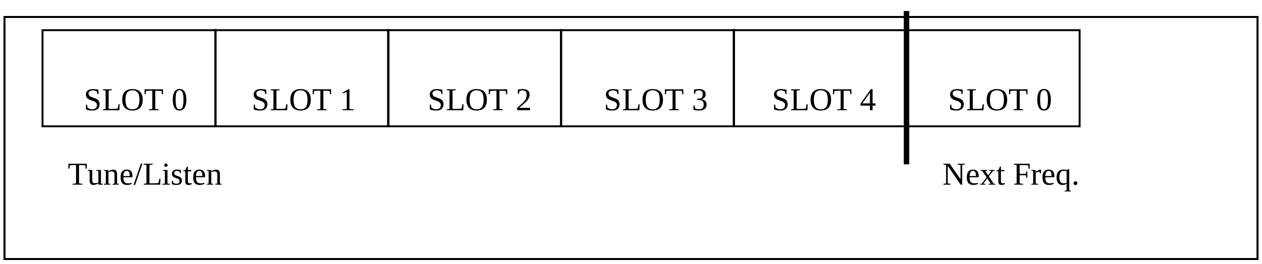

FIGURE 4.3

Synchronous dwell structure

4.9 Synchronous calling overview

The 3G-ALE synchronous calling protocol seeks to find suitable channel(s) for traffic and transition to them as quickly as possible. This minimizes occupancy of the calling channels, which is important in any CSMA system. 3G-ALE calls indicate the type of traffic to be carried (in general terms), and the first traffic channel(s) that will support this grade of service will be used. Note that the default system does not spend time seeking the *best* channels for traffic.

Figure 4.4 and Figure 4.5 show two methods of connection set up and traffic exchange: separate control and traffic frequencies, and identical control and traffic frequencies. Each figure shows connection set-up, a transition to the traffic frequency, traffic set-up, and finally traffic exchange. When directed to establish a link to a prospective *responding* station, the *calling* station will compute the frequency to be scanned by the responding station during the next dwell and randomly (though not uniformly) select a calling slot within that dwell time. During slot 0 of that dwell, the calling station listens to a nearby traffic channel that has recently been free of traffic. (A station with multiple receivers listens to multiple traffic channels during slot 0). If not calling in slot 1, the calling station listens on the calling channel for other calls during the slots that precede its call. If it detects a handshake, it will defer its call until after that handshake. If no other handshake is detected before its chosen slot, the calling station sends a probe PDU (described later) in that slot and listens for a response in the next slot.

When a station receives a probe PDU addressed to it, it responds in the next slot with a handshake PDU. The handshake PDU may indicate a good traffic channel for transmissions to that responding station. If it does, the stations will immediately proceed to the negotiated traffic channel for a traffic set-up handshake, followed by the traffic described in the call.

If the handshake on a channel does not conclude in a transition to traffic channels, the handshake will proceed to the next calling channel in the responding station's scan list during the next dwell. The calling station will again select a slot and start the handshake in this new dwell by sending a probe PDU.

Listen-before-transmit. Every calling station that will send a PDU during a dwell must listen on its intended calling channel during the slot that precedes its transmission (except Slot 1). If it detects a handshake during that slot, it should defer its call. Thus, calls in early slots in a dwell may pre-empt calls in later slots.

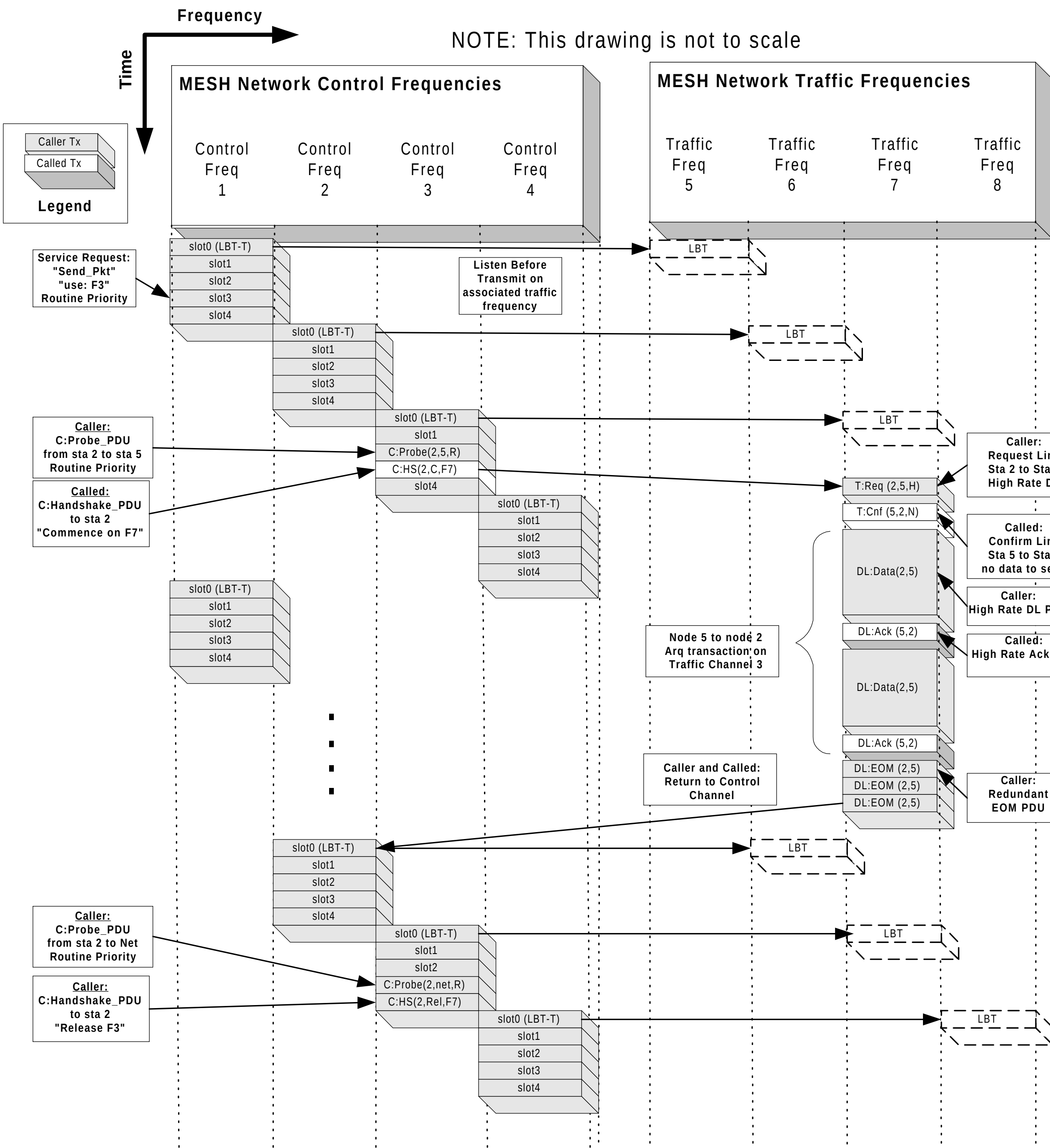

FIGURE 4.4

Concept overview: separate control and data frequencies

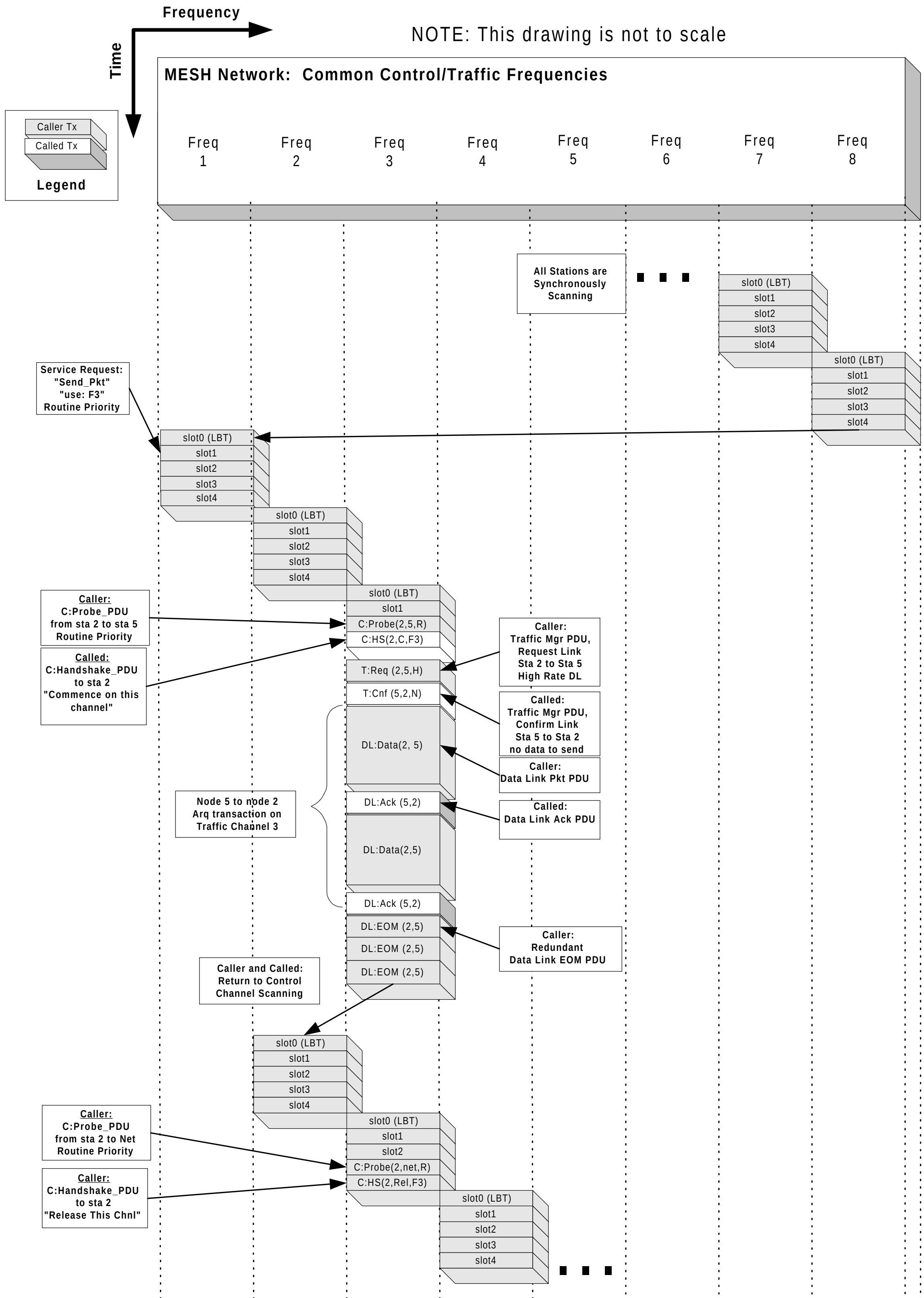

FIGURE 4.5

Concept overview: shared control and data frequencies

Prioritized Slot Selection. The probability of selecting a slot is randomized over all usable slots, but the probabilities for higher-priority calls are skewed toward the early slots while low-priority calls are skewed toward the later slots. Such a scheme will operate reasonably well in all situations, while hard partitioning of early slots for high and late slots for low priorities would exhibit inordinate congestion in crisis and/or routine times. A suggested set of probabilities is shown below for a four-priority implementation:

TABLE 4.2

Probability of slot selection

Call Priority	*Slot 1*	*Slot 2*	*Slot 3*	*Slot 4*
Flash	***50%***	***30%***	***15%***	***5%***
Immediate	***30%***	***50%***	***15%***	***5%***
Priority	***5%***	***15%***	***50%***	***30%***
Routine	***5%***	***15%***	***30%***	***50%***

4.10 Third generation ALE PDUs

The contents of the various PDUs used by the connection manager are shown in Figure 4.6. The PDUs used in one-to-one calling are the probe and handshake PDUs, as noted above. These two key PDUs are discussed below. Readers are directed to the formal draft specification for a description of the more specialized PDUs.

4.10.1 Probe PDU

The probe PDU needs to convey sufficient information to the called station so that it will know whether it wants to respond, and what to listen for during the traffic channel check. The probe PDU must therefore report

- the calling station identification
- the priority of the incoming call
- what resources will be needed if the call is accepted
- what traffic channel quality is required.

The call type field in the probe PDU includes a bit that flags high priority calls, an indication of whether analog voice or a modem will be used for traffic, and the duration of the traffic. Duration is categorized as a “short” data message, a “long” data message, or unbounded duration (virtual circuit). The specific meaning of short versus long is left to the discretion of the network designer. The 3G-DLP uses this field to optimize its choice of data transfer waveform and protocol. The full called station address is not needed in the probe PDU, because the called station group number is implicit in the choice of channel that carries the probe.

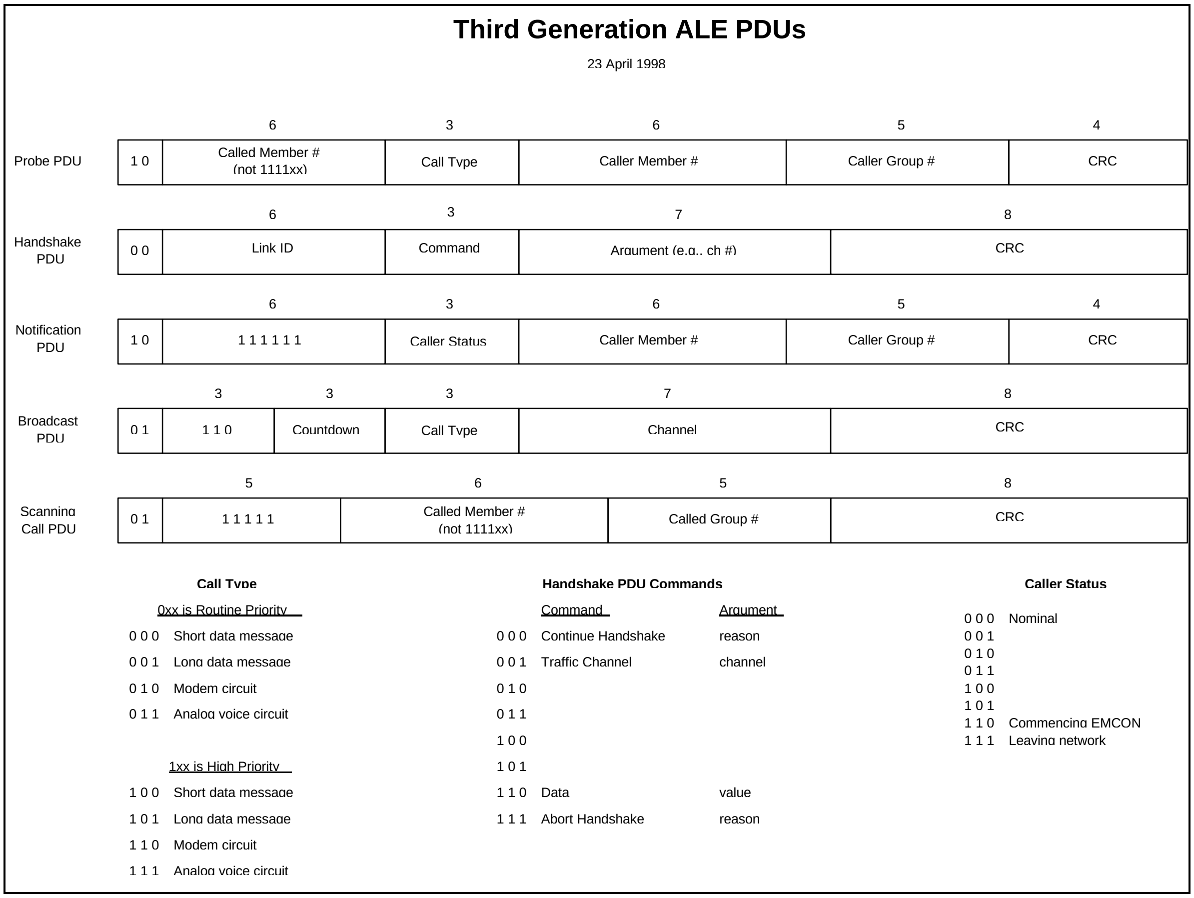

FIGURE 4.6

Third generation ALE PDUs

4.10.2 Handshake PDU

The Handshake PDU is used by both calling and called stations. It is sent only after a Probe PDU has established the identities of both stations in one-to-one link establishment, as well as the key characteristics of the traffic that will use the link. The Link ID field contains a 6-bit hash of the 11-bit addresses of the calling and responding stations. The commands carried in Handshake PDUs include the following:

Continue Handshake	The handshake will continue for at least another two-way handshake and will proceed to the next assigned called station dwell frequency. The argument is a Reason code (*e.g.*, Poor Propagation or Channel Busy).
Traffic Channel	This is the final command sent on a calling channel. The argument is the channel number on which the responding station will listen for traffic. Following this command, both stations proceed to that traffic channel.
Abort Handshake	This command immediately terminates the handshake and needs no response. It is analogous to the TWAS preamble in second-generation ALE.
Data	This command is used only in special-purpose protocols. The argument carries previously requested data.

4.11 One-to-one link establishment

The one-to-one linking protocol identifies a frequency for traffic use relatively quickly (*i.e*., within a few seconds), and minimizes channel occupancy during this link establishment process. It will conclude the link establishment process as soon as a suitable frequency has been identified, and makes no attempt to find the best available frequency.

4.12 Multicast calls

A multicast call employs a reserved member number in each affected dwell group (similar to a 2G-ALE Net Call). 3G-ALE controllers must be programmed to recognize multicast addresses to which they subscribe. That is, multicast addresses are reserved within a network, not in the protocol standard.

The multicast protocol works as follows:

1. A Probe PDU is sent as usual, but it contains a multicast responding-station address, which suppresses responses by the responding station(s). The Call Type field specifies whether the multicast link will carry modem or analog voice traffic when established.

2. The *caller* then sends a Traffic Channel PDU in the immediately following time slot that directs the responding stations to a traffic channel where they are to listen for the type of traffic specified in the call. This completes the multicast calling protocol.

4.13 Other CM PDUs

Other types of connection manager PDUs are provided to support broadcast calls, notification calls, and asynchronous scanning calls. Readers are referred to the formal draft specification for a description of these connection manager services.

4.14 Traffic manager

Traffic set-up is accomplished using the BW1 40-bit burst waveform. The traffic management (TM) protocol is used to co-ordinate traffic exchanges on connections established using the connection management (CM) protocol. Following the end of the connection set-up (CSU) phase in which a connection is established, the stations participating in the connection enter the traffic set-up (TSU) phase in which the traffic management protocol is used to establish a traffic link on which traffic can be delivered.

Once a connection has been established, the stations participating in it have determined:

1. the identities of the stations intended to participate in the connection;
2. the connection topology: point-to-point, multicast, or broadcast;
3. the link mode: packet or circuit (“hard link”)
4. the HF frequency (or “traffic channel”) that will be used for signaling within the connection.

In addition, the initiating station knows it can transmit a traffic management PDU in the first transmit time-slot of the TSU phase.

During the TSU phase, the participating stations exchange TM PDUs in order to determine:

1. which data link protocol(s), waveform(s), and/or baseband modulation formats will be used to deliver traffic on the connection;
2. the priority of the traffic to be delivered;
3. the fine time synchronization required for the MIL-STD-188-141B Appendix C High-Rate and Low-Rate Data Link Protocols, on traffic links established for packet traffic.

TABLE 4.3
Traffic management (TM) PDU format

field name	size (bits)	values	description
Protocol	2	3 (fixed)	distinguishes TM PDUs from HDL_ACK and HDL_EOM PDUs (equal to 11 binary)
Priority	2	In all TM_REQ and some TM_CONF PDUs (i.e., TM PDUs having Type = TM_REQUEST or TM_CONFIRM), indicates the priority level of the traffic (if any) that the sender of the PDU intends to send on the traffic link once it is established.	
		0	Flash: highest priority
		1	Immediate
		2	Priority
		3	Routine: lowest priority
Dest Addr	11	any	address of the station to which this PDU is being sent. In the PDUs exchanged to manage a broadcast or multicast traffic link, this address may be the all-ones broadcast address (“BCaddr”) or a net multicast address (“MCaddr”) with all ones in the dwell group number subfield.
Source Addr	11	any	address of the station that is sending this PDU. Is always the station address of a single station — never a multicast or broadcast address.
Type	3	Type of PDU, indicating its role in the Traffic Management protocol. Note that the state diagrams and other materials refer to, for instance, a “TM_REQ PDU”; this is a Traffic Management PDU whose Type field value is 0 (TM_REQUEST).	
		0	TM_REQUEST: A PDU with Type = TM_REQUEST is sent in order to request that a traffic link be established between the station sending the TM_REQUEST and the other stations specified by the PDU’s destination address.
		1	TM_CONFIRM: A PDU with Type = TM_CONFIRM is sent in response to a received TM_REQUEST PDU, to confirm the sender’s readiness to participate in a traffic link.
		2	TM_TERM: a PDU with Type = TM_TERM is sent in order to terminate the station’s participation in a traffic link (during or after link establishment), and when sent by the link master, to terminate the link as a whole.
		3..7	reserved
Argument	3	variant field whose usage and meaning depend on the value of the Type field.	
CRC	8	any	8-bit Cyclic Redundancy Check (CRC) computed across the remaining 32 bits of each Traffic Management PDU, using the generator polynomial $X^8 + X^7 + X^4 + X^3 + X^1 + 1$.

If the traffic link is to be used for multicast communication, the participating stations conduct a roll-call procedure to determine which of the stations in the multicast group received the CSU signaling and are now present on the traffic frequency.

When traffic exchanges have been completed on a traffic link, the traffic management protocol is used to co-ordinate the participating stations’ departure from the traffic link.

Behavioral descriptions of the traffic management protocol refer to three kinds of PDUs: TM_REQ, TM_CONF, and TM_TERM. These PDUs all have the format shown in TABLE 4.3, and are distinguished from one another by the values of their Type fields:

- a “TM_REQ PDU” is a traffic management PDU having Type = TM_REQUEST (0)
- a “TM_CONF PDU” is a traffic management PDU having Type = TM_CONFIRM (1)
- a “TM_TERM PDU” is a traffic management PDU having Type = TM_TERM (2).

Figure 4.7 presents a state diagram defining the behavior of the traffic management protocol in setting up traffic links for packet traffic, and illustrates the state diagram notation used in the protocol specification. In the state diagram, each state transition is labeled with an event, an optional condition, and zero or more actions. This indicates that the state transition occurs whenever the event occurs *and* the condition obtains (is TRUE), causing the associated actions to be performed. In the diagram,

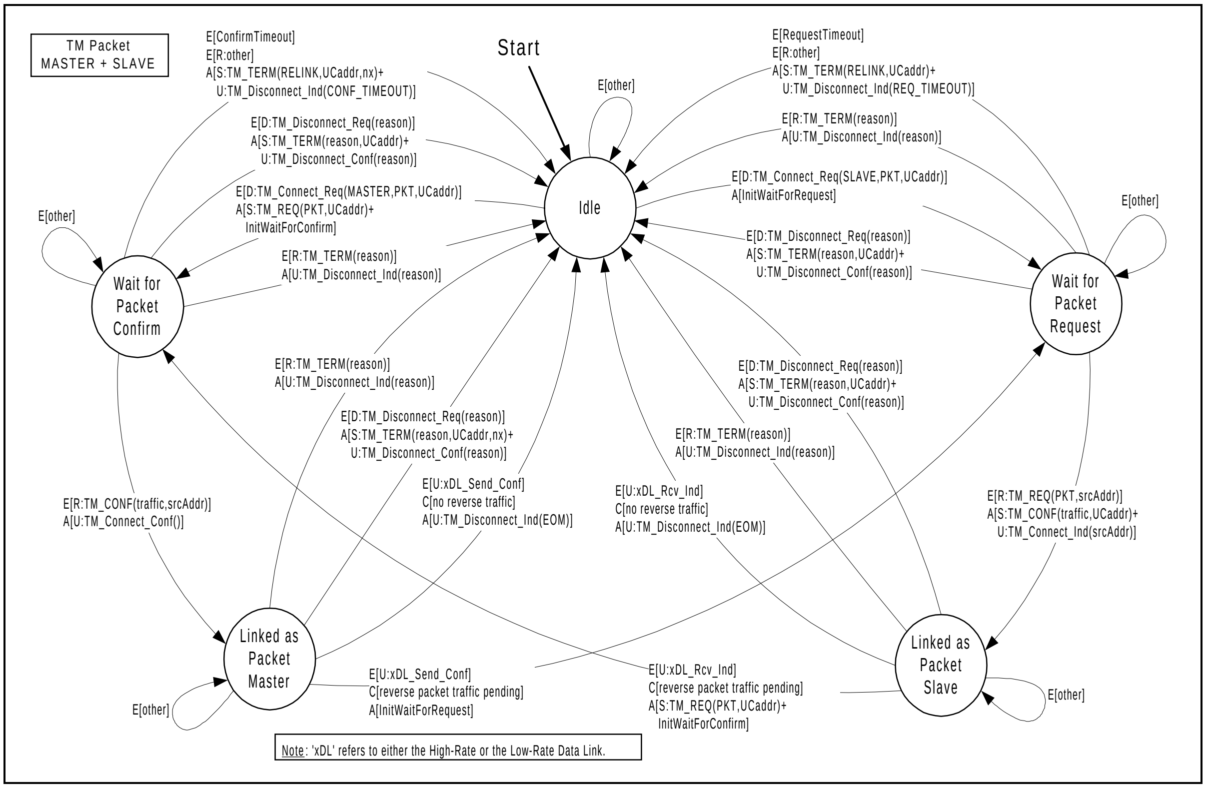

FIGURE 4.7

Traffic manager state diagram (excerpt)

- the name of each event is shown in brackets preceded by the letter 'E';
- the description of each condition is shown in brackets preceded by the letter 'C'; and
- the names of the actions associated with a transition are shown in brackets preceded by the letter 'A'.

Where a transition is labeled with two or more events, this indicates that the transition occurs whenever any of the events occurs. The prefix 'R:' in the name of an event indicates that the event is the receipt of a PDU from the remote station. 'D:' indicates that the event is an Traffic Management service primitive passed *down* to TM from a higher-layer entity; 'U:' indicates a lower-layer service primitive passed *up* to TM from a lower-layer entity. Similar conventions are used in naming actions, with the addition that the prefix 'S:' in the name of an action indicates that the action sends a PDU to the remote station.

4.15 Data link protocols

Two data link protocols are provided: one for large messages and/or good channel conditions, and a second for short messages and/or poor channel conditions. Both data link protocols use memory combining and do not require data rate adaptation. This greatly simplifies the protocols while dramatically increasing throughput under nearly all channel conditions and signal to noise ratios.

4.15.1 High-rate data link protocol

The high-rate data link protocol (HDL) is used to provide acknowledged point-to-point delivery of datagrams from a transmitting station to a receiving station across an already established HF link, with selective retransmission (ARQ) of data received in error. The datagram passed to the high-rate data link for delivery is an ordered sequence of up to 7,634,944 8-bit data bytes (octets). The high-rate data link protocol is best suited to delivering relatively large datagrams under good to fair HF channel conditions. By contrast, the low-rate data link protocol described below provides better performance for all datagram lengths under fair to very poor HF channel conditions, and under all channel conditions for short datagrams.

Data transfer by HDL begins after the stations have already established the data link connection in the traffic set-up phase, in so doing negotiating the fact that HDL will be used (as opposed to LDL or some other mechanism), the number of data packets to be sent in each HDL_DATA PDU, and the precise time synchronization of data link transmissions.

In an HDL data transfer, the sending station and the receiving station alternate transmissions in the manner depicted in Figure 4.8, the sending station transmitting HDL_DATA PDUs containing payload data packets, and the receiving station transmitting HDL_ACK PDUs containing acknowledgements of the data packets received without errors in the preceding HDL_DATA PDU. If either station fails to receive a PDU at the expected time, it sends its own next outgoing PDU at the same time as if the incoming PDU had been received successfully. The times at which the burst waveforms conveying HDL_DATA, HDL_ACK, and HDL_EOM PDUs may be transmitted are determined precisely by the initial data link timing established during the traffic set-up phase.

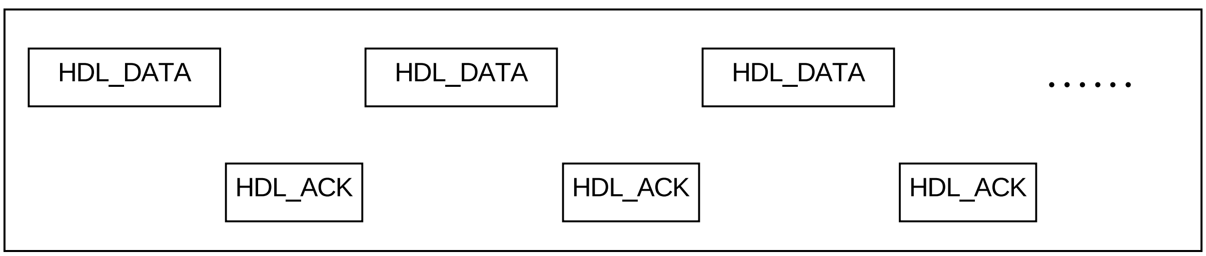

FIGURE 4.8.

HDL data transfer overview

The end of a data transfer is reached when the sending station has transmitted HDL_DATA PDUs containing all of the payload data in the delivered datagram, and the receiving station has received these data without errors and has acknowledged their successful delivery. When the sending station receives an HDL_ACK PDU indicating that the entire contents of the datagram have been delivered successfully, it sends an HDL_EOM PDU repeated as many times as possible within the duration of an HDL_DATA PDU, starting at the time at which it would have otherwise transmitted the next HDL_DATA PDU, to indicate to the receiving station that the data transfer will be terminated. This link termination scenario is depicted in Figure 4.9.

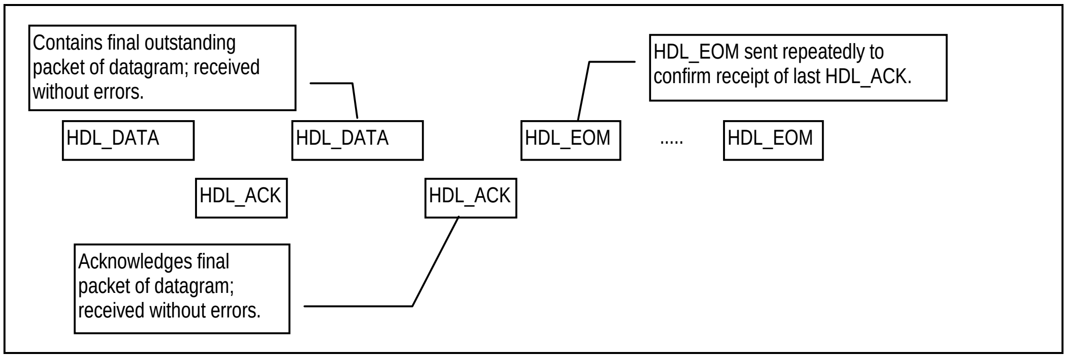

FIGURE 4.9

HDL link termination scenario overview

4.15.2 High-rate data link PDUs

Figure 4.10 depicts the format and contents of the high-rate data link's PDUs. Each HDL_DATA PDU is a sequence of 24, 12, 6, or 3 data packets, in which each packet is composed of 1881 bits of payload data (1864 bits of user data plus a 17-bit sequence number added by the data link). During the traffic set-up phase, the user process determines the number of data packets per HDL_DATA PDU so as to deliver the user data efficiently, shortening the HDL_DATA PDU whenever the entire datagram is short enough to fit within the shortened PDU. Once it is determined, the number of data packets per HDL_DATA PDU for the current datagram delivery is communicated to the receiving station in the traffic set-up sequence (see Section 4). Thereafter, every HDL_DATA PDU contains the same number of data packets until the entire datagram has been delivered. The BW2 waveform is used to transmit each HDL_DATA PDU; further description of BW2 processing is provided below.

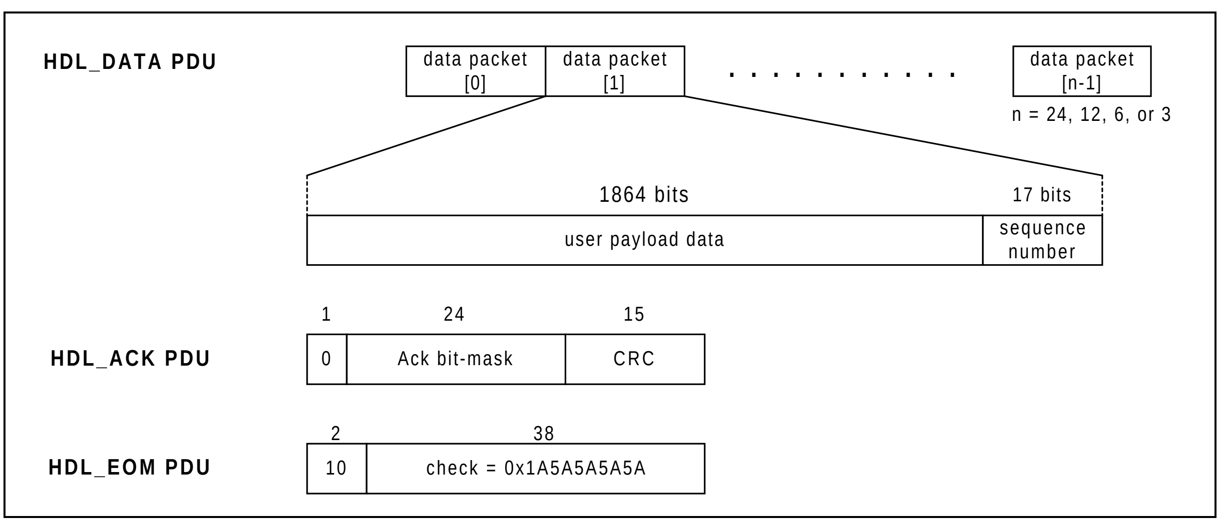

FIGURE 4.10

High-rate data link PDUs

The HDL_ACK PDU is used to convey data acknowledgements from the receiving station to the sending station. Each HDL_ACK PDU contains acknowledgements for the immediately preceding HDL_DATA PDU sent in the opposite direction; each bit in the 'Ack bit-mask' field acknowledges a single corresponding data packet from the HDL_DATA PDU. The HDL_ACK PDU contents are protected by a 15-bit CRC.

The HDL_EOM PDU is transmitted in the forward direction, in place of an HDL_DATA PDU, when the sending station receives an error-free HDL_ACK PDU indicating that the entire user datagram has been delivered to the receiving station without errors.

BW1 is used to transmit both the HDL_ACK and HDL_EOM PDUs. The marker bits at the beginning of each PDU are used to distinguish the two kinds of PDUs.

4.15.3 High-rate ARQ processing

Figure 4.11 depicts the manner in which an HDL_DATA PDU is incorporated into a BW2 burst transmission. Each data packet in the HDL_DATA PDU is extended by appending to it a 32-bit CRC, followed by an encoder flush sequence consisting of seven zero bits. The resulting sequence of extended packets is FEC-encoded using a ¼-rate convolutional encoder. The encoder produces four output bits, $Bitout_0$ .. $Bitout_3$, for each input bit. As each packet is encoded, the bits from each encoder output are accumulated into a block, resulting in four blocks of coded bits, $EBlk_0$ .. $EBlk_3$. Each time a data packet is transmitted in an HDL_DATA PDU, only one of the four blocks of coded bits from the packet is transmitted, starting with $EBlk_0$ the first time. (The original contents of the packet can be recovered from any single block of coded bits that is received without errors.) Each time the data packet cannot be decoded without errors and must be retransmitted, a different block of coded bits is transmitted; blocks are transmitted in the order $EBlk_0$, $EBlk_1$, $EBlk_2$, $EBlk_3$, $EBlk_0$, ... The transmission of different blocks of coded bits for each packet, in successive transmissions of the packet, provides additional information that can be used in decoding the packet.

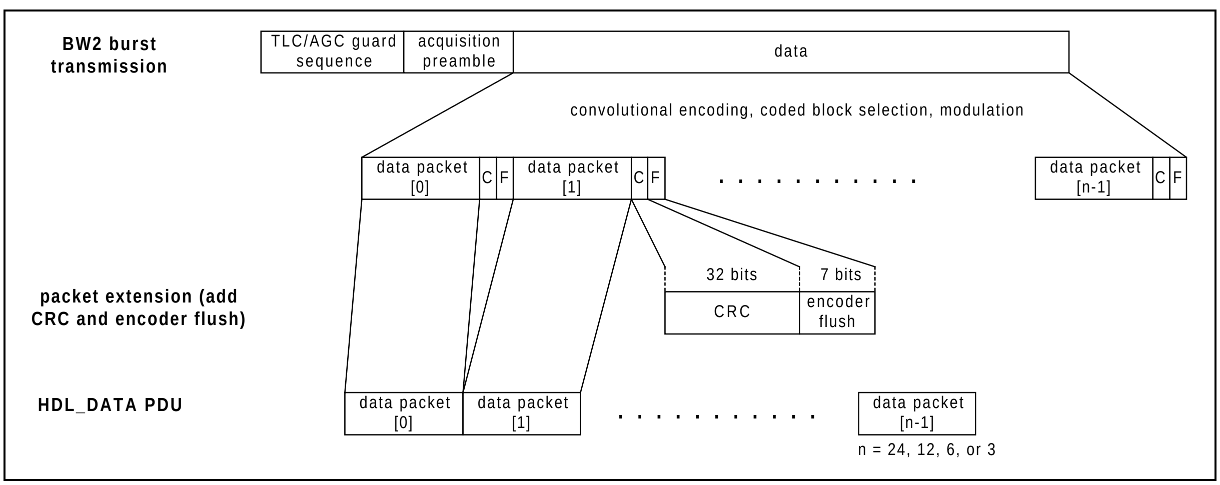

FIGURE 4.11

BW2 encoding and modulation of HDL_DATA PDU

The sequence of coded bits is modulated using a modulation process similar to that of the 110A serial tone waveform at 4800 bits per second. This results in a sequence of unknown/known symbol frames, each consisting of 32 unknown symbols (8-ary PSK symbols carrying three bits each, Gray-coded), followed by 16 known symbols. A TLC/AGC guard sequence and a sequence of 64 known symbols used for initial equalizer training are prepended to the beginning of the frame sequence. Note that no acquisition preamble is required in the BW2 waveform, since the precise time of arrival of each BW2 transmission is known once the traffic set-up handshake is used to establish data link timing.

4.16 Low-rate data link protocol

The low-rate data link protocol (LDL) is used to provide reliable acknowledged point-to-point delivery of datagrams from a transmitting station to a receiving station across an already-established HF link. The datagram passed to the low-rate data link protocol entity for delivery is an ordered sequence of up to 16,384,000 8-bit data bytes (octets). The low-rate data link protocol provides better performance than does the high-rate data link protocol for all datagram lengths under fair to very poor HF channel conditions, and under all channel conditions for short datagrams.

Data transfer by LDL begins after the traffic management sublayer has already established the data link connection, in so doing negotiating the fact that LDL will be used (as opposed to HDL), and the precise time synchronization of data link transmissions. In an LDL data transfer, the sending station and the receiving station alternate transmissions in the manner depicted in Figure 4.12, the sending station transmitting LDL_DATA PDUs containing payload data packets, and the receiving station transmitting LDL_ACK PDUs each containing an acknowledgement of whether or not the data packet in the preceding LDL_DATA PDU was received without error. If either station fails to receive a PDU at the expected time, it sends its own next outgoing PDU at the same time as if the incoming PDU had been received successfully. The times at which the burst waveforms conveying LDL_DATA, LDL_ACK, and LDL_EOM PDUs may be emitted are determined precisely by the initial data link timing established during the traffic set-up phase.

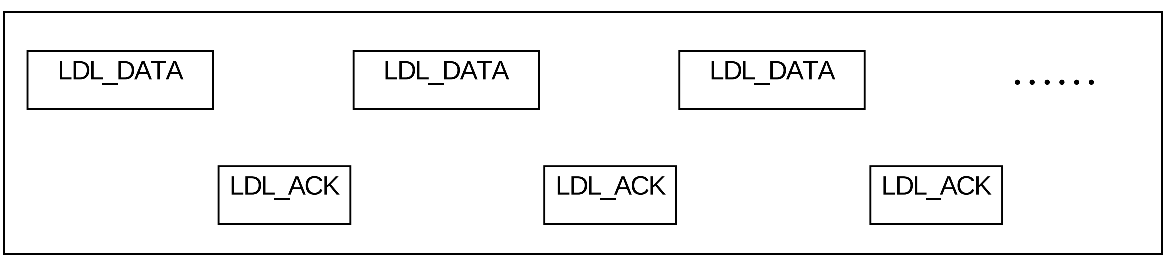

FIGURE 4.12

LDL data transfer overview

The end of a data transfer is reached when the sending station has transmitted LDL_DATA PDUs containing all of the payload data in the delivered datagram, and the receiving station has received these data without errors and has acknowledged their successful delivery. When the sending station receives an LDL_ACK PDU indicating that the entire contents of the datagram have been delivered successfully, it sends an LDL_EOM PDU repeated as many times as possible within the duration of an LDL_DATA PDU, starting at the time at which it would have otherwise transmitted the next LDL_DATA PDU, to indicate to the receiving station that the data transfer will be terminated. This link termination scenario is depicted in Figure 4.13.

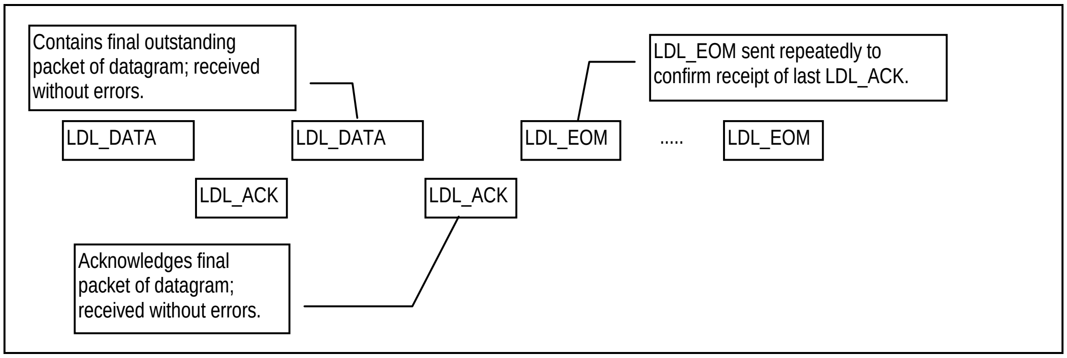

FIGURE 4.13

LDL link termination scenario overview

4.16.1 Low-rate data link PDUs

Figure 4.14 depicts the format and contents of the low-rate data link PDUs. Each LDL_DATA PDU carries a single data packet composed of payload data (512, 256, 128, or 64 *bytes* (octets) of user data) followed by a 17-bit sequence number and an 8-bit control field (presently unused) added by the low-rate data link. During the traffic set-up phase, the user process determines the number of data bytes per LDL_DATA PDU so as to deliver the user data efficiently, shortening the LDL_DATA PDU whenever the entire datagram is short enough to fit within the shortened PDU. Once it is determined, the number of data bytes per LDL_DATA PDU for the current datagram delivery is communicated to the receiving station in the traffic set-up sequence. Thereafter, every transmitted LDL_DATA PDU contains the same number of data bytes until the entire datagram has been delivered.

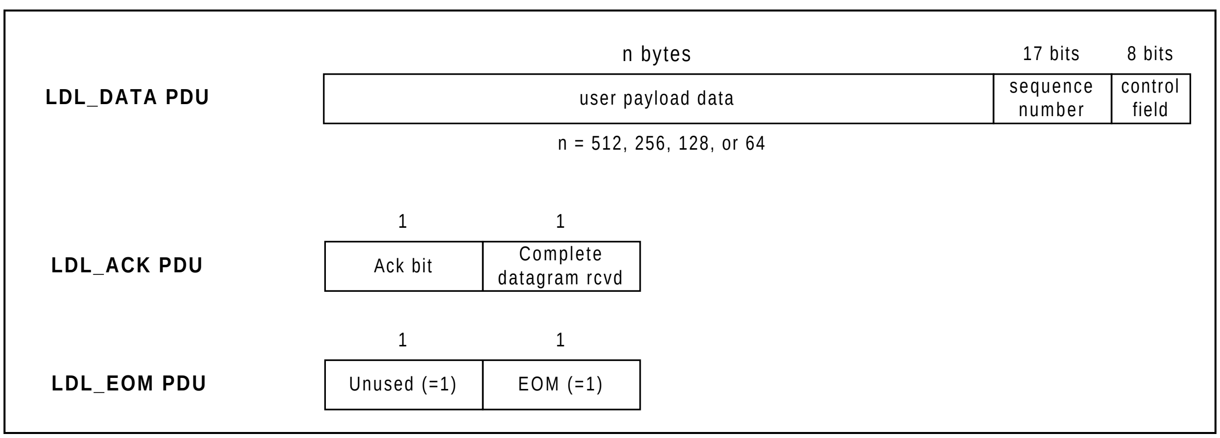

FIGURE 4.14

Low-rate data link PDUs

The LDL_ACK PDU is used to convey data acknowledgements from the receiving station to the sending station. Each LDL_ACK PDU contains acknowledgements for the immediately preceding LDL_DATA PDU sent in the opposite direction; the single bit in the ‘Ack bit’ field acknowledges the single data packet in the LDL_DATA PDU. The ‘Complete datagram rcvd’ bit is set when the receiving station determines that it has received all of the contents of the datagram without errors, so that the data link transfer can be ended. The LDL_ACK PDU is transmitted using the very robust BW4 waveform. Due to the robustness of the waveform, no CRC is included in the PDU.

The LDL_EOM PDU is transmitted in the forward direction, in place of an LDL_DATA PDU, when the sending station receives an error-free LDL_ACK PDU indicating that the entire user datagram has been delivered to the receiving station without errors. This PDU is also transmitted using the BW4 waveform. LDL_EOM PDUs are distinguished from LDL_ACK PDUs by context: any BW4 transmission in the *forward* direction of a low-rate data link transfer is an LDL_EOM PDU.

4.16.2 Low-rate ARQ processing

Figure 4.15 depicts the manner in which an LDL_DATA PDU is incorporated into a BW3 burst transmission. The LDL_DATA PDU is extended by appending to it a 32-bit CRC, followed by an encoder flush sequence consisting of seven zero bits. The resulting data sequence is FEC-encoded using a ½-rate convolutional encoder. The encoder produces two output bits, $Bitout_0$ and $Bitout_1$, for each input bit. As each packet is encoded, the bits from each encoder output are accumulated into a block, resulting in two blocks of coded bits, $EBlk_0$ and $EBlk_1$. Each time a data packet is transmitted in an LDL_DATA PDU, only one of the two blocks of coded bits from the packet is transmitted, starting with $EBlk_0$ the first time. (The original contents of the packet can be recovered from any single block of coded bits that is received without errors.) Each time the data packet cannot be decoded without errors and must be retransmitted, a different block of coded bits is transmitted; blocks are transmitted in the order $EBlk_0$, $EBlk_1$, $EBlk_0$, $EBlk_1$, ... The transmission of different blocks of coded bits for each packet, in successive transmissions of the packet, provides additional information that can be used in decoding the packet.

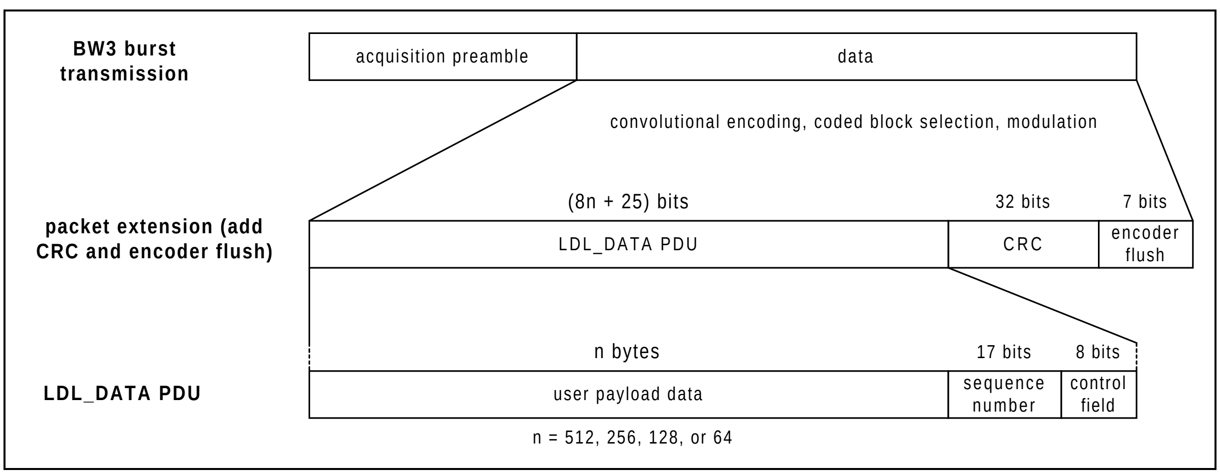

FIGURE 4.15

BW3 encoding and modulation of LDL_DATA PDU

The sequence of coded bits is interleaved using a convolutional block interleaver similar to that of MIL-STD-188-110A. The interleaved bit sequence is then modulated using a modulation process similar to that of the 110A serial tone waveform at 75 bits per second. This results in a sequence of 16-ary orthogonal Walsh frames, each composed of 16 PSK symbols, with each 16-ary Walsh frame representing the values of four coded bits fetched from the interleaver.

An acquisition preamble of 640 8-ary PSK symbols is prepended to the beginning of the Walsh frame sequence. This sequence is used for initial channel estimation but need not be used for synchronization, since the precise time of arrival of each BW3 transmission is known once the traffic set-up handshake is used to establish data link timing.

4.6.3 Data link performance

Data link protocol performance is typically defined and measured in terms of the average throughput in bits per second. The throughput achieved is dependent on many factors, including HF channel conditions, both short term and long term, as well as datagram size. Protocol parameters, which may be selected by the user or automatically adapted, can also play a large role in determining throughput. These parameters may include modem transmission rates, frame or packet size, link turn around times, *etc*.

Data link protocol performance for the high-rate data link protocol (HDL) and the low-rate data link protocol (LDL) are presented in this section. Also presented in this section, for comparison, is the measured performance of the U.S. Federal Standard 1052 data link protocol (FS-1052) [2]. FS-1052 uses the U.S. MIL-STD-188-110A serial tone modem waveform. The autobaud capability of the modem is used extensively as the protocol adapts the baud rate and interleaver settings to the HF channel conditions. Reference [3] presents an overview of the protocol as well as some performance data. Reference [4] presents the asymptotic performance of the data link protocol.

The throughput rates presented in the following figures account for the entire time spent on the Traffic frequency after the completion of a successful call set-up (CSU), including the time for the traffic set-up handshake and the time for the transfer of the message. For HDL and LDL, the traffic set up times are based on the BW1 handshake. In the case of FS-1052, the data link's own handshake timing is included instead of the BW1 handshake timing.

Figures 4-16 through 4-21 present simulated throughput performance for HDL and LDL, and compare their performance to measured 1052 performance for 50, 500, and 50K byte files. Each data link protocol's performance is given for the additive gaussian noise (AWGN) and CCIR Poor HF channel conditions. AWGN refers to a single non-fading path with additive white Gaussian noise. CCIR Poor refers to dual fading paths, separated by 2 ms, each path with a 2 sigma fading bandwidth of 1 Hz.

In comparing the HDL and LDL throughput performance curves against FS-1052, one must be careful to understand some of the basic differences between the two data link protocol techniques. The throughput curves for FS-1052 do not contain a two-way handshake between the two stations in transfers of smaller files (*i.e.,* 50 and 500 bytes); instead, FS-1052 sends a single one-way herald at the beginning of the data transfer. The handshake in the front of the data transfer can dominate throughputs for small files. For larger size files, FS-1052 uses a two-way Call-Response handshake and link termination as part of the file transfer, and therefore allows for a better comparison between techniques. Also note that FS-1052's user-selected forward bit-rate setting can bias its indicated throughput for smaller files. A high initial bit rate setting helps for high SNR at the cost of reduced throughput for low SNR conditions. The FS-1052 data presented here uses 1200 b/s as the initial forward bit rate setting. Finally, overall performance of either system is influenced by the call set-up and traffic set-up mechanisms as well as by the data link protocol. It is hard to compare the performance of the data link protocols in isolation because the data link protocol is not always the limiting factor in the performance of the system as a whole.

In comparing HDL to LDL some interesting observations can be made. HDL has been optimized for higher throughputs for fair to good channel conditions. LDL has been optimized for better operation under severe to fair channel conditions through its choice of its underlying waveform. LDL's orthogonal signaling allows for better throughput performance at lower signal to noise ratios than does HDL's 8-ary PSK signaling. Also, LDL performs better for small message sizes because it incurs less overhead than HDL at these sizes. HDL incurs less protocol overhead for larger files because of its better ratio of forward- to back- channel transmission times. Therefore, HDL is more efficient at the high end of the curves for larger file sizes.

It is important to see that in all of the conditions presented, either HDL or LDL provides throughput performance at least roughly equal to that of FS-1052; in many conditions, the performance of HDL or LDL is dramatically superior. In many conditions, HDL or LDL achieves throughput performance equal to that of FS-1052 at much lower SNR. This fact allows the delivery of equivalent FS-1052 throughput performance at a substantial reduction in radio transmit power. Additionally, for good SNR conditions, HDL can deliver substantially higher throughputs than can FS-1052.

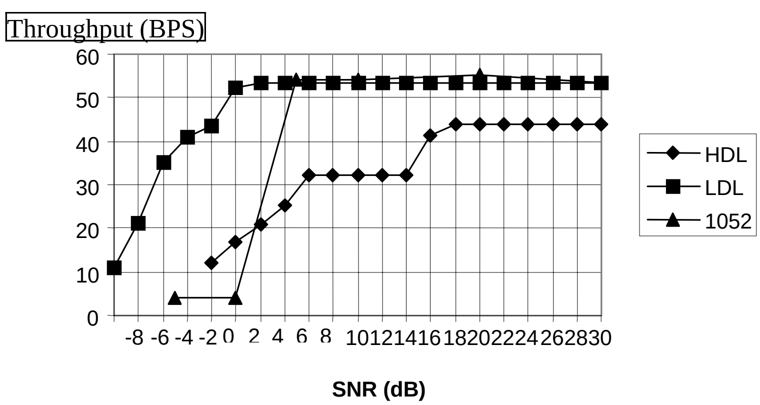

FIGURE 4.16

Gaussian, 50-byte message

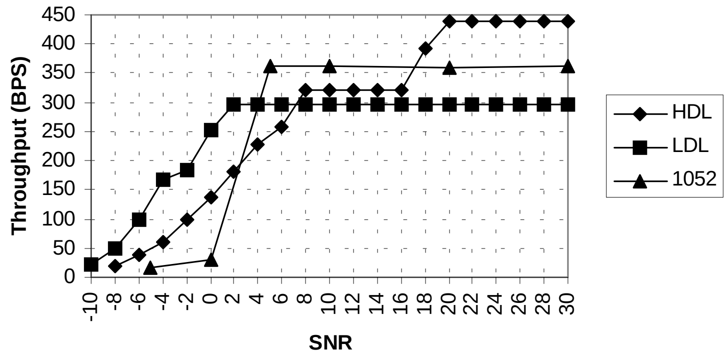

FIGURE 4.17

Gaussian, 500-byte message

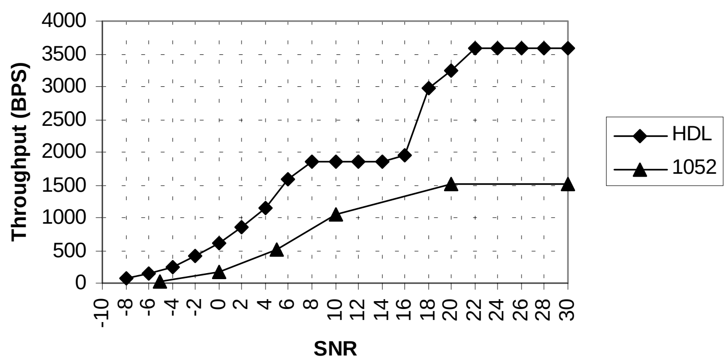

FIGURE 4.18

Gaussian, 50-kbyte message

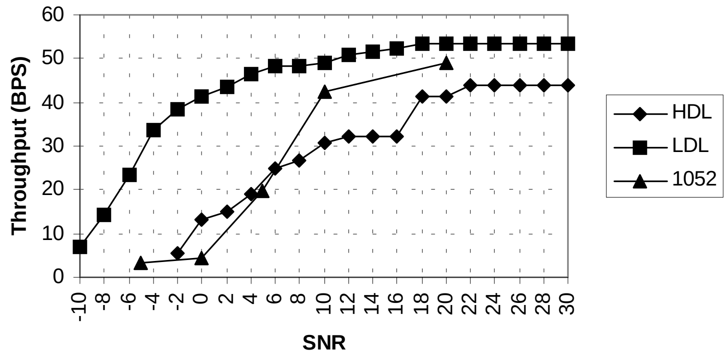

FIGURE 4.19

CCIR Poor, 50-byte message

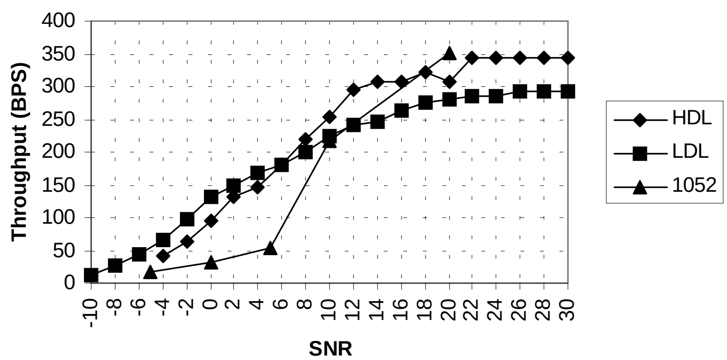

FIGURE 4.20

CCIR Poor, 500-byte message

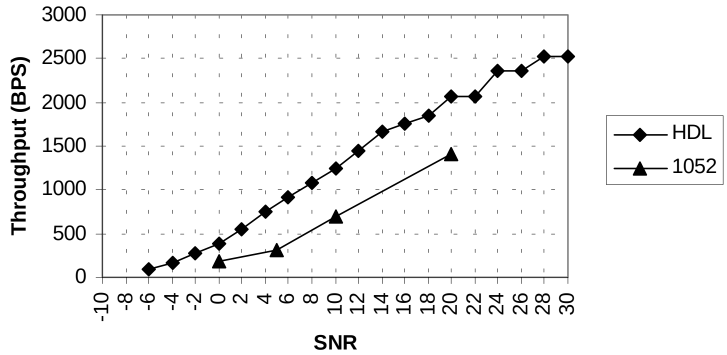

FIGURE 4.21

CCIR Poor, 50-kbyte message

4.17 Circuit link protocol

4.17.1 Overview

The circuit link controller monitors and coordinates traffic on an established circuit link. It provides a simple listen-before-transmit access control mechanism:

- Transmission of new outgoing traffic is inhibited whenever the CLC detects that the circuit link is busy, due to either traffic being received from another station, or traffic currently being transmitted by the local station.
- At the end of each outgoing or incoming traffic transmission, the CLC continues to inhibit transmission of new outgoing traffic for the duration of a backoff interval.

In addition, the CLC provides a traffic timeout indication when an interval of a specified duration elapses in which no outgoing or incoming traffic is detected on the circuit link, allowing the traffic link to be terminated when no longer required.

The CLC is employed only on simplex circuit links (in which all signaling by participating stations is transmitted on a single frequency).

4.17.2 Behavior

The state diagram in Figure 4.22 specifies the behavior of the circuit link controller. In its Idle state, the CLC does not monitor link traffic or control access to the link. When a circuit link is established, the CLC is placed in its Ready state and begins to monitor traffic on the circuit link. From Ready it proceeds to its Transmit or its Receive state, respectively, when outgoing or incoming traffic is detected. When the traffic ends, the CLC proceeds into its Backoff state where it waits for the duration of a backoff interval before returning to its ready state. If incoming signal presence is lost during reception of incoming modem signaling, the CLC enters its “Signal Reacq” state, where it remains until either incoming signal presence is reacquired, or a “ReacqTimeout” event occurs causing the CLC to decide that the incoming traffic has ended and proceed to its backoff state. Note that on the occurrence of any event not shown here, the CLC will take no action and remain in its current state.

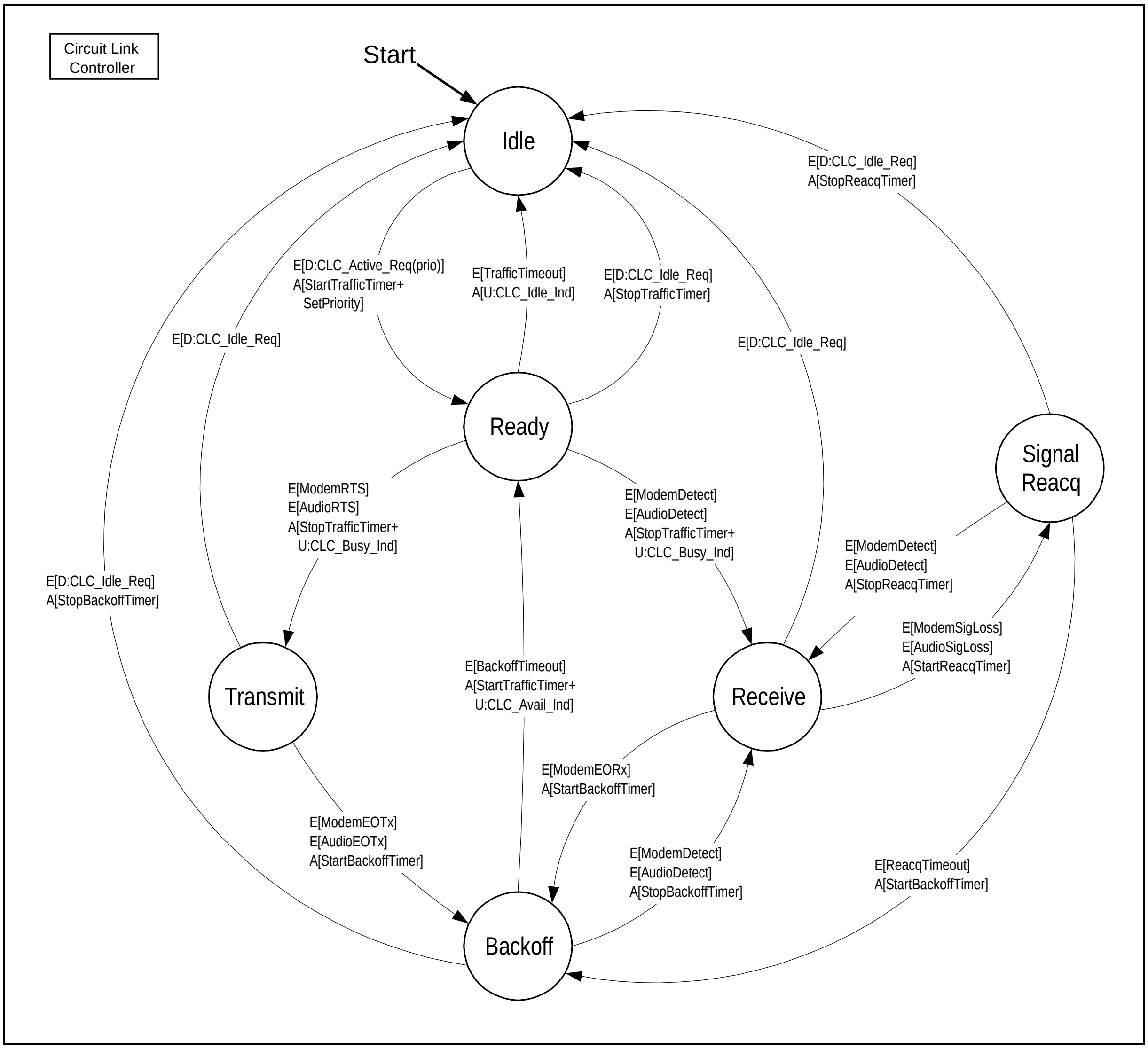

FIGURE 4.22

CLC state diagram

4.18 Simulation framework

This section describes the simulation framework used to predict the performance of 3G-HF subnetworks. Specifically, this section will discuss the modeling approach to be used and the details of physical layer modeling. In addition, waveform performance modeling and the application of the modeling framework to developing performance expectations for 3G-HF subnetworks will be discussed briefly.

4.19 Modeling approach

MIL-STD-188-141B Appendix C defines a synchronous ALE scheme for media access and two synchronous data link protocols to be used to convey data once a link has been established. Heretofore, the performance of ALE protocols and of data link protocols have been treated as separate topics. With ALE protocols, the performance metrics of concern are probability of linking given channel conditions, time to link given channel conditions, and optimality/suitability of the selected channel. With data link protocols, the performance metric of interest is typically data throughput (in bits per second) as a function of message size and channel conditions. However, for HF *subnetworks* (combining ALE, data link, and probably higher-layer protocols), the performance metrics that are ultimately of interest are message delivery rate and message delivery delay as a function of message generation rate, message size, number of network nodes, propagation conditions, and available bandwidth. The performance metrics for the ALE and data link protocols in isolation certainly provide some insight into HF subnetwork performance. However, these metrics by themselves are insufficient to predict HF subnetwork performance for subnetworks containing more than two nodes, as they do not account for the effects of arbitration failures and resulting collisions, collision avoidance mechanisms (if any), message routing, and the allocation of bandwidth between the ALE and data link protocols.

There presently exists no HF-industry-standard framework to permit evaluation and comparison of HF subnetwork designs in a simulation environment. A framework for simulation of HF subnetwork performance is required which provides:

1. Simulation of multiple network nodes (stations) in varying and dynamic network topologies.
2. Simulation of varying and dynamic network traffic loads.
3. Simulation of the media access and associated client protocols, and data link and associated client protocols within each network node.
4. Simulation of the physical layer to include:
    - HF skywave, Near Vertically Incident Skywave (NVIS), and groundwave propagation characteristics.
    - The time-varying nature of HF propagation.
    - Waveform performance in such propagation conditions.
    - The effects of on-air traffic collisions.
    - The effects of collocation and RF interference.
5. Results that are in good agreement with empirical data from on-air testing.

In the absence of an HF industry standard, the simulation framework described herein is based on the commercially-available event-driven simulation framework, OPNET[1]. This tool readily satisfies requirements 1, 2, and 3 above and is flexible enough to support the addition of an HF-specific physical layer model. The next three sections describe the means by which an HF physical layer model is included in the chosen framework.

4.20 Physical Layer Modeling

Ideally, the event-driven simulation framework would be mated with the same data flow simulation of the constituent 3G-HF waveforms and the Watterson channel model used to validate the waveform design to create an event-driven/data-flow simulation hybrid. However, this inclusion of a data flow simulation results in unacceptably long execution times when performed on desktop computers/workstations. As a result, some sort of simplified model of waveform performance is required to determine detection and demodulation outcomes for each constituent waveform. In turn, a simplified waveform performance model requires a propagation model, which is discussed in the next section.

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[1] OPNET was recently used by the NETWARS Project Standards Working Group of the Joint Chiefs of Staff as the basis for a tactical communications modeling interoperability standard [11]. OPNET is a registered trademark of MIL3 Inc.

4.20.1 Physical Layer Modeling: Propagation

The propagation model must provide median SNR and propagation delay information as a function of time-of-day, frequency, node position, type of antenna, and antenna orientation. IONCAP [5] (or one of its more recent incarnations) is the logical choice to provide such information. Four options of increasing complexity exist:

1. Network nodes are fixed in space; median SNR and propagation delay between network nodes are fixed in time to produce a 'snapshot' of the diurnal variation.
2. Network nodes are fixed in space; median SNR and propagation delay between network nodes vary with time to reflect diurnal propagation variations.
3. Network nodes are mobile; median SNR and propagation delay between grid points are fixed in time. The actual median SNR and propagation delay is based on the grid points closest to the node pair.[2]
4. Network nodes are mobile; median SNR and propagation delay between grid points vary with time to reflect diurnal propagation variations. The actual median SNR and propagation delay are based on the grid points closest to the node pair.

Options 1-4 can all be used to specify median SNR and propagation delay for each node pair during the course of simulation. Each requires that a database of increasing complexity be generated prior to simulation and the application of suitable interpolation methods. Initially, to minimize the complexity of the model, network nodes will be fixed in space. To further minimize initial complexity, and since groundwave propagation is comparatively benign, we defer inclusion of a groundwave propagation model for a later time and thus assume nodes are spaced so as to ensure that groundwave propagation is not relevant. Similarly, collocation effects will be neglected initially.

At this point, we have a model for long-term (hourly) variation of node-pair SNR with time. Such long-term variations are required to properly stress 3G-HF connection management. An intermediate-term (fractions of minutes) variation in node-pair SNR as reported and characterized in [6] is applied to modulate the node-pair SNR values obtained from IONCAP. Such intermediate-term variations are required to properly stress third generation data link protocols. In addition, short-term (seconds and fractions of a second) variation of node-pair SNR with time due to fading is included, as it is of critical interest in a system employing short burst waveforms

Since the time constant of the short-term SNR variations can vary so as to be greater than, comparable to, or less than the duration of the waveforms of interest, an SNR profile as a function of time for each waveform arrival is used to predict detection and demodulation outcomes. A simple model of short-term node-pair SNR variation would periodically sample a random process having a particular distribution and autocorrelation function, and use this process to modulate a nominal node-pair SNR value as provided by the longer-term SNR variation processes. CCIR Reports 266-6[7] and 304-2[8] give examples of distributions and autocorrelation behavior measured for various propagation conditions and fading mechanisms. However, the choice of distribution (Rayleigh, Rician, Log-Normal, and others) and autocorrelation behavior is problematic, as it depends strongly on the fading mechanism(s) in effect, and there exists no generally-accepted method to select the appropriate distribution and autocorrelation function in effect between any two locations at any given time.

[2] If one node is located directly on a grid point, two-dimensional interpolation is available to reduce inaccuracies with respect to a direct calculation using the exact node positions [12].

For this reason, a slightly more complicated approach akin to that adopted in CCIR Recommendation 520-1[9] is used, where the dispersive properties of HF channels are modeled in the manner described by Watterson [10], having discrete, independent arrivals (time dispersion, referred to as differential time delay or multipath delay) each having IID Rayleigh amplitude (frequency dispersion, referred to as frequency spread or Doppler spread). CCIR Recommendation 520-1 assumes two discrete arrivals and provides a set of differential time delay and frequency spread values that are representative of common HF propagation conditions to be used in assessing and comparing the performance of HF data modems. It is proposed that this same framework and set of operating conditions is suitable for assessing and comparing the performance of HF networking schemes.

Thus each pair (permutation) of network nodes is provided with a fading process, as described previously, which is used to modulate the nominal SNR of the transmitted signal as determined from the long-term and intermediate-term node-pair SNR process. The fading process of each node pair is statistically independent from all other node-pair fading processes. Each node-pair has its own set of fading process parameters which can be chosen separately to be commensurate to node locations and time of day.

4.20.2 Physical layer modeling: collision

Having an SNR profile for each waveform arrival (or segment of a waveform arrival for longer transmissions) is necessary but not sufficient to determine detection and demodulation outcomes. A collision model is also required that accounts for the node-pair SNR profiles of both signal and interferer(s), and variations in arrival time. The collision model is as follows:

$$SNR_{Seff\,(dB)}(n) = 10\log_{10}\left(SNR_S(n) \Big/ 1+\sum_{i=0}^{M-1} SNR_{Ii}(n) \right)$$

where SNR_{Seff} is the instantaneous *effective* SNR affecting receipt of the desired signal (accounting for the effects of interfering signals), SNR_S is the instantaneous signal to noise ratio of the desired signal (ignoring interference), SNR_{Ii} is the instantaneous SNR of the i^{th} interferer, and M is the number of interferers in existence during reception of the desired signal. Time dispersion (multipath delay) is integrated out prior to this calculation. This effective SNR profile is then used to predict waveform detection and demodulation outcomes.

Certain simplifying assumptions are employed in this collision model: the separate multipath arrivals from the various interferers are all uncorrelated, the signal multipath arrivals are uncorrelated, and the background noise, signal arrivals and interferer arrivals are all uncorrelated. These assumptions are generally valid for serial tone waveforms (on which the third generation protocols are based), assuming that all arrivals, taken pairwise, have time-of-arrival variations greater than one PSK symbol duration (approx. 0.5 ms). It is accepted that there will be occasions when these assumptions are not satisfied; however, such occasions should be rare in practice as a consequence of typical multipath delay values and variations in both clock drift and propagation delay.

4.21 Waveform Performance Modeling

Waveform performance models must be developed that determine detection and demodulation outcomes based on the effective SNR profile. This task has been performed for the BW0 and BW1 waveforms, and it is proposed that the framework presented here is sufficient to develop a performance model for the remaining third generation waveforms.

4.22 Application of simulation framework to third generation HF messaging protocols

At this time, the focus of this simulation effort is on third generation connection management and traffic management, as these are the least-explored protocols to date. The data link protocols have been prototyped and evaluated on-air and are well understood at this time. At the time of this writing, the physical layer model and waveform performance models for BW0 and BW1 have been implemented, and the implementation of connection management and traffic management protocols is underway.

Once the connection management and traffic management protocols have been implemented, they will be mated with existing models of the FS-1052 data link protocol and the MIL-STD-188-110A serial tone waveform to assess the performance of an HF subnetwork employing these protocols. It is understood that the performance of FS-1052 is not identical to that of the third generation data link protocols. However, this approach will provide timely insight into the performance of the connection management and traffic management protocols, since their performance is expected to be the limiting factor on aggregate HF subnetwork performance in many cases. Models of the third generation data link protocols can be incorporated as time allows, to more precisely characterize the aggregate performance of third generation HF subnetworks. It is expected that the simulation results obtained using the FS-1052 model will be conservative.

As stated previously, the HF subnetwork performance metrics that are ultimately of interest are message delivery rate and message delivery delay as a function of message generation rate, message size, number of network nodes, propagation conditions, and available bandwidth. The simulation framework described herein will be used to assess subnetwork performance in this manner.

4.23 Conclusion

This paper has described the third generation HF messaging system currently being proposed for Appendix C of the forthcoming U.S. MIL-STD-141B revision. The overall framework containing connection management, traffic management, data link protocol, and circuit link protocols has been described. Some performance data on the scaleable burst HF modem utilized for connection and traffic management have been presented. Additionally, performance data on the newly defined data link protocols have been presented and contrasted with the performance of U.S. Federal Standard 1052. Recognizing the difficulties in predicting the performance of an entire 3G-HF system, a framework for simulation, utilizing a combination of OPNET and statistical HF waveform models, has been presented.

The third generation HF messaging system presented in this paper promises to provide significant improvements in capability and performance relative to systems based on present standards such as MIL-STD-188-141A and FED-STD-1052. Work completed to date includes the initial design of the system, the design and simulation of some of the basic components of the system, and establishment of a framework suitable to the accurate modelling of the entire system.

Future work will implement the simulation capability and provide accurate performance comparisons between the third generation HF system and systems based on existing standards.

PART II. SYSTEM ENGINEER'S GUIDE

CHAPTER 5

IMPLEMENTER/SYSTEM ENGINEER'S HANDBOOK

5.1 Aspects of system design

When the need for a new communications capability between two or more points is first envisioned, and HF radio is suggested as a possible solution, the sponsoring agency must conduct a preliminary system design and feasibility study to analyze and define the requirements. This study will verify that HF is the appropriate means of communication for the set of system requirements pending, and that the costs for the new system are reasonable.

5.1.1 Definition and analysis of requirements

A rigorous analysis of the expectations and requirements for the new system should show whether or not this communication medium is proper for this application. Some of the factors that support the use of HF radio over other means of communication are:

- **Distance**
  The distances between the terminal points are suitable for HF propagation, and are too long for line-of-sight (LOS) radio (with repeaters, if necessary), or for microwave radio. HF radio propagation supports long-distance communications except when conditions are unfavorable.

- **Reliability**
  The reliability of HF radio is not as great as that of other mediums because of its susceptibility to atmospheric disturbances.

- **Terrain**
  Impassible terrain (such as mountains or oceans) or international borders between the terminal points may preclude the use of other media, making HF radio communication a viable alternative.

- **Traffic**
  HF radio communication is typically used for voice or low data rate communication. This alternative is viable if the amount of traffic to be passed via the HF system is small enough to be satisfied by one or two HF radio channels.

- **Priority**

The priority and sensitivity of the traffic is such that the performance and reliability of HF systems will be satisfactory.

- **Costs**
  The costs to install, maintain, and operate the HF system are less than those of any other means of communications that could satisfy the requirements.

- **Solar cycle**
  The predicted long-range propagation forecasts are favorable for the frequency set that is planned to be used.

- **Frequency Set**
  Adequate frequencies to support the HF mission can be obtained. Also if this unit will be operating with other units already using HF radio frequencies, the choice of this frequency band may already be dictated.

- **Real estate**
  Adequate real estate (sites) are or can be made available to support the mission. Typically a HF radio installation would required a larger antenna, making the location (field, building top, *etc*.) of the antenna a major consideration.

A review of the above items will determine if the use of HF radio equipment is appropriate for the proposed application.

5.1.2 Preliminary system design and feasibility study

Once it has been determined that HF is a viable solution to the communications requirement, then a preliminary system design and feasibility study must be conducted. The items which the system engineer must consider make up the remainder of this chapter.

5.1.3 Trunking/routing plans

The trunking and routing plans in the design analysis provide information on the number and types of channels needed to interconnect each of the terminals within the HF system. If the radio system is to be a part of larger network of radios the implementing engineer will work with the network manager to identify all the stations or nodes to be included in the network as well as their geographical locations

The designer of trunking/routing plans must be aware of the physical location of each node and the relationship to other nodes in the network. He/she must identify any physical obstacle (*i.e.*, mountains, buildings, antenna, *etc*.) which may be present in the paths between the various nodes. He/she should be acquainted with the equipment located at each node, especially the power and antenna characteristics. He/she must be keenly aware of all the various propagation paths between the various stations involved (*i.e.*, skywave, groundwave, and line-of-sight). The network manager will need to know details about the characteristics and volume of the communications traffic that will be traveling between the various nodes at various times during the day. He/she must be aware of the communication interfaces that are connected to each node and how the loss of one or more of these interfaces could affect message traffic across the network. The manager must be made aware of the priority of messages through each node as well as the importance of each net member to the total mission of the network. If messages are to be forwarded through intermediate nodes to accommodate the case where coverage may not be universal, this special routing must be considered in his/her traffic analysis.

5.1.4 Frequency plan

Planning must begin early in the project to secure an adequate list of frequencies to support each link in the HF radio system so that uninterrupted operations are possible both day and night, at any time of the year, and throughout the whole 11-year solar cycle. Frequency prediction programs such as IONCAP, ICEPAK, or VOACAP are ideal for determining frequency requirements in different conditions. Annex 2 of this document provides detailed information about these propagation prediction programs and other methods that will aid the implementing engineer in determining a frequency plan.

5.1.5 Personnel manning requirements

To einsure that each station in the network is operated and maintained properly, an analysis of the numbers, training and experience of the personnel that will be required to staff each of the nodes in the network during the required period of service (*i.e.*, 8 hr/day, 12 hr/day, 24 hrs/day, 5 days/wk, or 7 days/wk) should be conducted early in the planning process. Are adequately trained personnel available? Or does the usage of new technology require that all personnel receive training on the new equipment? Who will provide the training? The vendor, an in-house training organization, or a combination of the two? Perhaps, some of the site personnel can receive on-the-job training from other site personnel.

5.1.6 Support requirements

The system designer must select a site having adequate access roads, water and electrical power supply, fuel for generators, telephone service, post office, medical facilities, and adequate housing and shopping areas for site personnel. In the vast majority of cases, the radio site will be located near a city or large town, and the support considerations mentioned above, will normally be available. But in a few cases obtaining these services may require special logistics effort.

5.1.7 Local user requirements

Local users' requirements include characteristics that may be specific only to this site. Some of these characteristics may include:

1. Priority or special messages needed only on this site;

2. Special licenses or building covenant releases, environmental impact statements (see Section 5.1.16);

3. Special power or communication needs specific to this site.

5.1.8 Modes of communications required (voice, data, image)

The original requirements from the using agency will specify what type(s) of traffic the HF station must be capable of handling. This may be voice only, both voice and data, or may indicate the need to handle other forms of information, such as image, facsimile, or encrypted voice. Each of these types of traffic will indicate additional pieces of equipment that must be considered by the system engineer.

5.1.9 Required Signal-to-noise ratios

The modes of communications required (*i.e*., voice, data, *etc*.) Will determine the required SNR. CCIR Recommendation 339-5 or similar guidance can be used to determine what SNR is needed for the required grade of service (orderwire quality, marginal commercial grade, or good commercial grade).

5.1.10 Modulation data rates

Information is transmitted in communications by means of sending time-varying waveforms generated by the source and transmitted to the destination. These waveforms may use either analog or digital techniques for coding. In radio communication, the varying waveforms derived from the source are transmitted by changing parameters of a sinusoidal wave at the desired transmission frequency. This process is referred to as modulation, and the sinusoidal is referred to as the carrier [Ulrich *et al*., 1988]. The radio transmitter must modulate the carrier before it is emitted from the antenna. The radio receiver must be designed to extract (demodulate) the information from the received signal. For analog systems the carrier wave is modified by the transmitter based on a information waveform. The analog receiver must demodulate the carrier to return to the information waveform. For digital systems the transmitter imposes a code based on the desired carrier information that must be decoded by the receiver and turned back into the original information. Important characteristics of a particular system are expressed in terms of distortion, error rate, bandwidth, occupancy, cost, *etc*. [Ulrich *et al*., 1988]

To review the differences between analog and digital we offer the following explanations:

a. Types of signals

(1) *Analog signals*

An analog signal is a continuous signal that varies in some direct correlation to a signal impressed on a transducer such as a microphone. The electrical signal may vary its frequency, phase, or amplitude, for instance, in response to a change in phenomena or characteristics such as sound, light, heat, position, or pressure. Analog signals do not lend themselves to extraction of signal from noise (regeneration) because there is no way to distinguish between the signal and any noise and distortion.

(2) *Digital signals*

A digital signal is a discontinuous electrical signal that changes from one state to another in discrete steps. The electrical signal could change its amplitude or polarity, for instance, in response to outputs from such devices as computers and teletypewriters. An analog signal such as voice may be converted to a digital form with an analog-to-digital converter and back to analog by a digital-to-analog converter.

(3) *Quasi-analog signals*

A quasi-analog signal is a digital signal that has been converted to a form suitable for transmission over an analog circuit. An important consideration in the use of quasi-analog signal transmission is that, while the signal remains in quasi-analog form, no signal regeneration can be performed.

b. Types of modulation

The modulation types discussed in this manual are defined in Table 5.1.

TABLE 5.1

Types of modulation

Designator	Modulation Form	Definition
cw	continuous wave	Defined as a radio wave of constant amplitude and constant frequency. As a modulation form, cw is defined as an interrupted continuous wave which is on-off keyed using Morse code.
AM	amplitude modulation	A form of modulation in which the amplitude of a carrier wave is varied in accordance with some characteristic of the modulating signal.
FM	frequency modulation	Amplitude changes of the modulating signal are used to vary the instantaneous frequency of the carrier wave from its unmodulated value.
SSB	single sideband	A form of amplitude modulation in which the carrier and one sideband are suppressed and the remaining sideband is transmitted. Also designated as USB and LSB, for upper and lower sideband.
ISB	independent sideband	A method of double-sideband transmission in which the information carried by each sideband is different.
RTTY	radio teletypewriter	A teletypewriter used in a communication system using radio circuits. Mark/space teletypewriter signals are modulated on radio systems either by a two-frequency shift of the carrier wave, called frequency-shift keying (FSK) or by a two-frequency audio signal, called voice frequency telegraph (VFTG) or audio frequency-shift keying (AFSK).
Data	binary digital	Information that is represented by a code consisting of a sequence of discrete elements. Digital data is produced by teletypewriters, digital facsimile equipment and computer terminals, among other sources. The signals are generally transmitted by digital-to-analog conversion to frequency-shift keying or phase-shift keying (PSK).

c. Modulation data rates

Normally this information will be furnished the system designer with the equipment specifications. Most modern HF data modems will be capable of several data rates. Care must be taken to assure that equipment interfaced together operates at the same data rates and uses the same modulation types.

5.1.11 Types of service (full time, on-call, encrypted, *etc*.)

This information will generally be provided with the initial system requirements.

5.1.12 Required circuit reliability

HF circuits are able to provide circuit reliability of 80% (19.2 hours/day) to 95% (22.8 hours/day). Modern, adaptive equipment such as ALE will operate near the high end of the reliability spectrum.

5.1.13 Terminal facilities required

The terms *terminal facilities* are used here to describe all of the physical plant, primary and auxiliary power, and environmental control systems required to support the new HF system.

5.1.14 Required system lifetime of service

The length of time that the new HF system will be expected to be in service, will have an impact on the selection of equipment. If the service is only for a short period of time (several months to a few years), it may be possible to operate with transportable or tactical equipment. Any longer life expectancy will usually require permanently installed equipment.

5.1.15 Real estate requirements

Because of the long wavelengths involved with HF operations, large amounts of real estate are required for HF stations. A simple dipole antenna usually requires at least one acre of ground, and a rhombic antenna can require from 5 to 15 acres. If the new HF system cannot use an existing site, then planning must begin very early in the project to find and acquire a suitable location. Additionally, if operation is contemplated on several circuits or full-duplex operation on one circuit, then the various antennas must be separated to prevent co-site interference. This antenna separation compounds the need for additional real estate. Sections 5.2.4 and 5.2.7 give more details on antenna site selection.

5.1.16 Environmental Impact Assessments

Frequently, the construction of an HF radio site, or the upgrade to an existing site, will require environmental impact assessments. This requirement is, more and more, becoming the norm, rather than the exception. If towers in excess of 200 feet are anticipated, or if the site is or planned to be located near an existing airport or heliport, then notification of the Federal Aviation Administration (FAA) is required.

5.1.17 Required operational date

The date that the station is required to be operational (or the new equipment is required to be operational) may be given in the original statement of requirements, or it may require negotiation with the operational agency. Some of the major system components may have delayed delivery times, so their delivery schedule should be factored into the plans for an operational date.

5.1.18 Cost estimate

The total project cost of development of a new or expanded HF radio capability includes more than just the cost of the equipment. This section contains the direct and indirect project costs including details about:

1. Start-up costs,
2. Equipment costs,
3. Installation costs.

5.1.18.1 Startup Costs.

- **Project management costs**
  Cost estimates must include the cost of direct and indirect labor for the project manager and any staff, for the time spent monitoring and managing the project. Also included are other direct costs, such as travel costs.

- **System engineering costs**
  Cost estimates must include the direct and indirect labor costs of the system engineer and any assigned staff, for time spent reviewing the project requirements, and the time devoted to system design work. These costs may also include other direct costs for items such as travel, printing, drafting, *etc*.

- **Real Estate/land acquisition costs**
  If the site for the new HF station(s) is/are not owned by the operational agency, the site(s) must be acquired through purchase or lease. These acquisition costs include all costs associated with the acquiring of the land for the site(s), including the purchase, yearly lease, legal fees, and any taxes that apply.

- **Site preparation costs**
  These costs include costs associated with leveling or grading the land, constructing fences, digging trenches for antenna cables, constructing concrete piers for antenna towers, as well as the major costs listed below.

- **Construction or modifications to equipment building(s)**
  If the site is a new one, then an equipment building/control facility must be constructed to house the equipment and to provide a place for the site's personnel to operate. If the site is

an existing one, then it may be necessary to construct additional rooms for the site building(s) to house the new capability.

- **Construction or modifications to the site's primary and auxiliary power system**
  The HF system requires ac power, from the local power company grid to run the HF equipment and site to provide support for equipment such as heating, ventilation, and air-conditioning (HVAC). If the site is an existing one, this power may be already provided, but in many cases the power distribution system may have to be upgraded with larger transformers, and additional circuit breakers. The engineering plan may also call for the installation of an auxiliary power source, such as a gasoline- or diesel-powered electrical power generator for emergency use.

5.1.18.2 Equipment costs

- **Equipment purchases**
  The cost of the HF system equipment may or may not be the largest cost of the project, depending on how many circuits are required, what power levels the transmitters require and the distances between sites. Equipment is usually purchased through one supplier or vendor, although it is not uncommon for multiple vendors to support a large contract. The usual process is for the using agency to notify all qualified vendors of intent to purchase equipment and/or services, through the Request for Proposal (RFP). The interested vendors respond to the RFP with their proposed solution to the customer's need, and with a cost estimate. The customer can then choose among several competing solutions, and choose the one that best meets their needs. The vendors, often will propose a "turnkey solution", whereby they will provide not only all the required equipment, but will also provide or subcontract the installation and site-preparation work as well. The following is a listing of the most common components of an HF radio system,
    1. Transmitter/receiver or transceiver,
    2. Antenna components,
    3. Antenna switches,
    4. Transmission lines,
    5. Terminating devices,
    6. Multicouplers,
    7. rf patching,
    8. Terminal equipment,
    9. Voice terminals,
    10. Audio patching equipment,
    11. dc patching facility,
    12. Spare parts facility.

Annex 3 of this document is a tutorial explanation of the basic elements of an HF radio system.

- **Transmitter/receiver or transceivers**

Depending on the power levels required, the station might be equipped with either transceivers or separate transmitters and receivers. For low-power to medium-power operations, say from 100 W to 1000 W, it is the usual practice to use transceivers (a combination of transmitter and receiver in the same package). For high-power operation, >10 kW, the standard practice is to run a split site, with the transmitters at one location and the receivers at another. This configuration allows for full-duplex operation, if required.

- **Antenna components**

  Antennas used in the HF radio operations range from a simple, thin wire, half-wave dipole to large, fixed, or rotatable log-periodic antennas or rhombic antennas, covering many acres of land. The selection of antennas depends on the number of frequencies to be covered, the rf power levels used, and the circuit-reliability requirements. Whether or not the antenna has an omnidirectional or directional pattern is a function of where the stations to be contacted are located. Additional antenna subsystem components that may be needed are transmission line (balanced or coaxial), antenna switching matrix, multicouplers, terminating devices, impedance matching networks, and high- and low-level rf patching. Sectopms 5.2.4 and 5.2.7 give more details on antenna selection.

- **Antenna switches**

  Antenna switches are found where there are multiple antennas or where different antennas are to be used for different circuit paths. The switch allows the radio operator to switch antennas by a manual switch, located in the radio room, or electrically, from a control console.

- **Transmission lines**

  Transmission line is used to connect the transmitters/receivers to the antenna. They are selected during the detailed engineering phase, based on the transmitter power, system impedance, possibility of coupling with other nearby lines, line loss, cost, and atmospheric environment. In general, low- to medium-power transmitters (100 W to 1000 W) use some form of coaxial cable for transmission line, while high-power stations (>10 kW) use open wire, balanced transmission lines.

- **Terminating devices**

  Terminating devices are used with nonresonant antennas, such as long wires, Vees, and rhombics to make them unidirectional. There are two types of terminating devices: a lumped constant (nonreactive resistance) and a distributed constant (lossy transmission line) terminating device. These terminating devices are provided in the characteristic impedance of the particular antenna, and must be capable of dissipating (at least) the average power of the transmitter.

- **Multicouplers**

Multicouplers are devices used to permit two or more receivers or transmitters to share the same antenna. In general, only low-powered transmitters use multicouplers, due to the amount of isolation required between transmitters.

- **RF patching**
  Low-level rf patching is used to interconnect equipment when frequency synthesizers or exciters are used with linear power amplifiers. The output of the synthesizers or exciters is usually on the order of a few milliwatts. High-level rf patching is used to interconnect low-powered transmitters (100 W to 500 W) to linear power amplifiers.

- **Terminal equipment**
  For the purpose of this handbook, terminal equipment will include all other ancillary equipment, such as voice terminals, audio switchboards and patching, dc patching and teletype terminals, multiplexors for voice-frequency carrier telegraph (FVCT), facsimile equipment, HF data modems, and crypto devices.

- **Voice terminals**
  Voice terminals provide the interface between the customer's equipment and the transmission system, call signaling, electrical isolation between the transmit and receive paths, and signal conditioning.

- **Audio patching equipment**
  Every HF terminal station should have some form of audio patching. It can be as simple as a single jack strip or many jack strips. The purpose of this patching facility is to give the station personnel the ability to have access to all of the audio circuits for:

  1. emergency traffic routing
  2. switching or substituting equipment
  3. monitoring the signal quality
  4. circuit test and maintenance.

  All incoming, outgoing, and most of the intra-station audio circuits will appear on the audio patch. For small installations, the audio patch may be located with the other equipment. In larger sites the audio patch will be separately located and manned, and may even be in a separate building. The audio patch plugs and jacks ***must*** be a different size from the dc patching equipment, to prevent patching errors.

- **dc patching facility**
  A dc patching facility is required if teletypewriters or other dc equipment is present. This patch may be a single- or multiple-jack strip, and is usually co-located with the other ancillary equipment.

- **Spare parts**
  The mission of the site may dictate at what level spares are kept. If the station has a 24-hour per day mission it may need to keep not only spares such as fuses, coaxial jumper cables, *etc*., but may also need to have spare equipment available to swap out with defective equipment, to keep the station operational. Agency policy or regulations may also dictate the storage of additional spare parts.

5.1.18.3 Installation costs

Other items to be included in the cost estimate deal with the installation process. These costs might include the following:

1. Bill of materials for installation,
2. Costs of outside consultants/professional engineers,
3. Costs of installation labor,
4. Cost of acceptance testing,
5. Training of site personnel,
6. Lifecycle Costs.

- **Bill of materials for installation**
  The installation Bill of Materials (IBOM) is a list of every piece of equipment and parts needed to construct (or upgrade) the HF station(s). In addition to the major items, such as antennas, transceivers, *etc.,* the IBOM includes such things as wire, cable circuit breakers, cable trays, screws, nails, *etc*. The IBOM is finalized only after the detailed engineering has been completed. Rules of thumb, or previous projects may provide estimated cost data for the initial stages of system planning.

- **Cost of outside consultants/professional engineers**
  Consultants or professional engineers are frequently employed for specialized tasks, such as locating suitable sites or measuring the local electrical noise levels (both man-made and natural).

- **Cost of installation labor**
  Unless this service is to be furnished by the equipment vendor (through a subcontract), it must be planned for by the project manager. Installation cost includes the cost of all construction required to make the site operational (*i.e.,* construction which was not completed during the site-preparation phase).

- **Cost of acceptance testing**
  Testing equipment is an important part of making the site fully operational. The test plan may call for formal testing of each feature of the new equipment, either by the receiving agency or by the vendor under user agency observation. Or testing may be as simple as providing a period of time, such as 30 days, where the site personnel are expected to check

out all of the equipment features. Direct and indirect labor costs of this testing must be included in overall project costs. Development of suitable test plans may be required if none exist. If these test plans are required, the effort associated with their development is another project cost that must be considered.

- **Training of site personnel**
  Training of site personnel on any new equipment installed during the project, must always be considered. Training may be provided under the equipment purchase contract, or if the agency is large enough to have in-house trainers, they may receive training from the vendor, then provide in-house training for the site personnel. In a small number of cases, the site may have a few personnel already trained, who can provide an on-the-job training program for the site's remaining personnel. No matter how it is accomplished, training must always be included in the project plans.

- **Lifecycle costs**
  Lastly, the system designer must consider the lifecycle costs of the system. These costs include the recurring costs to operate and maintain the new capability.

5.2 System analysis and design

The steps to system engineering a typical HF radio system might include the following three levels of planning.

1. The first is an analysis of the requirements for the communications system, to establish that the use of HF radio is feasible,

2. The second level of planning is to develop cost data to substantiate project funding requests and approvals,

3. Lastly, the third level of planning is the detailed engineering analysis. This detailed engineering is the subject of this section.

5.2.1 Network topology

For the cases where the HF ALE radio unit may be involved in a network configuration, one of the first steps in the system analysis and design is to the consider the network system needs. A network in communications may be defined as a method of connecting nodes so that any one radio unit in the network can communicate with any other radio unit. In the case of the Radio Frequency (rf) world where no physical connections are involved this amounts to having the units have a bonding that somehow makes these units common to some topology. To see how this bond might happen let us first look at how the units might have a virtual connection. Three of the more common methods of connection that exist in conventional telecommunications that would be applicable to our application: (1) the mesh, (2) star, and (3) double and higher order star. Figure 5.1 shows examples of each of these connections.

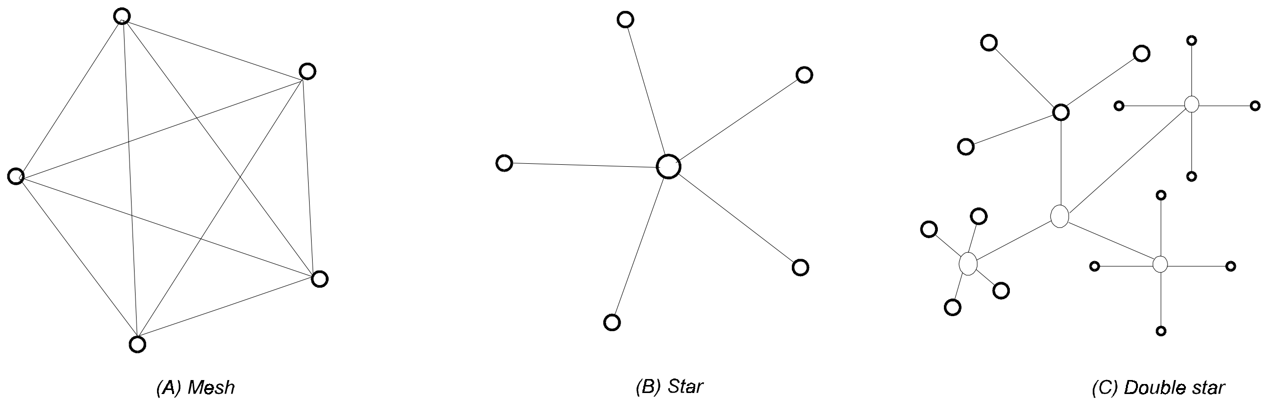


FIGURE 5.1
Examples of network topology

The mesh connection is one in which each and every exchange is connected by paths to every other exchange. Other network configurations are illustrated in Annex 8, under "*network topologies.*" The mesh connection would be the typical connection between units assuming a) nothing unusual is done, b) propagation exist between all units, c) all units are on the same frequency, and d) addressing considerations allow for communication. A star connection utilizes an intervening exchange, called a *tandem exchange,* such that each and every exchange is interconnected via a *single* tandem exchange. A star configuration would be useful in a situation where a central node is in control and all messages pass through this node before being dispersed to each node individually. An example of this type of topology might be a central command sending all messages to subordinate units. Possibly the most useful topology might be a double star configuration where sets of pure star subnetworks are connected via high-order tandem exchanges, as shown in Figure 5.1. This trend can be carried still further such as when hierarchical networks are implemented. In HF ALE radios the mesh topology would be used normally, while the star and double star would be implemented using special addressing techniques where a common call would receive responses from all members of the network. Each receiving member would respond to the sender in a time division multiplex access (TDMA) time slot defined for that unit.

As the system design progresses, a network topology plan should be developed. Usually this task is done with the help and agreement of the network manager. Since it will typically be the network manager's responsibility to maintain the network after its development, it is important to involve both the system integrator and network manager in the design phase. Using the objectives and requirements as a basis, the analysts can perform a *network design*. The design should give details about the network topology, network layout, and site selection. The network topology may be chosen based on where the traffic originates, the destination to which it is to be transmitted, and the projected data flow. The topology chosen could be point-to-point, star, mesh, multiplexed, *etc*. The topology might consist of a single network or a multi-network environment (*i.e*., a collection of networks linked together for communication). A traffic analysis can be used to show where traffic may be high or low, sporadic, priority, or non-priority.

In some cases the radio unit will contain the logical functions of a network controller. The network controller contains many higher level functions to add a degree of network automation and adaptivity to the radio unit. These functions can include message routing, message acknowledgement between adjacent nodes, and flow-control mechanisms to protect node resources from being exhausted. The network controller operates to interface the local communications channel with network users and to manage this channel to provide error-free transmissions. The requirements of a network controller may range from handling link errors to managing topology. The requirements may be grouped into three categories: source/destination, store-and-forward, and network-wide functions [1].

Source/destination functions provide the protocols required to permit communication between network users. These are the protocols that are required to interface with network users' equipment.

Store-and-forward functions are the functions that provide the services for message transmission ***through*** a network controller.

Network-wide functions pertain to the management and maintenance of the network, and the measurement of its behavior. These functions include preventing network-wide congestion, maintaining topological awareness, bringing up or taking down network nodes or links, and measuring network performance [14]. These functions may be centralized in a single node of the network such as with a Network Control Station (NCS). In this case, a control node performs all of these functions with minimal involvement from the other nodes. Alternately, each node may individually perform most of the functions and periodically update the control node.

5.2.2 Approximate geographical coordinates for each station

Once an approximate location for the station has been selected (or an existing site is selected for use), the latitude and longitude for the station can be determined. If an existing site is to be used, the geographic coordinates will be known (and can be checked by the use of a hand-held GPS receiver). If the site has not yet been firmly determined, an estimate of its geographic coordinates can be made from a recent topographic map.

5.2.3 Tentative site selection

The selection of an HF radio site requires a detailed analysis of the physical surroundings in which the radio site must function. Above all, the site chosen must be technically adequate. Specifically, the engineer must consider the site's noise environment, ground conductivity, the obstacles in the foreground, and things such as buildings or mountains nearby that would obstruct the received or transmitted signals. Secondary considerations include ease of construction, access to utilities (water, electrical power, *etc.*) and access to the site. But, the technical adequacy of the site is the most important factor.

5.2.4 Path operational parameters

The purpose of making the propagation forecast is to estimate the optimum frequency to be used and to predict the system performance throughout the 11-year solar cycle and throughout the whole year. These propagation forecasts are used by the design engineer to select the proper equipment for the path.

Annex 2 of this document provides detailed information about propagation prediction methods that will aid the implementing engineer.

5.2.4 Propagation forecast

An integral part of system design and analysis for an HF radio communication system is determining the atmospheric conditions through the use of a propagation forecast. The following details must be considered before an accurate propagation analysis may be made.

1. Site noise environment,
2. Antenna characteristics,
3. rf power available,
4. System gain.

- **Site noise environment**
  Atmospheric and man-made noise at the site should be measured throughout the day. Ideally, a site should be selected that is far from areas of high-noise concentration (*i.e.*, far from industrial and residential areas and airports). If possible, atmospheric noise should be greater than any man-made noise at the receiver site. If it is not possible to measure atmospheric noise throughout the entire year, estimates can be made by reference to CCIR Report 322-3, *Characteristics and Applications of Atmospheric Radio Noise Data*, International Telecommunication Union, Geneva, 1988. This ITU report provides information on local atmospheric noise for different times of the day and for each of the four seasons of the year.

- **Antenna characteristics**
  The primary selection factors which determine the antenna best suited for a particular application are:
  frequency range

gain,
directivity, take-off angle, vertical and horizontal radiation pattern,
total radiated power,
size and complexity, land area requirements,
beamwidth,
antenna bandwidth,
input impedance.

Since we are dealing with HF antennas, our interest is in the 2-to-30-MHz range. Gain is the ratio of the power density radiated by the antenna in a given direction to that radiated by a reference antenna (usually an isotropic source) when both have equal input powers. Directivity is the ratio of the maximum power radiated by an antenna to the average radiated power. Gain and directivity are related in that increased gain is accompanied by greater directivity. This is because the total radiated power remains constant. Thus, an increase in power in some directions results in a decrease in power in other directions. Generally, directivity is considered in terms of vertical (take-off angle) and horizontal (azimuthal beamwidth) angular patterns. The many types of antennas in common use in HF radio provide different combinations of the essential characteristics to meet specific radio link needs.

Table 5.2, HF Antenna Characteristics, shows many of the important characteristics of HF antennas. Table 5.3 is another comparison of antenna characteristics base on the concepts of unidirectional (single direction) and omnidirectional (receiving or sending equally in all directions) patterns. Figure 5.2 shows how an antenna can have a directional pattern and shows how the take-off angle affects the transmission of maximum power over an obstacle. This diagram is for the vertical plane, but, it would look very similar if it were plotted looking down (horizontal plane). The horizontal directivity is important because the antenna can be physically located or directionally turned toward the direction of interest. This increase in power in the direction of interest shows pictorially the concept of gain described in the previous paragraph.

TABLE 5.2
HF Antenna Characteristics

Antenna Type	(Note 1) Freq Range (MHZ)	(Note 2) Bandwidth	TakeOff Angle/Deg	Horizontal Angle/Deg	Gain (dBi)	Land Area Required Acres	(Note 3) Range	(Note 4) Use
Dipole	2-30	Narrow	10-90	80-2	2	1	S-M	G-N
Inverted V	2-30	Narrow	40-90	OMNI	2	1	S	G-N
Inverted L	2-30	Narrow	20-90	80-180	3	1	S-M	G-N
Vehicular Whip	2--30	Narrow	20-50	OMNI	-3	Vehicular	M	M
Vertical Quarter-wave	2-30	Narrow	5-40	OMNI	3-5	1	M-L	G-N
Quad Loop	5-30	Narrow	10-90	80-120	3	1	M	G-N
Long Wire	3-30	Broad	10-30	10-30	4-10	3	M-L	P
V Antenna	3-30	Broad	5-30	5-30	4-16	4	M-L	P

Yagi	7-30	Narrow	10-35	30-60	7-12	1	M-L	G-N
Half Rhombic	3-30	Broad	10-40	5-30	5-12	3	M-L	P
Vertical LPA	4-30	Broad	5-40	100	6-12	3-5	M-L	P
Horizontal LPA	2-30	Broad	10-45	40-75	8-16	2-6	M-L	P
Rotatable LPA	4-30	Broad	5-50	60-70	8-12	1	M-L	G-N-P

NOTES:

1. Frequency range is typical of the antenna type (not of an individual antenna).
2. Radiation angles are for comparison purposes. Values represent average range. Actual values depend on ground conductivity, antenna height, and operating frequency.
3. S-Short-0-400 km (0-250 mi); M-Medium-400-4000 km (250-2500 mi); L-Long-over 4000 km (2500 mi).
4. G-Ground-to-air; M-Mobile; N-Net station, fixed; P-Point-to-point L-Long over 4000 km (2500 mi).

TABLE 5.3
Additional HF Antenna Characteristics

Antenna Types Listed by Azimuthal Patterns and Polarization	Useful Frequency Range (MHZ) (Note 1)	Power Gain (Referred to Istropic) (dB) (Note 2)	Usable Radiation Angles (degrees) (Note 3)	Land Required (acres)	Approximate Material Cost ($ thousands) (Note 4)
Unidirectional Patterns					
Horizontal Rhombic	2-30	8 to 23	4-35	5-15	5-10
Terminated V	2-30	6 to 13	5-30	4-9	3-6
Horizontal Log-Periodic	2-30	10 to 17	5-45	2-10	15-25
Vertical Log-Periodic (Dipole)	2-30	6 to 10	3-25	3-5	20-30
Yagi (Horizontal	6-30	12 to 19	5-30	<1	5-10
Billboard (Horizontal)	4-30	9 to 17	5-30	1-2	10-15
Vertical Log-Periodic (Monopole)	2-30	4 to 8	3-25	3-5	20-30
Horizontal λ 2 Dipole	2-30	5 to 7	5-80	<1	1-2
Omnidirectional Patterns (Vertical)					
Conical Monopole	2-30	-2 to +2	3-45	2-4	5-15
Discone	6-30	2 to 5	4-40	<1	10-20
Inverted Discone	2-16	1 to 5	5-45	2-4	15-25
Sleeve (Not within the limits specified for antenna design in para. 3.2.2.2.6.1.4, it is included due to its widespread use)	2-25	-1 to +3	4-40	2-4	3-8
Vertical Tower	2-30	-5 to +2	3-35	2-4	5-10

Note 1 - The useful frequency range is the range of the antenna type, not necessarily the bandwidth of an individual antenna.

Note 2- Typical power gains are gains of antennas over good earth for vertical polarization and poor earth for horizontal polarization.

Note 3- Usable radiation angles are typical radiation angles over good earth for vertical polarization and poor earth for horizontal polarization; lower angles may be possible for vertical antennas over better earth, *e.g.,* sea water.

Note 4- Approximate material costs include steel towers, guys, and installation hardware. Costs are established only to provide a relative basis of comparison of one antenna against another.

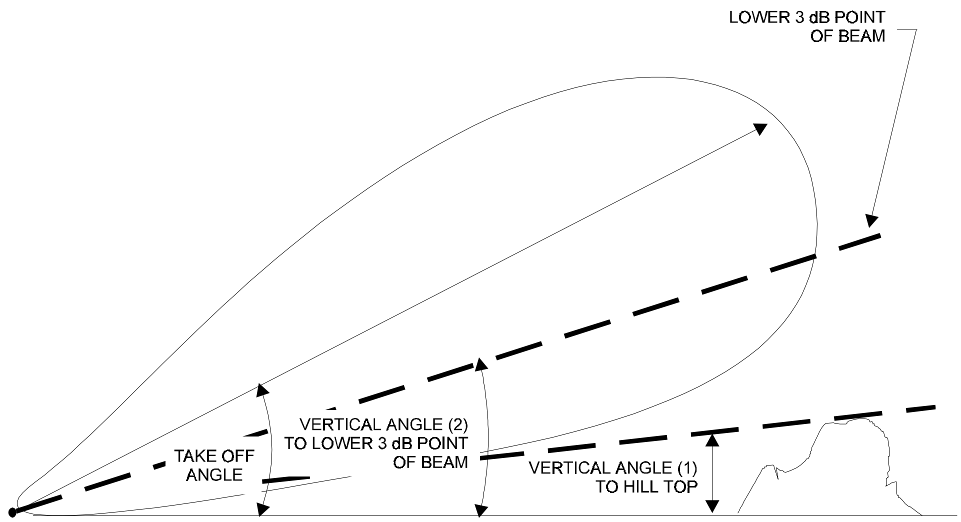


Figure 3-1. Minimum obstruction clearance angle

FIGURE 5.2
Minimum obstruction clearance angle

Frequency range of operation

The frequency range of operation determines the bandwidth requirement of the antenna. The frequency range of operation is determined based on a computer-operated propagation analysis program to determine the optimum traffic frequencies (FOT) for the path involved. An assigned frequency near or below the FOT is then used. Computer-based propagation programs are discussed in Annex 2. As a rule of thumb, the frequency ranges in Table 5.4 propagate the distances shown under normal ionospheric conditions.

Bandwidth

The bandwidth is the band over which the communication system can be used without modification to the antenna or its tuning. Antennas can be categorized as narrowband (*e.g.*, dipole or Yagi) or broadband (log-periodic or vertical half rhombic).

The vertical angle

The vertical angle of maximum radiation of the antenna is the takeoff angle (TOA). This angle marks the center line of the lobe of radiation above and below this median angle. The required TOA depends on the distance between stations, the height of the ionospheric layer, and the mode of propagation (number of hops and layer used). Table 5-5 shows the required TOA in degrees above the horizon for single hop daytime and nighttime operation. The values given are approximate and will vary greatly under differing conditions. However, the accuracy is sufficient for broad beamwidth tactical antennas. The mode of skywave operation (number of hops) should be estimated. Table 5-6 shows the number of F-layer hops which normally occur over different distance ranges. Multihop propagation mode TOAs can be approximated by dividing the total circuit distance by the number of hops and using the results as a link distance in Table 5.5. A more accurate procedure to determine TOA is contained in appendix C of FM 11-487-4/TO 31-10-24.

The horizontal range

The horizontal range of radiation angles (beamwidth) required for an antenna is determined by the area to be covered. Multipoint or net operation may require a broad or omnidirectional radiation pattern while point-to-point circuits can use narrowbeam, higher gain, directional antennas.

The gain

The gain of an antenna at the desired takeoff angle and azimuth can be determined by the vertical and horizontal radiation patterns which are depicted in earlier paragraphs in this chapter. Generally, antenna selection is based on the highest gain available in the desired direction.

TABLE 5.4
Propagation frequencies

Frequency range (MHZ)	Path length	
	km	(mi)
2-7	0- 320	(0- 200)
3-8	320- 640	(200- 400)
4-11	640-1290	(400- 800)
5-18	1290-2580	(800-1600)
7-28	2580-9650	(1600-6000)

TABLE 5.5
Take-off angle vs. distance

Take-off Angle (Degrees)	Link Distance F$_2$ Region Day Time km	mi	F$_2$ Region Night Time km	mi
0	3220	2000	4500	2800
5	2410	1500	3703	2300
10	1930	1200	2900	1800
15	1450	900	2550	1400
20	1125	700	1770	1100
25	965	600	1610	1000
30	725	450	1330	825
35	644	400	1125	700
40	565	350	965	600
45	443	275	805	500
50	403	250	685	425
60	258	160	443	275
70	153	95	290	180
80	80	50	145	90

TABLE 5.6
Number of hops for distances

Hops	Distance (km)	(mi)
1	less than 4000	(less than 2500)
2	4000- 8000	(2500-5000)
3	8000-12000	(5000-7500)

Physical size

A significant factor in HF antenna selection is the physical size of the site required for erection of the antenna. An antenna site should be a clear flat area with no trees, building, fences, power lines, or natural terrain obstructions. Large HF arrays require large land areas. Lack of available space may dictate the selection of smaller antennas with less gain.

Antenna selection procedures can be conducted in the following steps:

(1) Determine the frequency range of operation and select the bandwidth required. If a broadband antenna is required but not otherwise available, two or more narrowband antennas constructed to the available frequency complement may be selected.

(2) Determine the required takeoff angle for the required path distance using Table 5.5.

(3) Determine the area of coverage required: omnidirectional, bidirectional, or point-to-point coverage.

(4) Determine from tables 5.2 and 5.3, or by references to previous paragraphs, the antenna which possesses the desired properties and produces the highest gain in the desired direction. Check to determine if the chosen antenna can be erected in the available space. If the antenna is to be constructed on site, check to see if the required materials are available. If space and materials are not available, a lower performance antenna may have to be selected.

5.2.5 Equipment selection

The following is a listing of the most common components of an HF radio system,

1. Transmitter/receiver or transceiver,
2. Antenna subsystem
3. Voice frequency interfaces
4. Digital Interfaces
5. Transmission lines.

Annex 3 shows the elements of an HF radio system.

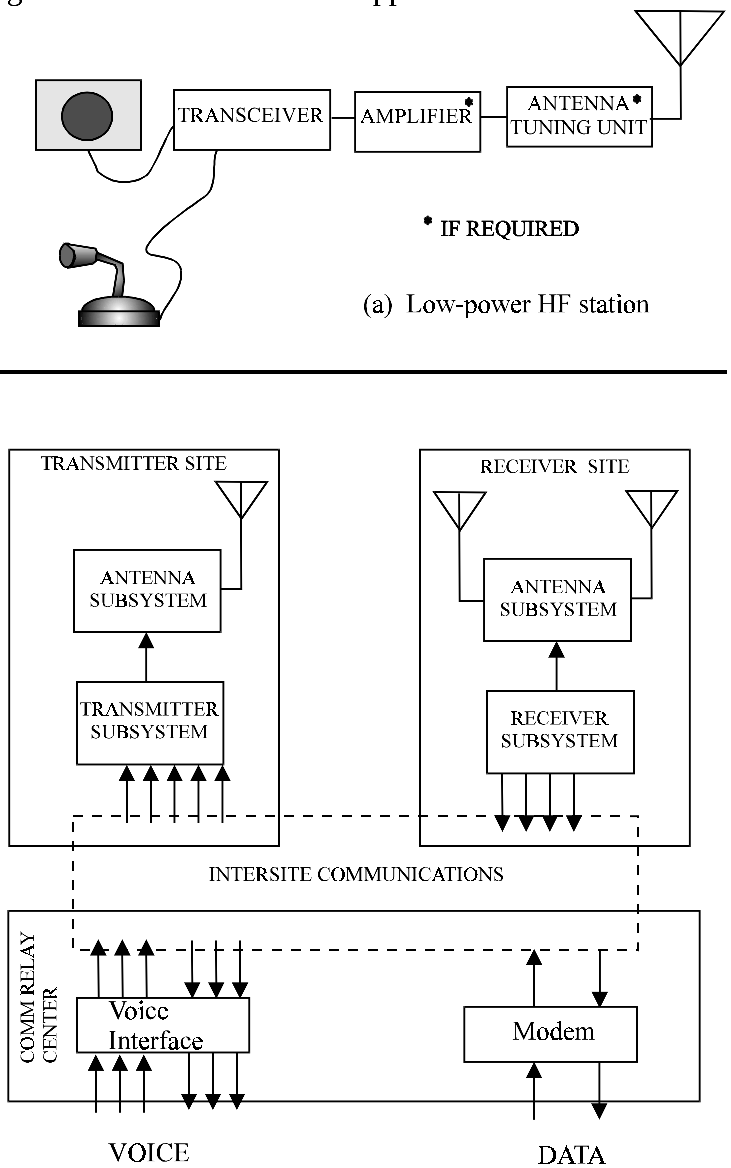
- **Typical HF systems configurations**

a. Single channel systems

(1) *Continuous wave (cw).* In the early days of radio, a telegraph key was used to switch the radio frequency (rf) carrier on and off in accordance with a telegraph code. Since the rf was a continuous wave when it was on, this form of transmission was called interrupted continuous wave. It is most often referred to simply as continuous wave (cw). Most commercial and military equipment have a backup cw communications capability. The cw form of communication is useful as emergency communications when other forms of transmission cannot be used. The cw form is also used in a form of transmission known as burst communication in which telegraph code is recorded in advance and transmitted in short, high-speed bursts. The purpose is to evade enemy interception of the transmission and location of the transmitter.

(2) *Single sideband (SSB) voice.* SSB voice stations are typically small size, frequently desk top transceivers. Power output is usually about 100 watts (W). Coupled with a linear amplifier, output will normally range from 400 to 1000 W. Figure 5.3 illustrates a typical low-powered single channel HF station. There are many military uses for SSB voice systems such as command and control nets, administrative networks, Military Affiliate Radio Service (MARS), ground-to-air and

air-to-ground communications, convoy control nets, other mobile applications, and engineering circuits for transportable communications systems. Typical antennas may be a whip for mobile and transportable applications, a simple dipole, or a rotatable directional array such as a log-periodic or Yagi antenna for fixed station applications.



(a) Low-power HF station

(b) Multichannel HF radio system

FIGURE 5.3
Low power HF station and Multichannel HF radio system

b. Multi-sited systems

(1) *Medium power independent sideband station*

Unlike small, low-power installations where transmitters and receivers can be co-sited, larger, higher power (over 1000 W) multichannel HF facilities (see Figure 5.3(b)) usually require separate transmitter and receiver sites with a normal separation of 8 kilometers (km) (5 miles (mi)) or more. A third facility, the communications relay center (CRC) may be necessary. The CRC performs the control, switching, and message processing activities. The sites are interconnected by a multichannel telephone link, either by multipair cable or by microwave radio.

- **Transmitter subsytem**

Transmitting equipment may be procured in a number of configurations with separate components or as completely self-contained end items. Large transmitters are usually configured into functional components including a frequency synthesizer, exciter, and a power amplifier section. Transmitter exciters are available which provide from one to four independent 3-kilohertz (kHz) channel inputs. The four voice channels are used to provide the four-channel input to the independent sideband mode. More details about the transmitter subsystem are included in Annex 3 of this handbook.

- **Receiver subsystems**

Most current receivers designed for larger HF facilities are tunable by the use of a frequency synthesizer. A synthesizer may be a separate component or it may be an integral component of the receiver. More sophisticated frequency control techniques now available use microprocessor-controlled tuning mechanisms for rapid and accurate frequency changes. Independent sideband (ISB) receivers are designed to provide the four 3-kHz voice frequency channels to the voice frequency termination and multiplex equipment. More details about the receiver subsystem are included in Annex 3 of this handbook.

- **Transceiver systems**

A transceiver is a transmitter, receiver and interface combination.

- **Antenna subsystem**

A typical large site antenna subsystem consists of all items related to the antennas, including the transmission lines, the antenna curtains, supports, dissipation lines (if applicable), switching and impedance matching devices, and entrance devices to the equipment shelters or site buildings. Descriptions of various antenna subsystems and considerations to be made in the choice of antenna are contained in Section 5.2.4 and Annex 3.

- **Voice frequency interface equipment**

Voice frequency interface equipment provides the interconnection between the subscriber and the transmission system. Interface equipment provides the in-band signaling, equalization, attenuation, amplification, or other signal conditioning that is needed for an interface between the transmission means and the voice frequency end instrument.

- **Transmission lines**:

Transmission lines are basically of two types: balanced lines and unbalanced lines. Balanced transmission lines have two identical conductors or groups of conductors operated at equal potential (but opposite polarity) from ground. Unbalanced lines have one conductor above ground potential and the other at ground. Both types of lines may be enclosed in an external shielding conductor.

a. Coaxial line. A coaxial line is an unbalanced, shielded transmission line designed with one conductor in the center and the other as a hollow cylinder completely enclosing the center conductor. When properly designed, the outer conductor gives near perfect shielding since it is normally grounded, resulting in very little pickup of outside interference. This characteristic, more than any other, makes the coaxial transmission line the best choice for receiving use. In transmitting applications, coaxial lines have little radiation loss and are not affected by objects, conductors, or other transmission lines in the vicinity. Compared to open wire lines, however, coaxial lines generally have significantly higher line losses and, for high power applications, are more expensive. The loss characteristics and the power handling capabilities depend largely on the dielectric material separating the conductors. Power handling capability is related to the distance between the inner and outer conductors and the ability of the dielectric to withstand the heat generated in the inner conductor. Coaxial lines are divided into rigid, semirigid, and flexible.

(1) *Rigid.* Rigid coaxial line is normally used: to connect high-power transmitter outputs to an antenna switching matrix, to an impedance matching device such as a balun or transformer, or to another type of 50 ohm coaxial line; or to enter or exit buildings. Rigid line has a tubular center conductor supported concentrically with respect to the outer conductor by discs or crossed pins made of dielectric material. The line sections are connected by flanges and use manufactured elbows to change direction. Diameters generally range from 2.2 to 15.6 cm (□ to 6 □ in.). Attenuation loss is generally less than for open wire lines.

(2) *Semirigid.* Semirigid coaxial line is generally used in moderate sized power systems to approximately 20 kW. The semirigid cable can be carefully bent on a radius of 10 to 15 times the diameter of the line. The inner conductor is tubular, except for the smallest lines, where it is solid. The inner conductor is supported within the outer conductor by a helix of polystyrene. The outer conductor is frequently of a spiral wrap semiflexible armored construction and is generally covered with a polyethylene or a vinyl protective covering. Attenuation losses are somewhat higher than those of open wire lines.

(3) *Flexible.* Flexible coaxial cable is the most popular transmission line for small and medium HF station applications. There are types of flexible coaxial lines available to meet more requirements. They range in size from 0.3 to 3.2 cm (□ to 1 □ in.) And they range in impedance from 50 to 150 ohms. Attenuation loss is quite high when compared to open wire, especially for the smaller cables.

(a) A flexible coaxial line consists of a solid or stranded wire inner conductor surrounded by a polyethylene dielectric. Copper braid is woven over the dielectric to form the outer conductor. The copper braid should be capable of providing at least 95 % shielding. Commercially available, inexpensive coaxial cable, providing only 60 % to 80 % shielding, should not be used. A waterproof vinyl or polyvinyl covering is placed over the woven braid. This outer insulating jacket is used solely as protection from dirt, moisture, and chemicals. These substances, if allowed to penetrate the insulating jacket, will contaminate the dielectric and will cause the cable to become lossy.

(b) As antenna transmission lines, flexible coaxial lines have their largest application in receiving systems. Receiving antennas with higher impedance, such as the log-periodics, ordinarily use coaxial cable with a matching transformer at the antenna end. Although coaxial cable makes a good impedance match to the center of a balanced half-wave antenna, without a balun the unbalanced nature of the coaxial line will cause a skew in the antenna radiation pattern.

(c) One advantage of flexible coaxial line is that it can be installed with almost no regard for its surroundings. It requires no insulation, can be run on or in the ground or in piping, can be bent around corners with a reasonable radius, and can be □snaked□ through places such as the space between walls where it would be impractical to use other types of line. Outside of the building, all permanent coaxial cable runs should be underground. The cable should be buried at least 50 cm (20 in.) in cold climates. The minimum burial depth is determined by the frost line or surface load. The cable should be cushioned with about 8 cm (3 in.) of sand below and above the cable, and planks should be laid above the top layer of sand prior to filling the trench. In this way the cable is protected from cuts if excavation is required. Concrete markers should be placed beside the trench at all turns to assist in location and protection of the cable. To minimize radio noise pickup on the receiving transmission lines, the matching balun should be installed on the termination pole of the antenna. The connecting coaxial cable is then run, preferably underground, to the receiver building. Cables for rf signals within the site building should be standardized at the same characteristic impedance, normally 50 ohms. Equipment with other characteristic impedances are matched to the 50 ohm rf line system by impedance matching transformers. Throughout the station, the rf cables should be physically grouped by service such as exciter cables, monitor cables, or patch panel cables.

b. Open wire line. An open wire line consists of two or more parallel wires of the same size, maintained at a uniform spacing by insulated spreaders or spacers at suitable intervals. These lines can be balanced or unbalanced.

(1) *Unbalanced open wire line.* The characteristic impedance of unbalanced, open wire lines ranges from 20 to 200 ohms depending on the construction. Unbalanced open wire lines are used primarily for impedance matching.

(2) *Balanced open wire line.* For transmission, balanced open wire lines are frequently preferred instead of coaxial transmission lines. At all but very low power levels, the open wire line costs less than coaxial line.

(a) Transmission line runs. For long transmission line runs, open wire balanced lines will have considerably smaller attenuation than will coaxial lines of comparable cost. The velocity of wave propagation is nearly that of free-space. The maximum voltage rating depends on the spacing of the wires and the type, size, and condition of the insulators. Construction details and installation practices for open wire rf transmission lines are contained in Air Force *Technical Orders*, TO 31-10-4 and TO 31-10-22.

(b) Feeder lines. Open wire line is especially suited for feeding most broadband balanced antennas such as the Vee antenna. Open wire feeders are relatively simple to construct. Materials required are two conductors of copper-clad steel or hard-drawn copper wire long enough to reach from the antenna feed connection to the balun, along with spacers and insulators. The spacers need to be of high quality insulating material such as polystyrene or phenolic material and long enough to keep the feeder conductors at a uniform 15 cm (6 in.) spacing. The spacers are installed at intervals sufficiently frequent to preserve the spacing and prevent the line from twisting and shorting out. The intervals between spacers vary from 1 to 2 m (3 to 6 ft.). The balun should be connected as close to the lower insulators as is safe and practical. Open wire lines should be treated with caution. At a transmitter power output of 1000 W, there are approximately 775 V on the wires.

5.2.6 Equipment performance requirements

- **Transmitting subsystem**

a. Typical HF transmitters. HF transmitters are available in many sizes and power ranges. Two power ranges, low power (below 1000 W) and medium power (1000 to 10,000 W), have been selected as representative of available equipment.

(1) *Typical characteristics of low-power HF transmitters:*

Frequency range	1.6 – 30 megahertz (MHz)
Output power	400 W
Operational modes	CW, USB, LSB, ISB, AM, FSK
Output impedance	50 ohms unbalanced
Frequency control	Synthesized frequency generator, integrally or remotely controlled, present frequency settings available
Tuning	Automatic with manual override
Cooling	Forced air, filtered

Cooling conditions	0° to 50° C (32° to 122°F) 90 % relative humidity
Input power	115/230 Volts alternating current (V ac) 50/60 Hz single phase 1200 W

(a) Installation. Transmitters in this power range are available for installation in standard equipment cabinets. A complete transmitter as described above can be installed in approximately 2 linear feet (1/3 meter) of cabinet space and would weigh about 160 kilograms (kg) 350 pounds (lb)). Two such transmitters can readily be installed in a standard 183 cm (72 in.) high equipment cabinet allowing adequate room between units for cooling.

(b) Operation. The typical low-power transmitter can be used in either fixed stations or transportable stations. Frequency is set by a synthesized exciter which may be removed from its normal position in the transmitter cabinet and located elsewhere within the station. It also has a capability for a number of preset channels.

(2) *Typical characteristics of medium-power HF transmitters.* Typical medium-power transmitters have the same general electrical characteristics as smaller transmitters. The notable differences are in size, weight, and input power requirements. Typical input power is 230 V ac, 50-60 Hz, 3-phase, 20,000 W. Typical size is 200 cm (78 in.) high, 140 cm (54 in.) wide, 100 cm (40 in.) deep, and the approximate weight is 1600 kg (3500 lb). The medium-power transmitter is normally installed in a single cabinet with power supplies on the bottom, final amplifier at the top, and control circuits in the center. Figure 5.4 is a typical diagram for a 10 kW transmitter.

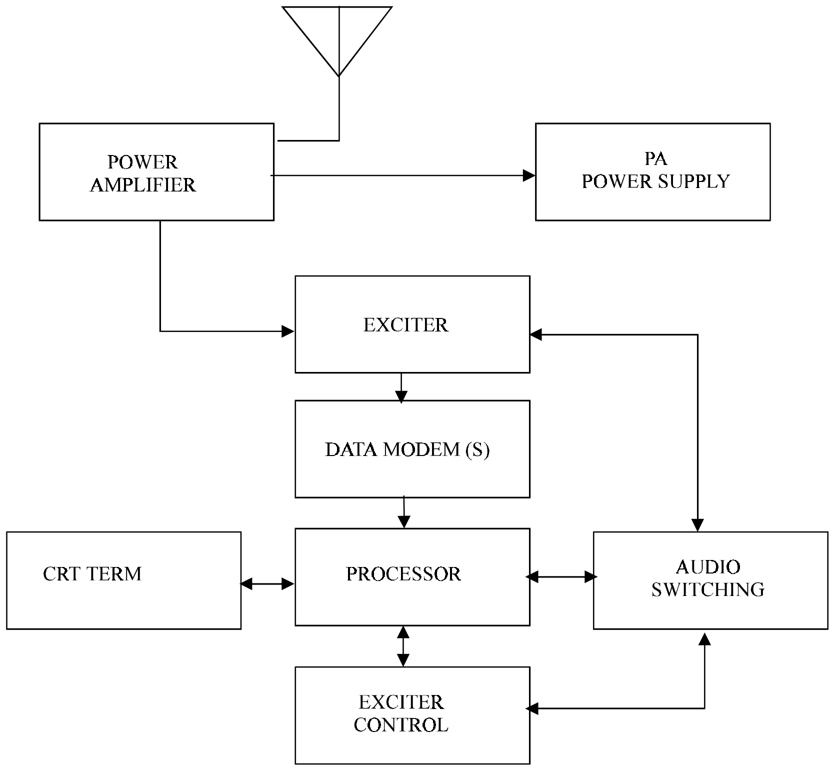


FIGURE 5.4

Example of 10 kW transmitter with automatic processor control.

- **Transmitting power**

Transmitting power is closely tied to the considerations to be made when considering propagation forecast. See Section 5.2.4 for details.

- **Receiving subsystem**

HF general coverage receivers are of two general categories. Fixed frequency receivers are designed with frequency settings dials or switches and are intended for single frequency operation for hours or days at a time. Variable or tunable receivers are designed for rapid frequency changing and are more suitable for signal search operations. They may have a frequency lock feature to prevent accidental frequency change. There are also some receivers available which cover both the HF and very high frequency (VHF) spectrum as part of their general coverage. Characteristics for each type of typical high quality generic receiver are listed below.

(1) *Single or multiple channel fixed frequency receiver.*

Frequency range	1.6 to 30 MHz
Frequency stability	1 part in 10^6
Operational modes	cw, USB, LSB, ISB, AM, FSK

Sensitivity	0.5 microvolts for 10 decibels (dB) signal-plus-noise-to-noise ratio (S+N)/N
Bandwidths	Selectable for 2.1, 3, and 6 kHz
Input impedance	50 ohms unbalanced
Temperature range	–30°C to + 50°C (–22°F to + 122°F) 95% relative humidity
Input power	115/230 V ac, 50/60 Hz, single-phase, 125 W 13 cm (5 in.) High, 48 cm (19 in.) wide, 48 cm (19 in.) deep, weight 45 kg (100 lb)

(2) *Continuous tuning, general coverage receiver.* The term *continuous tuning* is used here to indicate tuning is accomplished by a single dial as opposed a bank of switches or push buttons for setting a frequency.

Frequency range	2.0 to 30 MHz
Frequency stability	1 part in 10^6
Operational modes	cw, USB, LSB, ISB, AM, FSK
Sensitivity	0.6 microvolts for 10 dB (S+N)/N
Bandwidths	Selectable for 1.1, 2.1, 3, and 6 kHz
Input impedance	50 ohms unbalanced
Temperature range	0°C to 50°C (32°F to 122°F) 90% relative humidity
Input power	115/230 VAC, 50 to 400 Hz, single-phase, 125 W
Size	20 cm (8 in.) high, 38 cm (15 in.) wide, 36 cm (14 in.) deep, weight 12 kg (26 lb)

d. Typical HF transceivers. There are many types of transceivers available off-the-shelf. In general, most have power outputs in 100 to 200 W range and are ideally suited for use in small communications sites. A typical transceiver will be entirely solid state, including the final amplifier. Frequency can be changed rapidly, requiring no peaking or tuning. Stability is excellent requiring little or no adjustment between frequency changes. Transceivers are light weight and entirely self-contained, requiring only a microphone or key connected to the input and a suitable antenna connected to the output. The essential characteristics of a typical transceiver are as follows:

Frequency range	1.6 to 30 MHz
Frequency setting	Decade switches or continuous tuning by dial with frequency lock
Power output	150 W peak envelope power (PEP) or 100 W average
Operational modes	cw, USB, LSB, AM, FSK
Output impedance	50 ohms, unbalanced
Receiver sensitivity	0.5 microvolts for 10 dB (S+N)/N
Bandwidth	2.7 kHz for SSB, 375 Hz for CW
Size	18 cm (7 in.) high, 43 cm (17 in.) wide, 43 cm (17 in.) deep, weight 25 kg (55 lb)
Power input	115/230 V ac 50/60 Hz, single-phase, 400 W

e. Ancillary HF components. A transmitter or receiver usually requires certain peripheral items to constitute a complete operating system. Some of the common items used are described in the following paragraphs.

(1) *Exciters.* An exciter is a low-power transmitter which generates the modulated carrier frequency for the amplifier (transmitter) stages which follow. The exciter includes a signal input stage, a frequency synthesizer, a modulator, frequency translation stages, and a postselector. It may be more practicable from an operational standpoint to install exciters at some central point rather than have each individual transmitter with its own exciter nearby. A spare exciter could thus be available for any number of transmitters. Many types of frequency synthesized exciters are available having low-power outputs (up to 200 milliwatts (mW)) which are sufficient to drive higher power transmitters. Most transmitters in the 1000-watt and higher ranges are provided with an exciter module designed to be easily removed and operated from a remote location. Typical characteristics of a generic HF exciter are as follows:

Frequency range	2 to 30 MHz
Frequency selection	Rotary decade front panel switches
Modes of operation	cw, USB, LSB, ISB, AM, FSK
Power output	Variable up to 200 mW
Input/output	50 ohms unbalanced
Size	13 cm (5 in.) high, 48 cm (19 in.) wide, 51 cm (20 in.) deep, weight 16 kg (36 lb)
Temperature range	0°C to 50°C (32°F to 122°F) 95% relative humidity
Input power	115/230 V ac, 50/60 Hz, single-phase, 80 W

(2) *Low-pass filters.* Use of low-pass filters at the output of HF transmitters is often required. Since the frequency spectrum above 30 MHz is used by many low-power services susceptible to interference from harmonics of high-powered transmitters, it is necessary to use measures to suppress these spurious emissions as much as possible. Low-pass filters having attenuation of up to 60 dB at frequencies above 32 MHz are available for transmitter powers up to 40,000 W. The proper filters are included as an integral part of higher power transmitters.

(3) *Preselectors.* The purpose of a preselector is to minimize receiver overload from nearby transmitters and interference from adjacent rf channels. A preselector is required when the receiver must work in an rf environment that includes high levels of unwanted signals resulting in intermodulation and front-end overload problems. Preselectors are available which will provide protection to the receiver from signals as high as 200 volts at frequencies 10 % or more removed from the desired frequency. Typical specifications are as follows:

Frequency range	2 to 30 MHz
Bandpass	12 kHz

Noise figure	Not more than 12 dB
Input/output impedance	50 ohms unbalanced
Tuning	automatic from BCD (Binary Coded Decimal) frequency information
Tuning time	4 seconds maximum 13 cm (5 in.) high, 48 cm (19 in.) wide, 56 cm (22 in.) deep, weight 12 kg (27 lb)
Input power	115/230 V ac, 50/60 Hz, single-phase, 50 W

(4) *Independent sideband HF exciters.* By international agreement, ISB transmitters are permitted to have a 12 kHz bandwidth. This permits the transmitter to be modulated with four independent 3 kHz voice frequency sidebands. An exciter to drive and modulate the transmitter receives four independent voice frequency signals, converts them to higher single band signals, and combines them into a single band of modulating frequencies, 6 kHz above and 6 kHz below the transmitter frequency. The output of the exciter is at the transmitting frequency and is actually a very low-power transmitter having four independent sidebands. The purpose of the transmitter is to amplify these sidebands to a usable power level. Typical technical characteristics of an independent sideband HF exciter are as follows:

Frequency range	1.6 to 30 MHz
Frequency tuning steps	100 Hz
Audio inputs	600 ohms line input, 0 dBm
RF output	200 m W PEP with 1 mW input
Size	18 cm (7 in.) high, 48 cm (19 in.) wide, 56 cm (22 in.) deep, weight 14 kg (30 lb)
Power	115/230 V ac, 50/60 Hz, single-phase, 80 W

A simplified block diagram of an ISB exciter is shown in Figure 5.5. In this diagram, the four audio inputs are equalized in level in the audio amplifiers, which also provides for monitoring the audio. Each of the audio inputs is then converted in the modulators to an upper sideband, upper sideband, a lower sideband, and a lower sideband with a carrier frequency (suppressed) of 450 kHz. The four independent sidebands are then combined, translated, and filtered to a band centered at 9.45 MHz. The 9.45 MHz sideband signals are again translated to approximately 128 MHz to keep them well out of the range of 1.6 to 30 MHz to avoid interference and image frequency problems. At this point, they can be translated down by variable frequency oscillator (VFO) to the required range.

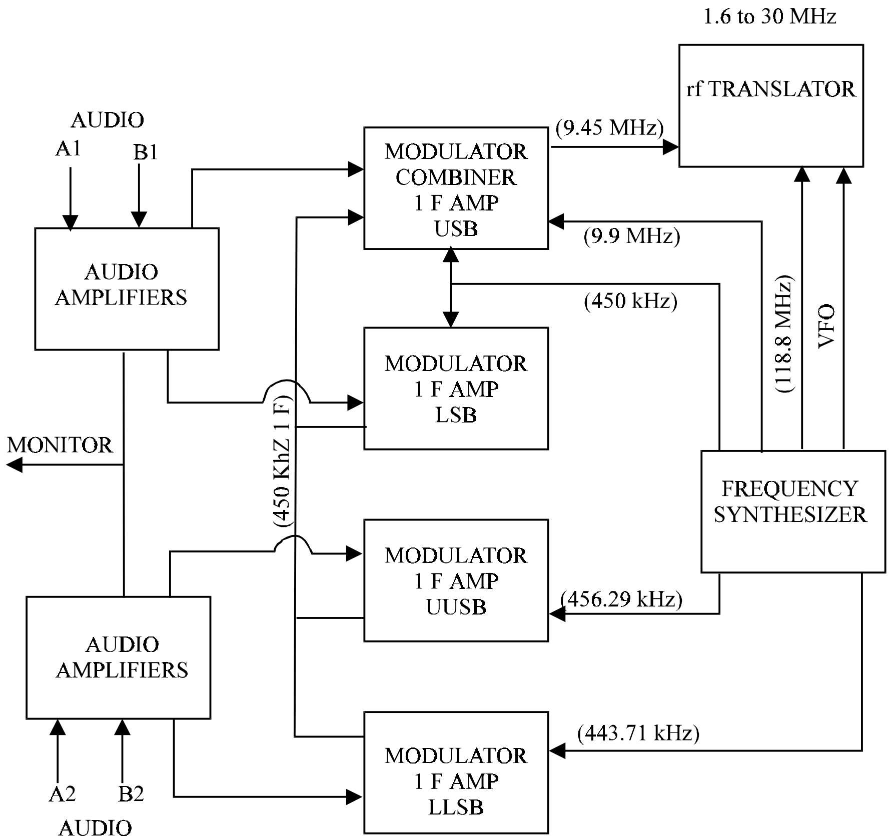


FIGURE 5.5
Block Diagram of an ISB exciter

- **Antenna subsystem**

Performance details for the antenna subsystem are outlined in Section 5.2.4, Propagation forecast, and in Section 5.2.7, Site/field surveys.

5.2.7 Site/field surveys

The primary technical objectives for a good HF radio site are to obtain the maximum signal-to-noise ratio at the receiver site and maximum effective power radiated in the desired direction from the transmitter site. Site topography affects the signal radiated from the transmitting site and signal arrival at the receiver site. The presence of natural and man-made noise detracts from the ability to obtain a good signal-to-noise ratio (SNR) at receiver sites. Desirable ground constants improve the performance of both transmit and receive antennas. These and other factors which enter into the selection of HF sites often involve compromises and trade-offs between economy, availability, and convenience. This chapter identifies items to look for in topography relative to terrain features and land-area requirements. Man-made radio frequency noise levels are defined for different areas. Site separation distances from noise sources are given. Earth constants in terms of resistivity and conductivity are discussed. General site requirements of availability, suitability, accessibility, and security are evaluated as to their influence on cost and practicality.

- **Topography**

The technically ideal HF radio site requires a broad expanse of flat, treeless land away from natural and man-made obstacles. Terrain flatness is necessary for uniform ground reflection of the antenna radiation. Obstacles may mask portions of the signal-radiation path at transmit and receive sites.

a. Site terrain features. The nature of the terrain in front of an antenna has a significant influence on the vertical radiation pattern. A good antenna site will have a smooth reflection zone and will be free of obstacles which may block the radiation path.

(1) *Reflection zone.* The reflection zone is the area directly in front of the antenna that is required for the reflection of the ground-reflected component of the skywave signal. The surface of the reflection zone should not have any abrupt changes in elevation greater than 10% of the antenna height nor a slope greater than 10% in any direction. Surface irregularities in the area should be limited to 0.1 wavelength in height at the highest operating frequency. The reflection zone at fixed sites and wherever else practicable should be cleared of all trees and brush. A low ground cover of grass, clover, or similar growth should be maintained for erosion control.

(2) *Obstacles.* In the direction of propagation, any substantial obstruction (such as a terrain mass, man-made structures, and trees) should subtend a vertical angle less than one-half of the angle between the horizontal and the lower 3-dB point of the required takeoff angle. See Figure 5.2. At potential HF sites where obstructions are likely to be encountered, a manually plotted site azimuth-elevation profile should be made. Elevation profile records are also useful for future planning in the event of expansion. Such a profile may be drawn by using a transit and a compass with azimuth readings corrected for the local magnetic variation. Normally, plotting the elevation in 10° increments of azimuth will be satisfactory. A method of plotting an azimuth-elevation profile is contained in appendix B of FM 11-487-4/TO 31-10-24.

b. Land area requirements. The area required for an HF site depends upon the size and number of antennas, the spacing between antennas, the clearance required for ground reflection, and the clearance required to avoid mutual coupling. In addition to known initial plans, space should usually be set aside for unspecified future antenna field expansion. Sites may vary from a minimum of a few acres for a small site to up to 60 acres for a medium-sized site. The land area requirements are determined by the system planner, based mainly on antenna field layout as discussed in 5.2.4, Propagation Forecast.

- **Environmental rf noise**

For reliable reception of weak signals from distant stations, the receiving antennas must be located in an electromagnetically quiet area relatively free from man-made noise. At HF, there are three major sources of rf noise: galactic, atmospheric, and man-made. The latter is of chief concern since it is the only source over which some control can be exercised. At many locations the noise from power lines dominates in the lower part of the HF band. Ignition noise from motor vehicles tends to predominate over power-line noise in the upper part of the HF band. Any strong, nearby source can be dominant in controlling the noise environment. The importance of locating an HF site in a quiet area is discussed in Section 5.2.4. A comparison between the values of man-made noise levels for "*quiet" "rural"*, "*rural"*, "*residential"*, and "*business"* areas shows an extreme difference of approximately 25 dB. Further information on man-made noise is contained in U.S. Department of Commerce OT Report 74-38.

a. Site separation. Radio transmitters located within several miles of a receiving station may create serious interference due to harmonics or co-channel operation. In addition, intermodulation products may be generated in receivers due to intense radio energy fields from nearby transmitters even when operated on widely separated frequencies. Radio receiver and transmitter sites must be isolated from each other, from other radio facilities, and from heavily traveled highways, cities, and industrial areas. Exceptions are sometimes required for small sites where antennas may be as close as 305 m (1000 ft) from each other. Transmitters with less than about 1 kW of transmitting power can be collocated with receivers if special attention is given to frequency selection. The use of rf filters may be necessary at collocated sites.

b. Ambient noise level surveys. Field-strength surveys should be made at receiver sites to evaluate the level and population of unwanted signals, to establish the ambient noise level, and, if possible, to locate sources of rf interference. A simple ambient noise survey can be conducted using an HF receiver with a signal strength meter (S-meter) and a portable antenna such as a whip or dipole. The receiver should be tuned to unoccupied frequencies near or on the intended operating frequencies. The test should be set up in the same configuration at each site if comparison tests are to be made. Noise measurements can be made by recording the S-meter readings when the receiver is tuned to unused frequencies. The receiver should be set to the AM position if it has one. A crude but useful test can be conducted with a hand-held battery powered AM broadcast receiver. Noise crashes are usually from thunderstorms within reception range. Hums, splattering, periodic noises and some noise crashes may be heard which can identify troublesome man-made noise sources. An initial survey with mobile equipment is recommended to spot check main highways and country roads in the vicinity of the site. The survey should identify noise sources and give an indication of the interference levels. A survey should be conducted from near the center of each receiver site being considered for comparison purposes. This survey should extend over sufficient time (usually several days) to gather statistically significant data for the noise characteristics of the site. Noise field strength measurements must be recorded to determine the ambient noise level of the site throughout the frequency spectrum of interest at various times of the day.

- **Earth constants**

Resistivity and conductivity of the earth and the relative dielectric constant at the HF site should be considered during site selection. The resistivity of the earth affects the quality of the earth electrode grounding system. The method of measuring the resistance-to-earth of grounding electrode systems is described in chapter 9 of FM 11-487-4/TO 31-10-24 and other documents. Soil resistivity measurement techniques are described in MIL-HDBK-419. Good conductivity of the earth increases the range of ground-wave propagation and lowers the take-off angle of skywave signals, thereby increasing their range. Ground conductivity is difficult to measure accurately. However, it may be estimated by the nature of the terrain.

- **General site requirements**

In addition to the technical factors, other important features of a general nature should be considered when selecting HF sites. They are as follows:

Availability
Suitability
Accessibility
Security

a. Availability. Land which meets the flatness criteria of an HF site is generally prime construction land or agricultural land. When this land is acquired in the acreage required even in small sites, it can be very expensive. In fact, land acquisition may be the single greatest expense in the project. Therefore, the site selector should always consider the use of existing facilities. The least expensive siting of an HF installation is to use and expand an existing HF site. The next least expensive choice is the use of unoccupied land already available to the Government. Land use within a military installation is normally controlled by the facility engineer. Non-military Federally owned land is controlled by various U.S. Government agencies, the primary one being the Bureau of Land Management.

b. Suitability. The general suitability of a potential site is dependent upon the magnitude of construction required for site development, implementation, and maintenance of facilities. The existence and capacity of nearby utilities such as electrical power, water, gas, and sewage disposal are important factors in site selection. Information relating to geological conditions such as soil and drainage data, wind and weather data (including icing conditions), and seismic activity should be gathered and considered. Soil and drainage data should be available from the supporting facility engineer. Wind and weather data are available from area weather stations, while records on seismic activity are usually available from the U.S. Geological Survey (USGS) or from a nearby university geophysics department.

c. Accessibility. Access to HF sites should be supported by the existence of adjacent roads and highways leading to the site. Conditions such as slopes, constrictions, curves, overhead and side clearances, surfacing, turnouts, and weight limitations on bridges and culverts should allow transportation of equipment during installation as well as during support operation and maintenance after installation. The facility engineer should be consulted about existing road conditions or for new road construction.

d. Security. HF radio site selection should consider provision for fences, area lighting, guard and alarm systems, proximity to other facilities, enemy threat, and defensibility of the local terrain. Transportable HF radio sites should be located to take tactical advantage of terrain obstacles, observation, and fields of fire, and to avoid possible enemy avenues of approach. In areas under enemy threat, it may be necessary to combine the transmitter and receiver sites to reduce vulnerability and to concentrate defensive forces. Physical security techniques are addressed in chapter 13 of FM 11-487-4/TO 31-10-24.

- **Site survey procedures**

Site surveys are conducted for the purpose of determining the technical and general suitability of land for an HF transmitting or receiving site. Each survey will have unique requirements for the number and size of transmitters, number of receivers, and the land and topography requirements for antennas. The process of selection of a site for a radio transmitting or receiving facility involves three distinct steps.

a. The first step entails map studies, ownership studies, logistics studies, and long range planning to select several tentative candidate areas.

b. The second step consists of teams who conduct preliminary site surveys to gather general site information of all the likely candidate areas. From the general site information, the list of candidate sites is then reduced to a potential few.

c. The third step involves survey teams who visit one or more of the final sites selected. The teams will gather detailed information which will be analyzed to determine the adequacy of the site or sites. From this information, a decision is made as to the best site to use for the facility. Appendix B of MIL-HDBK-420 contains procedures for conducting HF site surveys including a worksheet, which presents a general format that may be followed in preparing a site survey report. MIL-HDBK-420 is a general reference to communications site surveys.

- **Construction plans**

There is no standard configuration for the layout of HF radio sites. This is due to the wide variations in the makeup of HF radio stations. Some factors and considerations in HF station layout and development are contained in this chapter. When developing fixed small- and medium-sized HF systems, the selection of buildings, land, and related physical plant is usually limited to the modification of existing facilities. The development of HF radio communications systems within existing buildings and antenna layout on the existing land becomes a task of adapting the new system to available facilities. Antenna field layout specifications are governed by the area available to provide reflection zones and the clearances required to avoid mutual coupling between antennas. Other factors involve separation for purposes of diversity reception and consideration of interconnections between antennas and equipment. Typical site layouts which may serve as a point of departure to the site layout designer are depicted in this chapter. The development of HF transportable sites is also discussed in this chapter. The early establishment of the sequence of installation is the key to the orderly development of transportable HF communications. The transportable site development material in this chapter is intended to supplement the instructions in equipment technical manuals. This material is related to management and administration rather than specific technical details found in equipment manuals.

- **HF antenna layout**

One of the most important factors in the successful performance of HF radio communications is the correct positioning of antennas to provide maximum performance. An HF antenna layout requires a practical balance between choosing good sites, taking advantage of natural terrain features, separating noise sources, and taking into consideration the requirements for logistic support and accessibility. These factors were introduced in the Section 5.2.7 discussion of HF site surveys. HF antenna layout within a selected site involves three determinations: the requirements relating to the reflection zone area, the mutual separation clearances, and the physical layout of related facilities.

a. *Reflection zone areas.* The reflection zone is the area required in front of an antenna for the formation of the ground reflection lobe. The main lobe of an HF transmitting or receiving antenna is formed by the interaction of the direct radiation and the reflection from the ground plane. The ideal reflection zone has the following characteristics: a) it is perfectly smooth, unobstructed ground or water; b) it is of sufficient size as determined by the operating frequency and take-off angle, and c) it is an elliptically shaped area with the major axis in the direction of the radiation pattern of the antenna.

b. *Mutual coupling.* Mutual coupling is the effect of one antenna on another antenna when both antennas are located in the same general area. Mutual coupling occurs:
   - when the radiation pattern of one antenna passes through another antenna;
   - when antennas interact by being too close; or
   - when an antenna couples to a metal object or structure.

Mutual coupling may alter the radiation pattern of the antenna, may cause high reflection losses, may change the resonant frequency, or may introduce interference in other systems. Mutual coupling may be calculated as a function of the distance of separation, frequency of operation, and antenna gain. Table 4.2 of FM 11-487-4 gives simplified minimum clearances required by typical antennas at normal operating frequencies.

c. Other antenna siting considerations. In addition to separation distances to avoid mutual coupling, space diversity antennas must be separated to perform properly. Receive antennas operating in space diversity mode should be separated from each other by a minimum of 300 m (1000 ft) and, where space permits, by five wavelengths at their lowest operating frequency. Space diversity antennas should be located for both lateral and forward separation. Other considerations are:

1. Requirements for a spare antenna,
2. Room for future expansion,
3. Short and direct transmission-line runs,
4. Orderly arrangement of the transmission line,
5. Building entrance,
6. Equipment location with the building,
7. Separation between transmission lines,
8. Clearance of service roads and obstructions from in front of antennas.

- **Typical fixed site layout**

The physical size and layout of an HF facility are dictated by the communications traffic that the facility is expected to handle. Simple HF antennas often require space of less than one acre, however, a single large fixed HF antenna may require up to 15 acres. A small transmitting facility could consist of a single transmitter using a rotatable long-periodic (RLP) or Yagi antenna for transmission on different azimuths. A similar receiver site separated some distance for isolation could also contain remote control facilities for the transmitter. A single-circuit facility may have a transmitter and receiver collocated and may use the same antenna in simplex mode. A medium sized facility could consist of several fixed antenna systems serving an equal number of transmitters and receivers at separate sites up to 16 km (10 mi) apart. A large HF facility may consist of rows of equipment and hundreds of acres of antenna farms. Discussion of large fixed sites is beyond the scope of this manual.

a. A typical small site. The small HF facility layout shown in Figure 5.6 is typical of MARS stations and of stations operating in a small single HF command net. Such stations usually employ a single site layout, that is transmitters and receivers that are collocated. The emission mode is typically limited to cw, SSB, and RTTY. This configuration may consist of one or two fixed-azimuth antennas and an RLP antenna. The Vee antennas shown may be used for daily scheduled point-to-point medium range communications. The RLP antenna is useful for communications to a number of points at different times. In the configuration shown in Figure 5.6, one Vee antenna may be used for receiving and the other for transmitting. The RLP antenna can serve as a general purpose antenna for a simplex link. The dipole antennas, oriented 90° apart, can be added either for short distance links or as a receive antenna to check propagation. The antenna layout should facilitate the shortest and most direct transmission-line runs. The central location of the building avoids crossing of transmission lines. The single-access road diverts vehicular traffic away from high-powered radiation patterns.

b. A typical medium sized site. Separation of receiving and transmitting sites is one of the chief differences between smaller and larger facilities. One of two sets of transmitters and receivers can usually interoperate with relatively little interference with careful frequency selection. However, several high-powered transmitters will generate such interference problems in collocated receivers as to make the situation intolerable. A typical medium sized HF facility is shown in Figure 5.7. In this typical configuration, four sets of rhombic antennas are shown at distances of approximately 400 to 900 m (1300 to 3000 ft) from the operations building (receiving or transmitting). Transmitting antennas of large size, and at high power, are usually fed with open wire or rigid coaxial transmission lines. Such lines must be installed in the shortest, most direct path. At transmitting sites, antennas having the same orientation may be used alternately by separate transmitters for frequency changing with minimum loss of transmitting time. At receiver sites, antennas having the same orientation would be used as spares or as one of a diversity pair. The two RLP antennas and three monopole antennas shown may be used for coverage of azimuths not covered by rhombic antennas or may be used as spare antennas. Auxiliary power installations are sometimes required at larger HF sites. Generator power installations of 100 kW output power or less may be integrated into the operations building complex, but ideally are installed in a separate building near the operations building. Power building should be of well-bonded metal construction with fuel storage facilities. Fuel storage may be in above-ground tanks near the power building, but ideally should be buried and located with a diked area at least 10 m (30 ft) from the power building.

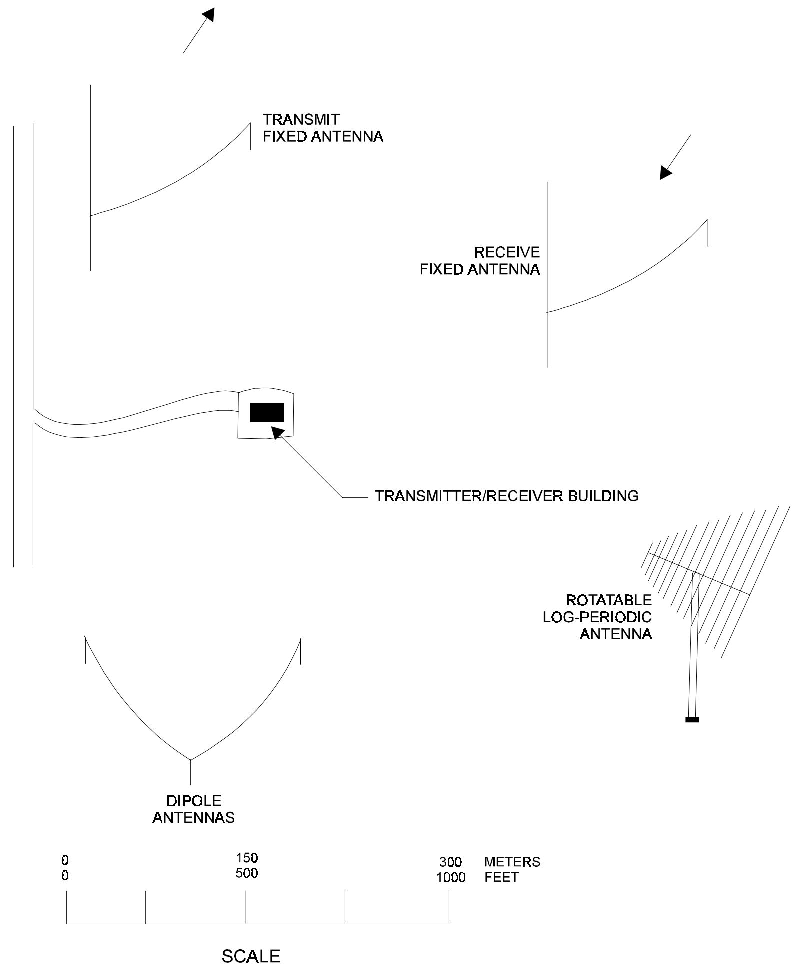


FIGURE 5.6

Typical small sized HF facility

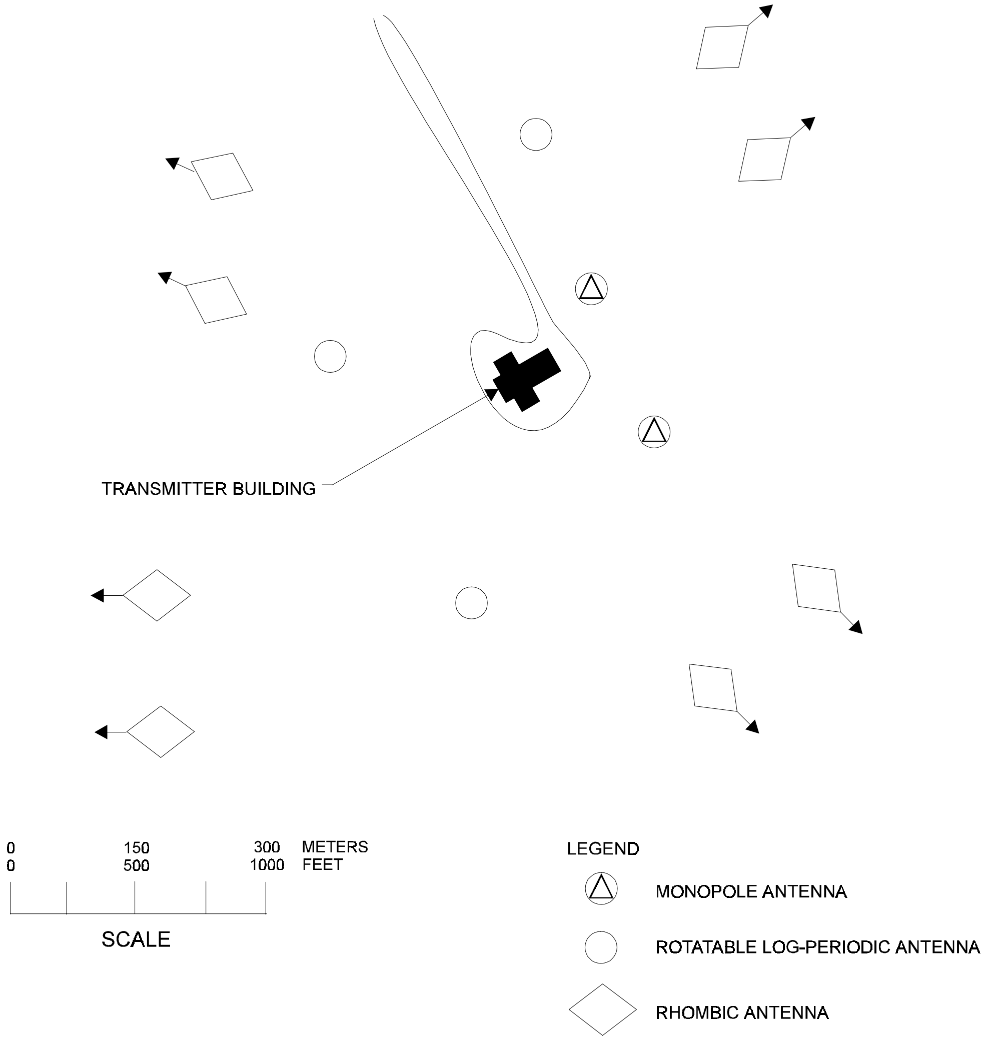


FIGURE 5.7
Typical medium sized HF facility

- **System test and evaluation plans**

An important part of any installation is to perform a system test and to evaluate the installation in a performing environment. As the system analysis and design phase progresses, thought should be given to how the system will be tested and evaluate after installation. One of the important steps that the system implementer and system engineer should generate is a System Test and Evaluation Plan that will be carried out as soon as installation and operation has begun. In cases where a network is involved, the network manager should be involved and the Network Design Plan should be considered an integral part of final system test. Areas that should be included in a System Test Plan might be:

- System Performance
- Network Performance
- Data and Message Throughput
- Power Considerations
- Physical and Network Security

5.3 System test

As the third phase of installation of the HF radio system, the system test and evaluation plan must be implemented. Possible areas that should be examined might include:

- System performance:
  - operating all equipment, which includes adjusting transmitter power, reading meters, rotating antennas, *etc.*,
  - equipment functioning properly:
  -transmitters, and receivers operating within specifications) ,
  - antenna performance:
  - are we reaching all the stations we wish
  - are radiation patterns as expected
  - environmental noise as expected.
- Network performance:
  - proper network connectivities,
  - proper network capabilities,
  - reasonable congestion,
  - reasonable number of system faults,
  - proper software installation,
  - network routing tables being filled properly,
  - linking protection scramblers functioning properly.

- Data and Message Throughput:
  - linking properly with all stations,
  - priority message handling adequate,
  - data message throughput adequate.

- Power considerations:

-adequate power for all operations, including emergency conditions
-clean power with only minor noise and fluctuations

- Review site security plan:
  - physical security adequate on all parameters
  - no hazardous conditions left from construction or implementation
  - network security is functioning

5.4 Conclusion

HF radio design process is not difficult if the proper up-front planning is done and the system engineer or system implementer understands just what is to be accomplished. To summarize the major steps:

1.The definition and analysis of the requirements should be detailed in a preliminary system design and feasibility study. This plan outlines requirements for frequencies, personnel, support, local issues, communication type, reliability, real estate, environmental impact, milestone dates, *etc*. Also included should be a detailed cost estimate of all known aspects of the design.

Individual steps to be accomplished in the system design are listed in Table 5.7.

TABLE 5.7
Step-by-step system design procedures

Step #	**Task to be Accomplished**
1.	Prepare system block diagram
2.	Tentatively select sites for HF equipment
3.	Determine final site locations from field survey data.
4.	Determine total required system gain.
5.	Develop a detailed block diagram for each facility.
6.	Research possible equipment sources – military inventory and commercial
7.	Write specifications for equipment not in the inventory.
8.	Develop equipment subsystem application drawings for each facility.
9.	Determine equipment installation requirements for installation.
10.	Complete installation package. (Specifications and drawings).
11.	Prepare acceptance test procedures for each equipment, subsystem, and the total system.

2. A system analysis and design is then completed, to identify the details of the network topology, operational parameters, propagation forecast, equipment selection, performance issues, site

surveys, and construction plans. Also included in the system design is the writing of a plan for system test and evaluation.

3. The third phase is the system test and evaluation phase where details of system are checked for proper performance.

The system engineer, system implementer, and network manager must fully cooperate and to assure that all details of the system design and network design are properly coordinated and completed.

With careful management, the HF radio system can be a valuable asset to the communication needs of the typical user. HF propagation has many valuable attributes and a few weaknesses. Through the use of proper planning, many of these weaknesses can be overcome.

.5.5 Summary of applicable standards

Many military and civilian standards exist that can be used for details when doing a system design or feasiblity study.

5.5.1 Federal Telecommunications Standards

FED STD 1037 C - Telecommunications: *Glossary of Telecommunication Terms*
FED STD 1045 A - Telecommunications: *HF Radio Automatic Link Establishment*
FED STD 1046/1 - Telecommunications: *HF Radio Automatic Networking, Section 1: Basic Networking-ALE Controller*
FED STD 1049/1 - *Telecommunications: HF Radio Automatic Operation in Stressed Environments, Section 1: Linking Protection*
FED STD 1052 - Telecommunications: *HF Radio Modems*

5.5.2 Federal Information Processing Standards (FIPS)

Federal Information Processing Standards (FIPS Pubs) are computer standards for use by the Federal Government. Some have adopted TIA/EIA industry standards and some are re-numbered Federal Standards. If interface of computer equipment with radio equipment is desired, then the appropriate FIPS Pub must be utilized for Government projects.

5.5.3 Military Standards

MIL STD 187-721 C - *Interface and Performance Standard for Automated Control Applique for HF Radio*
MIL STD 188-110 A - *Interoperability and Performance Standards for HF Data Modems*
MIL STD 188-114 - *Electrical Characteristics of Digital Interface Circuits*
MIL STD 188-124A - *Grounding, Bonding, and Shielding for Common Long Haul/Tactical Communication Systems*
MIL STD 188-141 B - *Interoperability and Performance Standards for Medium and High Frequency Radio Equipment*
MIL STD 188-148 - (S) *Interoperability Standard for Anti-Jam (AJ) Communications in the High Frequency Band (2-30 MHZ)* (U)
MIL STD 461 - *Electromagnetic Interference Characteristics Requirements for Equipment*
MIL STD 462 - *Measurement of Electromagnetic Interference Characteristics*
MIL STD 463 - *Definition and System of Units, Electromagnetic*
MIL STD 882 - *System Safety Program Requirements*
MIL STD 1472 - *Human Engineering Design Criteria for Military Systems, Equipment, and Facilities*

5.5.4 Military Handbooks

MIL HDBK 216 - *RF Transmission Lines and Fittings*
MIL HDBK 411 – *Long-Haul Communications (DCS) Power and Environmental Control for Physical Plant*
MIL HDBK 413 - *Design Handbook for High Frequency Radio Communications*
MIL HNBK 419 - *Grounding, Bonding, and Shielding for Electronic Equipments and Facilities*
MIL HDBK 420 - *Site Survey Handbook, Communications Facilities*

5.5.5 DISA (DCA) engineering standards

DCAC 300-95-1 – *Planner's Guide to Facilities Layout and Design for the Defense Communications System Physical Plant*
DCAC 300-175-9 - *DCS Operating-Maintenance Electrical Performance Standards*
DCAC 330-175-1 *DCS Engineering-Installation Standards Manual*
DCAC 330-175-1 *DCS Engineering-Installation Standards Manual, Addendum No. 1, MF/HF Communications Antennas*
DCAC 370-160-2 *DCS Circular- Site Surveys, Site Selection and Construction Design Criteria*
DCAC 370-160-3 *DCS Circular - Site Survey Data Book for Communication Facilities*
DCAC 370-185-1 - *DCS Applications Engineering Manual, Volume II*

5.5.6 Military Department Standards (Army, Navy, Air Force Technical manuals/Technical Orders, Post/Camp/Station Regulations or Directives)

AFCCP 100-6, *Communications-Electronics Activities-High Frequency Radio Communications in a Tactical Environment*
TO 31-10-4, *Air Force Standard Installation Practices*
TO 31-10-19, *Air Force Standard Installation Practices Antenna Systems—Anchors and Supports*
TO 31-10-22, *Air Force Standard Installation Practices-Antenna Systems—Open wire RF Transmission Lines*
TO 31-10-23, *Air Force Standard Installation Practices-Antenna Systems—HF Rhombic Antennas*
TO 31-10-28, *Air Force Standard Installation Practices--Erection of Steel Towers*
FM 11-65, *Army Manual—High Frequency Radio Communications*
FM 11-486-7/TO 31Z-10-22, *Army/Air Force Manual—Telecommunications Engineering-Electrical Power Systems for Telecommunications Facilities*
FM 11-486-8/TO 31Z-10-34, *Army/Air Force Manual—Telecommunications Engineering-Alternative Energy Sources*
FM 11-486-24/TO 31Z-10-25, *Army/Air Force Manual--Digital Data Transmission Error Protection*
FM 11-487-4/TO 31-10-24, Army/Air Force Manual -- Installation Practices: Communications Systems Grounding, Bonding, and shielding
NAVELEX 0101, 0102--*Naval Shore Electronics Criteria Naval Communications Station Design*
NAVELEX 0101, 0103--*Naval Shore Electronics Criteria HF Radio Propagation in Facility Site Selection*
NAVELEX 0101, 0104--*Naval Shore Electronics Criteria HF Radio Antenna Systems*

5.5.7 National (ANSI, IEEE, TIA/EIA, NEC) standards

IEEE C95.1-1991 - *IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz*
ANSI/IEEE STD 473-1985 - *IEEE Recommended Practice for an Electromagnetic Site Survey (10 kHz to 10 GHz)*

EIA Standard RS-232C-*Interface between Data Terminal Equipment and Data Communications Equipment Employing Serial Binary Data Exchange*
EIA Standard RS-258-*Semi-flexible Air Dielectric Coaxial Cables and Connectors, 50 Ohms*

5.5.8 International Standards (NATO, ITU-R Recommendations)

STANAG 4203	Technical Standards for Single Channel HF Radio Equipment
STANAG 4285	Characteristics of 1200/2400/3600 Bits per Second Modulators/Demodulators for HF Radio Links
STANAG 4415	Very Robust Version of 188-110A Single Tone
STANAG 4444	Slow Hopping HF Electronic Protection Measure
STANAG 4481	Naval HF Ship-to-Shore Broadcast System
STANAG 4529	Narrowband Version of 4285 Single Tone Appendix A
STANAG 4538	Automatic Radio Control System (ARCS)
STANAG 4539	Nonhopping Equivalent for Annex C of 4444
STANAG 5035	Introduction of an Improved System for Maritime Air Communications on HF, LF, and UHF
STANAG 5066	Profile for Maritime High Frequency Radio Data Communications
STANAG 5066 ANXG	Waveforms for Data Rates Above 2400 bps
QSTAG 733	Technical Standards for Single Channel High Frequency Radio Equipment

ITU-R RECOMMENDATION 455-1	Improved Transmission for HF Radiotelephone Circuits
ITU-R RECOMMENDATION 520	Use of High Frequency Ionospheric Channel Simulators

PART III. NETWORK MANAGER’S GUIDE

CHAPTER 6
NETWORK MANAGER'S GUIDE

6.1 Introduction

This section of this guide identifies some of the major steps to be taken when planning, implementing, and operating a network, specifically an HF ALE radio network. This guide identifies some of the pitfalls that could occur when implementing a network, and it presents a series of rational and orderly activities to support the planning and design process. Adherence to these guidelines could significantly minimize implementation risks.

The following is also a guide for understanding duties and functions associated with the position of *Network Manager* for a typical HF ALE network. The network manager and the network engineer work closely together to design and implement a smoothly functioning, efficient network. The term network manager refers to the function of network management, possibly a team of people, rather than a single individual holding that title. The network manager team has historically been responsible for the selection, implementation, testing, expansion, operation, and maintenance of the communication network. There are two primary objectives of network management: 1) to satisfy system users, 2) and to provide cost-effective solutions to the organization's communication requirements.

A summary of the duties of the network manager include the following:

- Work closely with the network system engineer to implement the details of the network design and to tune the specific network for the job at hand;
- Work closely with the network engineer to establish the physical network layout;
- Establish the necessary ALE network parameters and procedures;
- Be responsible for the establishment and maintenance of frequency sets and frequency assignments for the network;
- Be responsible for the establishment and maintenance of station addresses and associated parameters;
- Be involved in establishment of network operational procedures and disciplines needed for a smoothly operating network;
- Train and assist users in setting up or programming their equipment to assure smooth compliance with network operations procedures, and
- Be responsible for resolving network operational problems such as interference congestion, or faulty operator training.

The network manager is a key figure in all phases of network planning, implementation, and operation. A summary of these phases might be as follows:

- Planning,
- Implementation,
- Site Preparation
- Installation
- Pre-Cutover
- Cutover
- Operations [Wetterau, 1991].

6.2 Managing the network role of the network manager in an HF ALE radio system

The network manager has primary responsibility for the day-to-day operation of the particular HF ALE Radio communication network. His/her duties prescribe that he/she must be aware of all the underlying details of the network's operation as well as the personnel who staff the various stations within the net. The network manager must have a good understanding of the unique skywave propagation characteristics of HF radio as well as those of ground wave and line-of-sight propagation. He/she must be familiar with the various details and characteristics of HF ALE Radio equipment so he/she can guide the procurement, the setup, and the day-to-day functioning of the network operation.

The first preliminary phase of designing a new communication network is the *planning segment.* The major steps in network planning segment might include:

1. establishing objectives and requirements of the network,
2. doing a benefits and cost analysis,
3. doing network design to include network layout and site selection, and
4. doing equipment selection and procurement.

6.2.1 Network planning

Objectives and requirements

Objectives and requirements definition can be a very important prerequisite before any decisions on design alternatives can be made. This definition phase can be an iterative process where one examines the known requirements and then formulates a series of conceptual network solutions. The network manager should initially be provided with a list of network requirements and objectives, if not he or she should gather these facts from prospective users of the network. Usually it is well recognized that a need for the network exists, but different users may have different views of what the objectives and requirements of the network might be. In seeking out requirements, the network manager must be careful to determine why a requirement exists and if that requirement is real or imagined. It will be the job of the network manager to pull together the requirements and objectives, sift though them to find common threads, and to see if he can get the users to agree on a network architecture.

The requirements of a network can be described as falling into three general categories: Service Requirements, Interconnection Requirements, and Network Level Requirements.

The *Service requirements* include items such as:

1. overall scope of the network,
2. the nature of the network services to be included,
3. types of traffic to be carried,
4. costs involved, and
5. possible schedule constraints.

The *Interconnection Requirements* include those communication characteristics that relate to the paths within the network. Examples of these characteristics might include the location of nodes and resources; traffic classes between nodes; average traffic volumes; peaks and valleys of traffic volume; aggregate traffic flow; network performance; network security issues; and network availability issues.

The *Network Level Requirements* include issues beyond the functional characteristics (i.e., traffic, performance, security, and availability) such as network maintenance, network growth, and network management and control.

Benefits and cost analysis

The requirements analysis justifies the network architecture and quantifies user needs that will be met by the new network. The network designers uncover the technical needs and establish the network's benefits. Some of the issues that justify the network might be: the additional communication that it enables, the savings accrued from task reduction when it is deployed, the efficiency of traffic that can be handled, or the more traffic throughput that can be expected. Thus a benefits and cost analysis can show what are the true costs (in terms of money and perhaps in terms of performance) of networking for all the users.

Network design

Using the objectives and requirements as a basis, the analysts can perform a *network design.* The network manger must work with the network engineer to do the network design to include network topology, network layout, and site selection. The network topology may be chosen based on where the traffic originates , the destination to which it is to be transmitted, and the projected data flow. The topology chosen could be point-to-point, star, mesh, multiplexed, *etc.* The topology might consist of a single network or a multi-network environment (*i.e.,* a collection of networks linked together for communication). A traffic analysis can be used to show where traffic may be high or low, sporadic, priority or non-priority.

The network manager will identify all the stations or nodes to be included in the network as well as their geographical locations. He must be aware of the physical location of each node and the relationship to other nodes in the network. He must acquaint himself with any physical obstacle (*i.e.*, mountains, buildings, antenna, *etc*.) which may be present in the paths between the various nodes. He should be acquainted with the equipment located at each node especially the power and antenna characteristics. He must be keenly aware of all the various propagation paths between the various stations involved (*i.e.*, skywave, ground wave, and line-of-sight). The network manager will need to know details about the characteristics and volume of the communications traffic that will be traveling between the various nodes at various times during the day. He must be aware of the communication interfaces that are connected to each node and how the loss of one or more of these interfaces could affect message traffic across the network. The manager must be made aware of the priority of messages through each node as well as the importance of each net member to the total mission of the network. If messages are to be forwarded through intermediate nodes to accommodate the case where coverage may not be universal, this special routing must be considered in his traffic analysis.

To identify answers to the many questions the network manager may have at this point, he may wish to send a questionnaire to the managers of each potential node in the network. The purpose of the questionnaire will be to identify resources and equipment; availability of personnel; equipment types; traffic volumes; traffic classes; peak/normal loads; protocol overhead; performance considerations; reliability and availability considerations; aggregate traffic flow determination; and any special security, maintenance, management, or growth issues that might surface from this particular node.

1. Physical location. One of the first elements of the functional interconnection requirements is determining the *physical location* of each user or node of the network. The questionnaire should attempt to make a determination regarding the site location, general terrain considerations, *etc*. The identification process will also include the determination of whether the physical facilities are already occupied, are under construction, or are only be in the planning stages. The site may be a staffed or a remote unstaffed site.

2. Equipment type. It will be essential to identify the types of *existing equipment* located at each node including models, vendor, revision, memory/buffer capacities, power, antenna, etc., so its performance in the network can be modeled. Different equipment will have different address buffer sizes, link quality assessment (LQA) storage and reporting capabilities , traffic pattern paths, connectivity matrix capabilities, and message buffering capacities. Also the radio units will be of different networking capabilities (*i.e.* null datalink controller, basic network controller, hub network controller, *etc*.)

3. Traffic. The questionnaire should determine *anticipated traffic requirements* of each node. The traffic requirements encompass one of the most important characteristics to be accounted for in

the network system design. Knowing the peak, null, and aggregate traffic volumes of each node will allow the network manager to determine these values for the entire network.

4. Traffic classes. One way to begin defining traffic requirements is to determine the general *traffic classes* used by each node. These classes might include the need for real-time or immediate responses as well as the possible need for priority message traffic. The traffic may be interactive requiring ACK/NAK responses or may be simple broadcast mode. The traffic may be simple AMD messages or may be large blocks of data to be transferred between host computers or peer devices. The network manager is best advised to view file transfers of large blocks of data as only allowable under special conditions. The transfer of large blocks of data can be very time consuming and can tie up the network for long periods. For instance, if large block transfers were allowed, the normal traffic load could be delayed for minutes at a time; in general, this sort of traffic tie-up is an unacceptable practice. Data transfers of large blocks of data should be accomplished by other means (*i.e.,* data modem, *etc.*), rather than as traffic on the network.

   Another factor affecting traffic volume and the network as a whole is the protocol In general the overhead for most HF ALE radios will be approximately the same, but it could vary by equipment vendor, by the operator□s chosen variables, by the type of commands being used (*i.e*., procedural or control), by whether the message traffic contains LQA and AMD orderwires, and by use of data transfer protocols (such as DBM, DTM, *etc*.).

5. Performance A node may have special requirements in terms of *performance.* Performance may be defined for the network, for an individual path, or for an individual node. An individual node, in turn, may need to define acceptable delays according to mission, scenario, or logical path.

6. Availability/Reliability. The questionnaire should be structured to determine the *availability and reliability* requirements of the node. A node might have a need to define the minimum requirements for availability or reliability. The network manager might need to know about the user's sensitivity to transfer or duration failures. He will also have to make a determination of what is the tolerable impact of a failure on the user's operation. He might also have to study the results of losing a particular node to overall network operation such as when the network is no longer being able to use this node for forwarding messages. When designing a network for circuits with high priority traffic or network links that must have a high degree of availability, the network manager may conclude that the links should use redundant equipment for backup purposes. It might be necessary to have a complete backup of critical equipment installed and available in a powered-up "hotstack" to be used in case of failure. For the most critical paths and to increase the redundant capabilities of backup equipment, this equipment could be connected in a "mirror" configuration where the frequency scan list and address information matrixes of the backup equipment is as current as possible. This current information is achieved by constantly updating both the on-line and backup databases.

7. *Security*. The questionnaire should be designed to identify and evaluate any special *security* issues associated with this particular node. Security requirements can also be applied to individual nodes and to the network as a whole. Like reliability, there is a real cost associated with security; for that reason, it may be wise to determine precisely which paths and messages must be secure. The network manager should also make an attempt to address security in terms of physical facilities, access to the network, and the data itself.

8. *Maintenance*. The questionnaire should be designed to determine if any special *maintenance* requirements will be needed. Maintenance requirements will be dictated to a large extent by the availability requirements of the network. Preventive maintenance procedures should be implemented to maintain the hardware and software of the system. These maintenance procedures should be put on a scheduled program to assure that the procedures are undertaken at the prescribed interval.

9. *Network Management and control*. The questionnaire should be structured to determine what degree of network management and control will be needed. *Network Management and Control* requirements include such items as the design of central communication points and the handling of various types of information needed for control purposes.

10. *Growth*. The questionnaire should be designed to determine the anticipated growth issues of the node and network as seen by the individual node administrator. The issues of size and *growth* of the network should be resolved by accommodating decisions made in the requirements phase. Growth may be the result of adding new nodes, developing new applications, changing security requirements, and/or changing performance levels. Users often are more concerned with day-to-day operations than with long-term growth issues, and therefore it will be the network manager's responsibility to ask penetrating questions regarding long-term growth requirements.

Functional Design

Having analyzed the requirements and received responses from the node managers on the details for each node, the network manager has an insightful perspective of WHAT the network is to do. The task now is to translate the requirements into a functional design. The objective is to develop a network design that satisfies as many of the requirements as possible.

One of the first requirements that must be translated into design criteria is the user's expectation of *network performance*. Users perceive the network's performance in terms of *delay* experienced in getting a message to another user. This delay is usually measured from the first character of the request to the last character of the response, or the total time the channel is tied up with passing this message. Another type of delay is associated with an intermediate node in message forwarding. The delay here might be due to queuing the message for later transfer. This delay can be more significant than normal message passing but possibly not as great as the delay experienced with a switching node. A switching node is acting as a bridge between networks and possible buffering, decompression, queuing, compression, unbuffering can be taking place. By far the most significant contributor for delay in a HF ALE radio system is due to the changing HF Ionosphere conditions associated with the atmosphere. In some cases the delay experience by a particular message might be 12 to 24 hours or longer. HF ALE radio usually has several frequencies associated with a system in which case the delay may be associated with changing to another frequency. Or in the case of a complete shut down of all frequencies used by this station, delay would be until conditions change

The next issue to be addressed by the designer is that of network *throughput.* Throughput is typically defined as the rate at which data transfer can be sustained. To a very large extent, this is limited by the speed of transmission, delays due to distance, delays through nodes, possible switching delays, *etc*.

The *availability of a network* is usually expressed as the percentage of "up-time." It is determined by dividing the Mean-Time-Between Failure (MTBF) by the sum of the MTBF and the Mean-Time-To-Repair (MTTR). The availability is calculated for each component in the network, and the product of the availability of the components in a given path yields the overall availability of the path [Rothberg, 1988].

Design Methodology

Given the requirements and analysis of the design criteria, one can look at the *Topological Design* of the network. Typically, the network design can be divided into two areas: 1) the backbone design where the backbone topology is characterized, and 2) the local access design where local node characteristics are added issues [Rothberg, 1988].

At this point the *connectivity* of each node can be determined. By determining primary and alternate paths across the network, connectivity to all nodes in the network can be determined as well as connectivity plans covering all nodes in outage conditions (such as bad propagation or failures of primary nodes). A simple graph is a useful tool in analyzing the connectivity of the network.

Now applying the connectivity and the *delay analysis* done earlier, the delay for each path can be determined. In some cases multiple hops or store-and-forward message delivery may be required to connect all nodes under all conditions.

If store-and-forward capabilities will be necessary to cover cases where a blockage has occurred, some basic queuing analysis will have to be applied to account for the time that messages are sitting in queues waiting to proceed to the next node. The most common queue is a single-server queue where messages or packets arriving randomly are serviced one at a time before being forwarded to the next node. A single-server queue might best be compared with a *line at a bank teller* [Rothberg, 1988]. Another type of server is a multiserver that handles arriving messages (packets) that have formed a single queue or line. A good example of this type of queue is a *single line at a bank or airline counter, where the next available teller or agent takes the next person in line* [Rothberg, 1988].

Variables associated with queue theory might be:

1. The number of messages arriving within a defined period,
2. The time required for processing each transaction,
3. The percentage of time a user should be able to access the network without being blocked,
4. Number of required servers,
5. The time required before a message is dropped due to continued blockage.

Simple queuing models are available for this analysis, should they be necessary.

Equipment selection and procurement

Part of the manager□s duties in the planning function may include equipment procurement. It may be that the users themselves will procure their own equipment for individual stations, but there usually is some common equipment such as a master node, antenna, *etc.*, that must be purchased by the network manager. Also the users themselves may need some expertise in the procurement process and may call upon the network manager for assistance. The network manager should be a key figure in the *equipment procurement process*. The network engineer and the network manager usually have the most current and relevant information about the network, its equipment, and its mission. The procurement officer will need to draw on this knowledge when purchasing equipment for the network or for the individual nodes. It should be the network manager's responsibility to be available for consultation on matters related to equipment purchases.

Designing for efficiency

After the first cut at a network design is finalized, the network management team should step back and take very special note of any evident inefficiencies. The inefficiencies of such a design may be overcome by combining some paths, hardware, communications facilities, or other resources into a single integrated structure.

6.2.2 Network Implementation

The second phase of network planning is the *implementation phase*. Implementation can include the items of planning, schedules, and control. Since the network manager is responsible for the network in its entirety, he is the logical candidate for responsibility when it comes to initial planning and setting the schedule for the events that must happen for the network to become a reality. The network manager must also set up operating procedures that will assure that the network operates as everyone expects. The procedures will include perhaps unique characteristics or parameters, frequency sets and assignments, and individual and network addresses, and network standard operating conditions.

Network development requires an orderly and structured approach, as would be expected in any design activity. The phases of the network development life cycle might include:

1. Requirements definition,
2. Feasibility determinations,

3. Design constraint analysis,
4. Network loading analysis,
5. and Network Design.[Rothberg, 1988]

The network manager develops a *system implementation plan* with the primary purpose to identify all the necessary resources, activities and phases of the development life cycle.
The topics to be included in the implementation plan might include:

1. Functional overview and scope statement - outlining the network in terms of the services it will offer,
2. Estimate of overall project costs,
3. Estimate of project completion date which possibly might be supported by:
   a. detailed activity schedules,
   b. and/or milestone charts
   c. cost-resource requirements for each activity,
   d. project organization to identify personnel requirements—technical and supportive
   e. Assumptions that may have been used to arrive at the technical, cost, or schedule aspects of the program.[Rothberg, 1988]

Unique ALE parameters

The network manager must work with the network engineer to do the network design to identify any unique network (ALE) parameters. These items might include important details and trade-offs that are associated with setting-up and maintaining a HF ALE Radio network. Power, antennas, frequencies, address name groupings, etc., all can effect the operation of the network. The network manager, together with the network engineer must develop these details for the benefit of all network users and the efficiency of the total network.

Frequency sets and frequency assignments

The network manager must establish and maintain the frequency sets and frequency assignments necessary for network operation. The radios are capable of scanning a group of select frequencies or channels under manual control or under the direction of an automatic controller. The scanned channels should be selective by groups or sets, and also individually within the groups, to enable flexibility in channel management and network scan management.

The selection of optimum operating frequencies is one of the most important characteristics contributing to overall system performance. The frequency (cies) should be chosen based on the following general characteristics:

1. The frequency (cies) chosen is (are) has to be one of the assigned frequencies given to the net;
2. The propagation of that frequency is in the selected range which ensures signal-to-noise-ratio (SNR) or maximum signal reaching the receiver and minimum distortion;

3. The frequency(cies) chosen must propagate(s) well during at least some periods of the day (considering the whole 11-year solar cycle);
4. Be environmentally noise-free of man-made noise at least during some hours of the day; and
5. The propagation path between both end points should have similar characteristics in both directions during some period of the day

The network manager typically has a group of frequencies assigned to the network. He may or may not make them all accessible to all the members of the network. He may wish to distribute the frequencies across the network in a manner that establishes *subnetworks*. As an example, suppose the network is assigned 10 frequencies, but at the network manager's discretion, node 1 can only use channels 0,1,2,8,9, while node 2 can use channels 2,3,4,5,6,7,8. It is clear that for traffic between node 1 and 2, only channels 2 and 8 are in common and therefore one of these channels must be used for communication between these nodes. Each of these groups of frequencies is considered a *set* and the typical network can have as many sets as needed. The determination for sets might be physical location, stations with characteristics in common (i.e., mission, type, propagation limitation, etc.).

Refer to FED-STD-1045 for additional information on frequency sets and frequency assignments.

Station and network addresses

HF ALE stations are assigned one (or more) addresses to identify them during selective calling. The two basic types of station addresses are: *individual addresses* and *net addresses*.

The network manager must establish and maintain the individual and net addresses of the network. For some DoD and Federal networks, ALE addresses must be assigned and registered[1].

1 Proposed FTR1047/3 Network Coordination and Management- ALE Addressing and Registration, establishes procedures for the assignment and registration of ALE addresses for use in network operations in the DoD and Federal communities. This standard also provides guidance for closed departmental network operations and directives for intra-department and shared network operations [proposed FTR 1047/3]

An individual address is unique and is assigned to only one station in the network. Calls to individual addresses are responded to by only one station. Net addresses can be assigned to a group of stations that might have something in common within the network (*i.e*., mission, type, propagation limitation, *etc*.). Calls to net addresses are responded to by more than one station but require individual stations to respond only in predetermined time slots associated with that station individual address. There may be many nets associated with a network. Each station may have more than one individual, or net addresses. Wildcard addressing (Anycall or Allcall) can be used to further modify station addressing by changing the grouping of sets responding from “one,” to “many,” or “all.” [2]

Individual Self-Addresses: All ALE stations have the capacity to store and use at least 20 individual self-addresses, each having 3 to 15 characters. If the address is only 3 characters in length it is termed a *basic address*; if from 3 characters to 15 characters, it is termed an *extended address.*

Multiple stations: A prearranged collection of stations, with a commonly assigned address is termed a *net*. A non-prearranged collection of stations without a commonly assigned additional address is termed a *group*.

Net: A prearranged collection of stations.

Group: A non-prearranged selection of stations. In many cases, little or nothing is known about the stations, except their individual addresses and scanned common frequencies.

Network Self-Addresses: A net address is an address used to place a call to a prearranged group of stations that share a common address. A net call rapidly and efficiently establishes contact with a prearranged group of net stations by using a single net address, which is an additional address assigned in common to all net members.

Utility symbols in address: Addresses may be modified in some cases through the use of the utility symbols "@" and "?". These special utility symbol characters are used in the special calls such as:

- Stuffing
- Allcalls
- Anycalls
- Wildcards (after FED-STD-1046 /1)
- Self address
- Null Address

Stuffing. The quantity of available addresses with the system, and the flexibility of assigning addresses, are significantly increased by the use of address character stuffing. This technique allows address lengths, which are not multiples of three, to be compatibly contained in the standard (multiple of three) address fields by stuffing the empty trailing position with the utility symbol "@". Refer to FED-STD-1045 for details.

Allcall Addresses: An "allcall" is a general broadcast that does not request responses and does not designate any specific address. This can be in a global "allcall" or partial global "selective allcall" manner while not requesting responses. This essential function is required for emergencies ("HELP"), sounding data exchanges, and propagation and connectivity tracking.

Anycall Addresses: An ALE station may call and may receive responses from essentially unspecified stations, and it thereby can identify new stations and new connectivities. An "anycall" is a general broadcast which requests responses without designating any specific address(es). It is required for emergencies, reconstitution of network and systems, and creation of new networks. The anycall, selective-anycall, and double-selective anycall are characterized in Table X of FED-STD-1045A.

Net Addresses: The purpose of a net call is to establish contact rapidly and efficiently with multiple prearranged (net) stations (simultaneously, if possible) by the use of a single net address, which is an additional address assigned in common to all net members.

Group Address: The purpose of a group call is to establish contact with multiple non-prearranged (group) stations (simultaneously if possible) rapidly and efficiently by the use of a compact combination of their own addresses which are assigned individually.

Null Address: For test, maintenance, buffer times, and other purposes, the station can use a null address which is not directed to, accepted by, or responded to by any station. When an ALE station requires a null-address type of function, it can use the null address protocol. The null address special address pattern shall be "TO @@@," (or REPEAT @@@), if directly after another TO). The null address shall always use the TO (or REPEAT) and only in the calling cycle (T_{cc}). Null addresses may be mixed with other addresses (group call), in which case they shall appear only in the leading call (T_{1c}), and not in the scanning call (T_{sc}). Nulls will never be used in the conclusion (terminator) (THIS IS or THIS WAS). If a null address appears in a group call, no station is designated to respond in the associated slot; therefore, it remains empty (and may be used as a buffer for tuneups, or for overflow from the previous slot's responder, etc.).

Refer to FED-STD-1045 for additional information on station and network addresses.

Network manager addressing duties example

As an example of the duties of the network manager in a very large network one can look at the responsibilities of the HF ALE Network Manager in the HF Global Communications System Air/Ground/Air Network (see section 9.4 of this report). *The HF ALE Network Manager shall build and maintain a database of all their HF ALE stations, their configurations, ALE addresses, frequency lists, and system parameters. The manager must build databases and disseminate this information to all agencies supporting mission operation. The manager must work closely with frequency managers and their agency's tasking offices in order to build HF ALE networks* [HFALECoO, 1996].

HF ALE users of the HF Global Communications System Network must utilize addressing protocol procedures identified in the concept of operations (CONOPS) document to communicate with stations in this net. The goals of this document are to

-*Develop procedures that will ensure interoperability between DoD HF ALE users.*

1. Provide policy and procedures needed to establish a training and testing environment for HF ALE users,
2. Establish operational procedures that will ensure interoperability with other Federal agencies and connectivity to and from the National Command Authority (NCA).
3. Develop experience and generate *an operational data base for introducing HF ALE radio operations in the DoD.*[HFALECoO, 1996]

Network standard operating procedures

Every network has a set of standard operating procedures associated with its operation. These procedures establish protocol and permissive operation for purposes of establishing a network that is functional for all participants. Examples of standard operating procedures are:

1. Scan list: Setting up a scan list of individual radio parameters such as individual, net and group addresses. Every station may be assigned one or more individual (self-) addresses, and one or more net member (self-) addresses. Self-addresses—either individual or net—are identifiers that a station recognizes when receiving calls.

2. Sounding: Setting up to allow or disallow sounding—automatic or not—sounding interval, sound duration, sounding-retry time, etc., are operational parameters established in each individual node/radio. Sounding is the ability to empirically test selected channels (and propagation path) by providing a very brief, beacon-like, identifying broadcast which may be utilized by other stations to evaluate connectivity, propagation, and availability; and to select known channels for possible later use for communications. The sounding signal is a unilateral, one-way transmission which is performed at periodic intervals on unoccupied channels [FED-STD-1045]. Sounding may be used or not depending on the desires of the network manager and node personnel. If it is used, the following items need to be standard network operating

procedures administrated by the network manager: a) frequency of use, b) the amount of time it can be used, and c) the amount of time to wait after a faulty attempt.

3. Configuration parameters: Setting up individual radio parameters that will control calls; LQA updates, thresholds, maximum age, and reporting; network tune time; linking termination parameters; allow or disallow Anycalls or Allcalls; *etc.*

4. Message specific parameters: Setting up parameters considered specific to the individual message such as allowing or disallowing priority messages immediate message override *vs.* next break, *etc.*

5. Operational issues: Establishing operational procedures that will affect an individual station's communication within a network such as return to scan time, voice monitor, slot wait time, maximum slot used, net wait time, maximum wait before ACK, scan minimum dwell, *etc.*

6.2.3 Network Site Preparation

The third phase of network planning includes site preparation. Site preparation can include such things as contracts, permits, construction, and inspection. Few, if any of these items are typically the responsibility of the network manger unless some equipment is being installed that may not be the responsibility of the users, such as a master node unit or master control station which is common to all. The network manager will be responsible for site preparation details on common network equipment and will be an advisor regarding node equipment.

6.2.4 Network Installation

The fourth phase of network planning and implementation is the actual installation of equipment and procedures. The network manager must be involved in the installation of any common network equipment not the responsibility of the individual node stations. He also should be aware of the individual user's installations and should offer assistance wherever possible.

6.2.5 Network Pre-Cutover

The fifth phase of network planning and implementation is the pre-cutover phase, which consists of the last-minute items necessary prior to operation. Prior to putting the network in operation, the following items should be completed: installation inspection, final tests, establishment of support systems, assurance of operator training, assurance of address and frequency coordination/installation, and a check of network documentation.

Assist users in network setup and operation

The network manager is the person to consult when first beginning to set up a network or when a question arises over station operation. The network manager might be involved from the beginning with procurement issues, he will assign addresses and frequencies, he will establish operator training guidelines, and will be responsible for user training.

Frequency coordination/installation

The radios typically require the installation of address parameters as well as frequencies and frequency sets. The network manager can be involved to whatever extent necessary to assure that all users are ready for a smooth cutover.

6.2.6 Network Cutover

The sixth phase of network planning and implementation is the actual cutover phase where actual network operation begins. The network manager needs to schedule and to coordinate the cutover operation. He should assure that coverage is as anticipated in the design plan during the cutover period. He should try to determine that traffic patterns are as expected between the various nodes. He must also be prepared with a contingency plan, should things not occur as planned.

6.2.7 Network Operations

The seventh and final phase is the operation of the network. Once a system has been successfully installed, tested, and placed into operation, then the day-to-day management of the network begins. Operations deals with monitoring, control, diagnostics, and repair. The network manger should be instrumental in assuring that the network operates smoothly and efficiently. He should be responsible for continued configuration management, resolving network problems or faults, monitoring network performance/operations, network maintenance, user satisfaction, frequency and address maintenance, and network security.

Maintaining operational control may mean establishing a control center, complete with procedures for reporting problems, facilities for monitoring, and tools for support.

Continued configuration management

As an on-going task, the network manager must monitor the routes that information takes through the network and must compare it to the original details established during planning. Changes may be necessary in frequencies, frequency groups, addresses, nets, antennas, power, *etc.,* to correct an undesirable situation.

Resolve network problems or faults

The network manager must be notified when any network node or element has failed, is likely to be near failure, or is performing outside of its range of defined specifications. The network manager has the task of monitoring network conditions to detect out-of-tolerance behavior and then taking action when such conditions occur. A network cannot be found that will not have an occasional problem or glitch in its operation. Interference issues, grouping issues, operator errors due to poor training, etc., are a few of the issues that a network manager must deal with on a day-to-day basis. He must be prepared with knowledge concerning the network, standard operating procedures, assignments, and training issues, so that he/she is able to resolve misunderstanding or technical issues.

Performance management

The network manager is responsible for supervising the performance of the network and for controlling the flow of traffic to obtain maximum use of the network capacity. This task includes monitoring the network's traffic, its remaining capacity, the rate of flow, the incidents of delay, and other factors relating to the network's connection and flow services. This task also includes capacity management and planning functions. A summary of the specific work functions of the network manager might include:

- Monitoring the flow of traffic in the network on a real-time basis;
- Collecting and analyzing network performance data;
- Identifying abnormal network situations; and
- Investigating and determining the reasons for network traffic-flow problems.

Network maintenance

To support the network after implementation, maintenance procedures must be developed to maintain the hardware and software. These procedures can include preventative maintenance steps designed to protect both the hardware and software associated with the network. On the hardware side, procedures should be established to protect network equipment from premature failure. On the software side, procedures should be established to continually monitor the system responsiveness and traffic throughput. Also checks should be made to see if the latest version of software is being used. Checks should be made on buffers and matrixes to see that they are not becoming full or filled with useless information. Problem resolution can be at the network level or at the individual node level, but in all cases a report to the network manager should be required if the problem affects some aspect of the network. The network manager should be made aware of immediate and potential problems so that a pattern of trends might be established. He/she needs to be given enough information so that he/she is able to make changes in equipment, software, or procedures. The network manager will be key to tracking problem resolution and dispatching technicians/ programmers to solve problems.

Once procedures are in place, user training of personnel on maintenance concepts should be undertaken.

User satisfaction

User satisfaction implies the network must receive high marks in the areas of performance, availability, and reliability. User satisfaction can also be enhanced by supplying users with the latest information on system changes and by providing users with formal and informal training. The users of the network are the individuals and organizations with a mission, the network is their communication tool to bring about that mission. Keeping the users happy while at the same time operating an efficiently functioning network is a key task for the network manager.

Items that are keys to good user satisfaction include:

Good performance: Good performance means a predictable response time to message requests. In the HF ALE Radio system, the network manager has little control over the message processing and node operating parameters. He does, however, have control over the configuration aspects of the network. The configuration details include the number of users, user's message types, and hardware employed; all can affect the network performance.

Availability: Availability means that all necessary components are operable when the user requires them. For HF ALE radio systems this means availability or access to the radio media on demand or within a reasonable time period. But since HF propagation on one particular channel is not available at all times, availability will be construed to mean over at least one HF propagation path.

Reliability: Reliability of the network involves error characteristics of the medium and stability of the hardware and software components. Again, the network manager has little control over the varying conditions of the HF propagation paths but the stability of the hardware and software comes from good planning, good procurement, and good maintenance practices. These are issues that can be addressed by the network manager.

Repairing failures in a network: When failures occur, the network manager and his team must either patch around the failure, replace the failed component, or repair it.

Keeping Users Informed: In addition to performance, availability, and reliability, there are a number of other factors, less obvious, that can affect user satisfaction. Users should be informed of scheduled down time, periods of bad propagation conditions, certain changes in hardware and software, and changes in personnel with whom those users will be interfacing.

Frequency and address maintenance

As an on-going task, the network manager will review the frequency and frequency set assignments to determine if the choices are still the most efficient possible. The address choices should also be reviewed to determine if any details have changed and if the address scheme is still the most efficient possible.

Security management

The network manager has the task of controlling access to the network. In the case of a network such as an HF ALE radio system, access control will probably be by controlling the frequency and address components of the system to prevent illegal entry. The network manager must be aware of the possibility that security issues might arise at any time, and he/she must be prepared to resolve them. The network manager should have in place a procedure for resolving security issues. The following items could be used as examples for establishing a process for managing security risks:

1. Identify vulnerabilities of the network,
2. Analyze the likelihood of threats to the network,
3. Assess the consequences if each threat were carried out,
4. Estimate cost of each attack, and
5. Identify and cost out the potential countermeasures.
6. Select the security mechanisms that are justified. [Minoli, 1991]

Vulnerabilities to the network and the means of counteracting might be described as follows:

1. Physical security vulnerabilities. Protection for the physical aspects of the system such as equipment and facilities from such things as fires, floods, thief, abuse, etc. Usually common sense measures are what is required for protection against physical vulnerabilities (*i.e.* fire equipment, power protection systems, secured building, restricting physical access, *etc.)*

2. Personnel vulnerabilities. One of the principle threats to sensitive information or equipment has always been the individuals who are trusted to properly handle this responsibility [Walker, 1985]. The network manager must assure that principals associated with the network and network information are the only individuals exposed to sensitive information.

3. Procedural vulnerabilities. It is necessary to have a reasonable and complete set of procedures for the operation of the network. User passwords, system use procedures, outage recovery procedures, etc are all important to a smooth functioning network operation.

The vulnerability of the network constitutes a wide range of vulnerabilities in which failure of any element may compromise the integrity of the entire system [Walker *et al.*, 1985]

Security threats to a network might include:

1. Circumventing the access procedures and entering the network illegally;
2. Denial of service by jamming (through a tone or signal), or suppressing traffic by generating nuisance traffic;
3. A masquerade attack in which an entity claims to be a different entity;
4. Modification of messages by spurious signals or *etc.;*
5. A replay attack that is carried out when a message, or part of a message, is repeated in order to produce an unauthorized effect;
6. A trapdoor implanted when an entity of the system is modified to allow an attacker to produce a future unauthorized effect on a command or an predetermined event; and
7 A Trojan horse is an entity that, when innocuously introduced into the system, has deliberately planned unauthorized effect in addition to its authorized function.[Minoli, 1991].

If security mechanisms or countermeasures are deemed appropriate for the network, the following guidelines will aid the network manager in their use. Security controls and mechanisms are effective if they make the cost of obtaining or modifying data, and/or disrupting services greater than the potential value of carrying out the disruption. Security measures will usually increase the cost of the systems; therefore, the specific threats, if any, should be identified. Some controls that could be used in a HF ALE system might include:
- configuration of the system as a star, with strict controls imposed for host access;
- encryption and use of keys;
- node and hub, physical access controls;
- frequency and address management;
- call back; and
- message authentication. [Minoli, 1991]

The duties of the network manager in regards to security might include:

1. The creation, deletion, and control of security services and mechanisms;
2. The distribution of security-relevant information; and
3. The reporting of security-relevant events.

6.3 Automated HF Network Management

HF ALE radios are presently using automation to the extent of assisting the operator with establishment of the link, and passing traffic over marginal HF channels (those channels experiencing fading, or noise interference). Additional features and functions are being considered that would extend the requirements of the automated network management system and thus increasing the duties of the network manager. These features and functions might include:

1. monitoring and reporting network status (connectivity, capabilities, congestion, faults, *etc*.);
2. updating network routing tables;
3. manipulating the operating data of automated communications controllers (such as ALE controllers);
4. identifying software versions and updating the software, in ALE and other communication controllers;
5. rekeying linking-protection scramblers; and
6. remotely operating all communications equipment, which includes adjusting transmitter power of linked stations, reading meters, and rotating antennas.[Johnson *et al.*, 1997]

Annex 4 of this document contains some examples of typical HF ALE radio networks.

6.4 Conclusion

The network planning and design process is not difficult when one understands just what is to be accomplished. One simply remembers the fundamental steps for network planning: define the *network's scope*, collected together the *objectives and requirements*, do a *benefits and cost analysis*, and complete a *network design plan* to start the ball rolling. An *implementation plan, site plan, installation plan and cutover plan* gets your network running. While a good *operations plan* will keep the network running efficiently.

As the role for communication networks expands, so will the role and importance of network management. The keys to effective network management are personnel who are competent and knowledgeable, and who can plan a network for a wide range of uses, and who can work well with wide spectrum of users. With careful management, the network can be a valuable asset to the communication users of typical HF ALE radio systems.

ANNEX 1
THE PROPAGATION MEDIA

Introduction

There is a high correlation between solar activity and HF skywave propagation. The reflecting and absorbing layers of the ionosphere are produced by and are largely controlled by the radiation from the Sun. Some of the variations in the ionospheric characteristics are more or less regular and can be predicted with reasonable accuracy. Other variations, resulting from abnormal behavior of the Sun, are irregular and unpredictable. The one selectable parameter in radio communication is the frequency to be used. Frequencies that allow the best propagation vary with time of day, day of the week, season of the year, and even with the 11-year solar cycle. This annex deals with the concepts of understanding the propagation media. It introduces the concepts associated with radio-wave propagation and illustrates how the Sun influences all radio communication beyond ground-wave or line-of-sight communication. But, primarily, this annex discusses the details of HF radio-wave communication, and (since this frequency band is by far the most sensitive to ionospheric effects) how the propagation effects can be handled.

A1-1 Radio propagation

The usable frequency range for radio waves extends from the highest frequencies of sound, about 20 kHz, to above 30,000 MHz. The frequency band from 3 to 30 MHz is designated as the high frequency (HF) band. Most of the newer HF radios can operate in a larger range of 1.6 to 30 MHz, or higher. Most long-haul communications in this band, however, generally take place between 4 and 18 MHz. Depending on ionospheric conditions and the time of day, the upper frequency range of about 18 to 30 MHz may also be available. The HF band, of all of the frequency bands, is by far the most sensitive to ionospheric effects. HF radio waves, in fact, experience some form of almost every known propagation mode. The sun influences all radio communication beyond ground-wave or line-of-sight ranges. Conditions vary with such obvious sun-related cycles as time of day and season of the year. Since these conditions differ for appreciable changes in latitude and longitude, and everything is constantly changing as the Earth rotates, almost every communications circuit has unique features with respect to the band of frequencies that are useful and the quality of signals in portions of that band.

The two basic modes of radio wave propagation at HF are ground wave and skywave. Figure A1-1 illustrates these two modes.

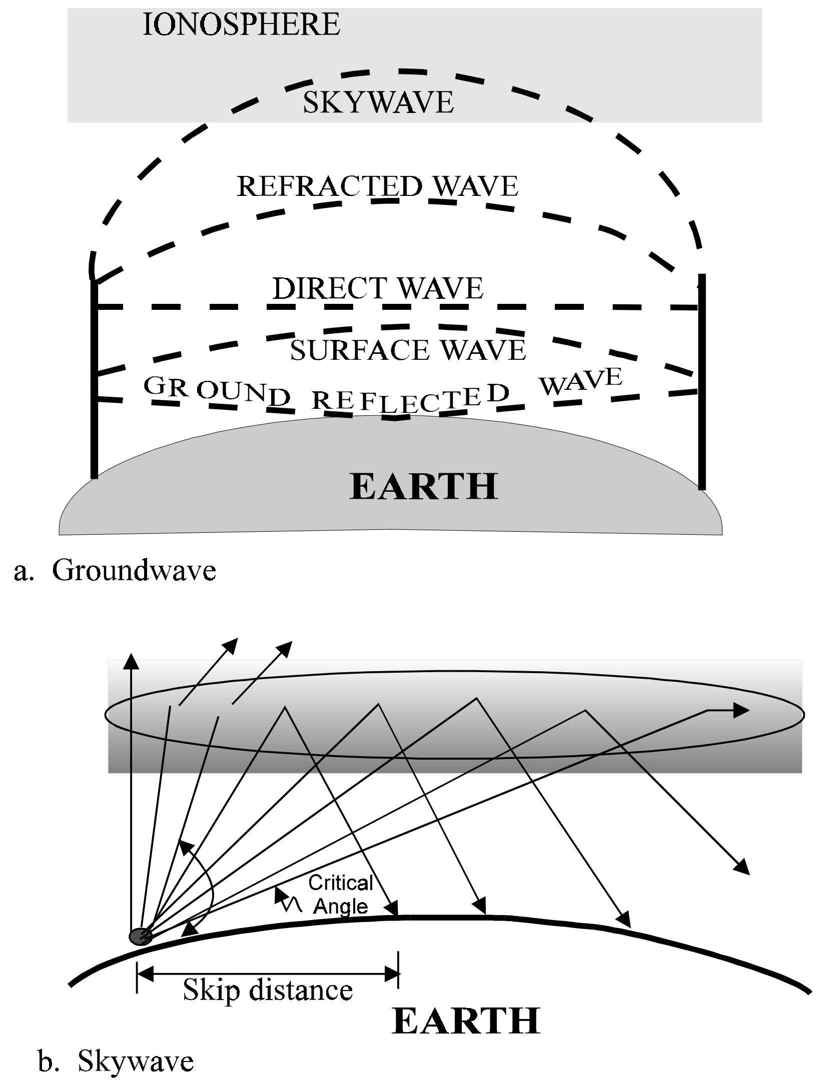


FIGURE A1-1
Ground wave and skywave

A1-1.1 Ground waves

A ground wave, as the name implies, travels along the surface of the earth, thus enabling short-range communications. Ground waves are those portions of the radio-wave radiation directly affected by the surface of the Earth. The principal components are

1) an Earth-guided surface wave,

2) a direct wave,
3) a ground-reflected wave,
4) a space wave, and sometimes
5) a tropospheric-reflected/refracted wave.

Ground-wave communication is more straightforward than skywave and it is generally assumed that the ground wave is merely an attenuated, delayed, but otherwise undistorted version of the transmitted signal. The received strength of transmitted radio signals in the ground-wave mode is dependent on such factors as: transmitter power, receiver sensitivity, ground conductivity and terrain roughness, antenna characteristics (such as height, polarization, directivity and gain), the radio frequency, and the type of path traveled. For a given complement of equipment, the range may extend out to as far as 400 km (250 mi) over a conductive, all-sea water path, but over arid, rocky, non-conductive terrain, however, the range may drop to less than 30 km (20 mi), even with the same equipment. Ground-wave propagation is almost always vertically polarized.

The *surface wave* is that component of the ground wave that is affected primarily by the conductivity and dielectric constant of the Earth and is able to follow the curvature of the Earth. When both transmitting and receiving antennas are on, or close to, the ground, the direct and ground-reflected components of the wave tend to cancel out, and the resulting field intensity at the receiving antenna is principally that of the surface wave. The surface-wave component is not confined to the Earth's surface, however, but extends up to considerable heights, diminishing in field strength with increased height. Because part of its energy is absorbed by the ground, the electric intensity of the surface wave is attenuated at a much greater rate than inversely as the distance. This attenuation depends on the relative conductivity of the surface over which the wave travels. The best type of surface for surface-wave transmission is sea water. The electrical properties of the underlying terrain that determine the attenuation of the surface-wave field intensity vary little from time to time, and therefore, this type of transmission has relatively stable characteristics. The surface-wave component generally is transmitted as a vertically polarized wave, and it remains vertically polarized at appreciable distances from the antenna. This polarization is chosen because the Earth has a short-circuiting effect on the electric intensity of a horizontally polarized wave but offers resistance to this component of the vertical wave.

Absorption of the radio wave increases with frequency and limits useful surface-wave propagation to the lower HF range. At frequencies below about 5 MHz, the surface wave is favored because the ground behaves as a conductor for the electromagnetic energy. Above 10 MHz, however, the ground behaves as a dielectric. In the region below 10 MHz, conductivity of the surface is a primary factor in attenuation of the surface wave. As frequencies approach 30 MHz, losses suffered by the surface wave become excessive and ground-wave communication is possible only by means of direct waves.

Direct waves, also known as line-of-sight (LOS) waves, follow a direct path through the troposphere from the transmitting antenna to the receiving antenna. Propagation can extend to somewhat beyond the visible horizon due to normal refraction in the atmosphere causing the path to be somewhat bent or refracted. Because the electric field intensity of a direct wave varies inversely with the distance of transmission, the wave becomes weaker as distance increases, much like the light beam from a lantern or headlight. The direct wave is not affected by the ground or by the tropospheric air over the path but the transmitting and receiving antennas must be able to "see" each other for communications to take place, making antenna height a very critical factor in determining range. Almost all of the communications systems above 30 MHz use the direct (LOS) mode. This includes the commercial broadcast FM stations, VHF, UHF, microwave, cellular telephone systems, and satellite systems.

Space waves constitute the combination of all signal types which may reach a receiver when both the transmitting and the receiving antennas are within LOS. In addition to the direct signal, space waves include all of any earth-reflected signals of significance and, under specific conditions, would include undesirable strong secondary ionospheric modes as well. Space waves will support a relatively high signal bandwidth, as compared to ionospheric modes.

Ground-reflected waves result from a portion of the propagated wave being reflected from the surface of the earth at some point between the transmitting and receiving antenna. This causes a phase change in the transmitted signal and can result in a reduction or an enhancement of the combined received signal, depending on the time of arrival of the reflected signal relative to the other components.

Tropospheric-reflected/refracted waves are generated when abrupt differences in atmospheric density and refractive index exist between large air masses. This type of refraction, associated with weather fronts, is not normally significant at HF.

A1-2.2 Skywaves

Skywaves are those main portions of the total radiation leaving the antenna at angles above the horizon. The term skywave describes the method of propagation by which signals originating from one terminal arrive at a second terminal by refraction from the ionosphere. The refracting (bending) qualities of the ionosphere enable global-range communications by "bouncing" the signals back to Earth and keeping them from being "beamed" into outer space. This is one of the primary characteristics of long-haul HF communication -- its dependence upon ionospheric refraction. Depending on frequency, time of day, and atmospheric conditions, a signal can bounce several times before reaching a receiver which may be thousands of kilometers away. Ionospheric skywave returns, however, in addition to experiencing a much greater variability of attenuation and delay, also suffer from fading, frequency (doppler) shifting and spreading, time dispersion and delay distortion.

Nearly all medium- and long-distance (beyond the range of ground wave) communications in the HF band is by means of skywaves. After leaving the transmitting antenna, the skywave travels from the antenna at an angle that would send it out into space if its path were not bent enough to bring it back to Earth. The radio wave path is essentially a straight line as it travels through the neutral atmospheric region below the ionosphere. As the radio wave travels outward from the Earth, the ionized particles in the ionosphere bend (refract) the radio waves. Figure A1-2 is an idealized depiction of the refraction process. Depending on the frequency and ionospheric ionization conditions, the continual refraction of the radio waves results in a curved propagation path. This curved path can eventually exit the ionosphere downward towards Earth so that the radio waves return to the Earth at a point hundreds or thousands of kilometers from where they first entered the ionosphere. In many cases, the radio waves reenter the ionosphere by "bouncing" from the Earth, and again be refracted back at a further distance. This is known as multihop and, under the right conditions, will give global reach. On a single HF link, many single-hop and multihop propagation paths are frequently possible.

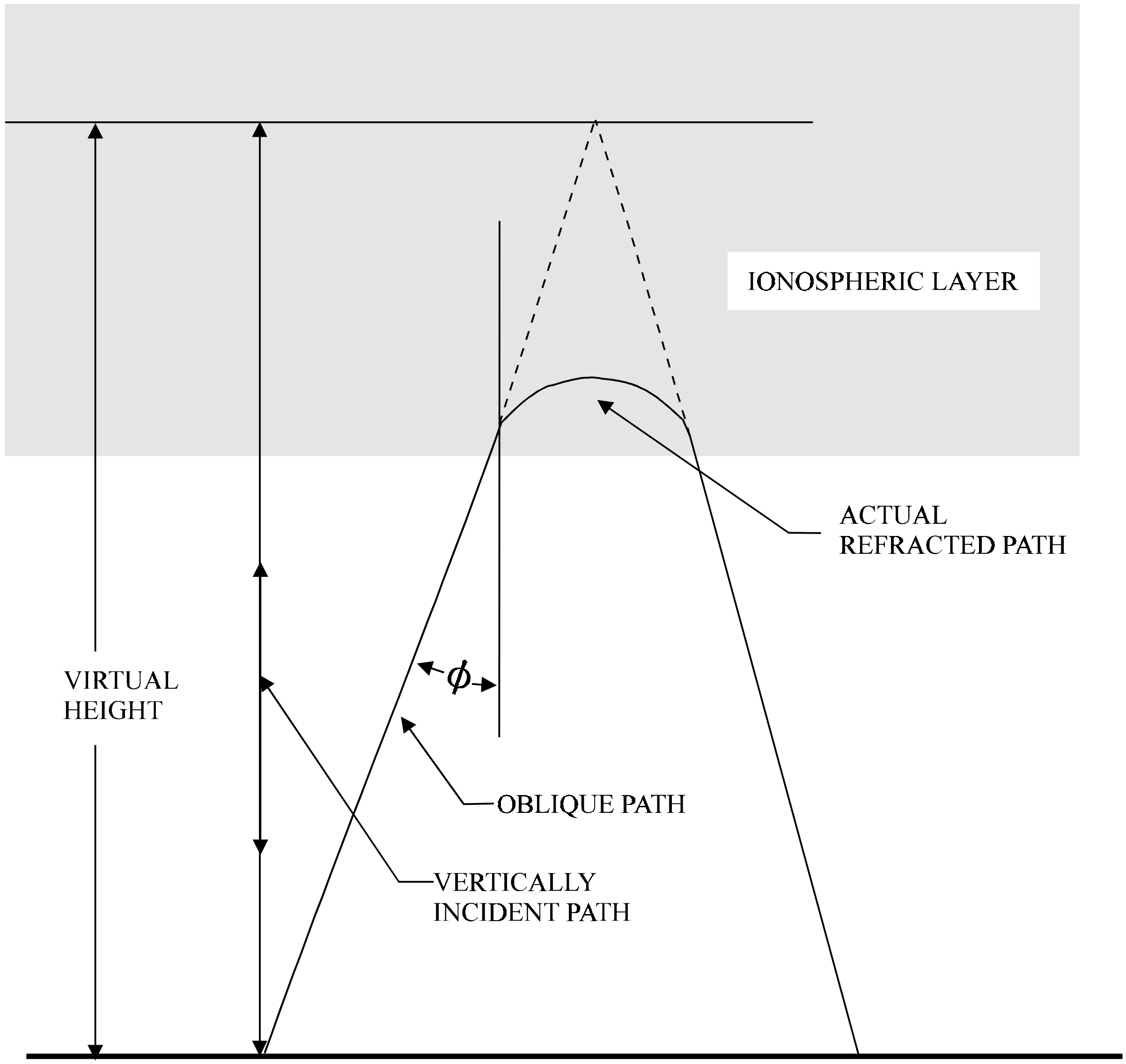


FIGURE A1-2

Refraction of radio waves

HF communication is widely regarded as the most challenging radio communication medium. HF systems that can adapt their operating frequencies to changing environmental conditions do much to offer reliable skywave communications. These systems must also accommodate received signal fading, frequency (Doppler) shift and spread, time delay shifts and spreads, and the results of multipath propagation (a radio signal that has been reflected from more than one ionospheric layer). The enormous variability of the ionosphere, however, makes it difficult to model the HF channel adequately.

The angle at which sky waves enter the ionosphere is known as the angle of incidence. This is determined by wavelength and the type of transmitting antenna. A radio wave refracts from the ionosphere at the same angle that it enters. Thus, the angle of incidence is an important factor in determining communications range. For long distances, the incident angle needs to be large, and conversely, for relatively short distances, the incident angle needs to be small. The frequency and the angle of incidence can often be changed to optimize link performance. The angle of incidence is critical, because if it is too nearly vertical, the radio wave will pass through the ionosphere without being refracted back to Earth. If the angle is too great, the waves will be absorbed by the lower ionospheric layers before reaching the more densely ionized upper layers. As shown on Figure A1-2, the virtual height is considerably greater than the actual layer height.

Virtual height is a convenient and an important quantity in measurements and applications involving ionospheric reflections. Because an ionospheric layer is a region of considerable depth, for practical purposes it is convenient to think of each layer as having a definite height. The height from which a simple reflection from the layer would give the same effects of the gradual bending that actually takes place is called the virtual height of that layer.

Among other qualities of a radio wave are strength and polarization. The strength (field strength or field intensity) of a radio wave decreases rapidly as the wave travels from the transmit antenna into free space because the original energy must be distributed over an increasingly larger surface area. Polarization generally matches the orientation of the electric (E) field, that is, if the E-field is parallel to the surface of the earth, the wave is said to be horizontally polarized. And, conversely, if the E-field is perpendicular to the Earth's surface, the wave is said to be vertically polarized.

Ionization is caused primarily by solar radiation. As was mentioned earlier, there are two types of radiation from the Sun that influence propagation -- electromagnetic radiation and particle emissions. The electromagnetic radiation includes EUV, UV, and X-rays. Each type of radiation has an impact on a different part of the ionosphere. A long term periodic variation results from the 11-year sunspot cycle. Sunspot cycles average 10.7 years in length, but have been as short as 7.3 years and as long as 17.1 years. The highs and lows also vary greatly. Sunspots generate bursts of radiation that cause higher levels of ionization. The more sunspots, the greater the ionization. At solar maxima (high sunspot number), the radiation from all the active regions around the sunspots makes the ionosphere capable of returning higher-frequency radio signals to the Earth instead of allowing them to pass through. It has not been unusual to have worldwide propagation on frequencies above 30 MHz. Frequencies up to 40 MHz or higher are often usable during solar maxima for long-distance communication. During periods of minimum solar activity, however, the amount of radiation is reduced, and frequencies above 20 MHz become unreliable for long-distance communication on a day-to-day basis. This is because the E- and F-layers are too weakly ionized to reflect the higher frequency signals back to Earth. There are no absolutes at either solar maximum or solar minimum. Periods of extremely intense activity have been observed from a single sunspot region during solar minimum and large numbers of very low radiation sunspots have also been observed during a solar maximum. These conditions allow unexpected propagation conditions to exist at either solar minimum or maximum. Particle emissions come in two forms -- high-energy particles (high-energy protons and alpha particles) and low-energy particles (low-energy protons and electrons). The different types of radiation travel from the Sun to the Earth at different speeds and have varied effects on skywave propagation. EUV ionizes the ionospheric F-region and is always present at some level. During periods of increased solar activity, the increased number of active regions on the Sun provide for increased EUV, which in turn increases the F-region ionization. This makes the use of higher frequencies for long-distance communication possible. UV and X-ray emissions, however, ionize the D-region, which absorbs HF energy. During solar flares, UV and X-ray emissions generally increase considerably and cause increased signal loss on those HF circuits facing the Sun. Traveling at the speed of light, it takes about 8.3 minutes for electromagnetic emissions from the Sun to travel to the Earth. High-energy particle radiation travels more slowly than does light, and reaches the Earth in from 15 minutes to several hours after a large solar flare. The high-energy particle emissions cause much higher absorption in the Earth’s polar regions. They also create a radiation hazard to satellite systems and personnel orbiting the Earth in spacecraft. The lower-energy particles travel even more slowly, typically taking 20 to 40 hours, and cause magnetic disturbances, auroras, sporadic-E layer ionization, and increased polar-region absorption.

A1-2 The ionosphere

The ionosphere is a region of electrically charged gases and particles in the earth’s atmosphere, which extends upward from approximately 50 km to 600 km (30 to 375 miles) above the earth’s surface. See Figure A1-3. During daylight hours, the lower boundary of the ionosphere is normally about 65 to 75 km above the earth’s surface, but can be as low as about 50 km. At night the absence of direct solar radiation causes the lower boundary to move upward to about 100 km.

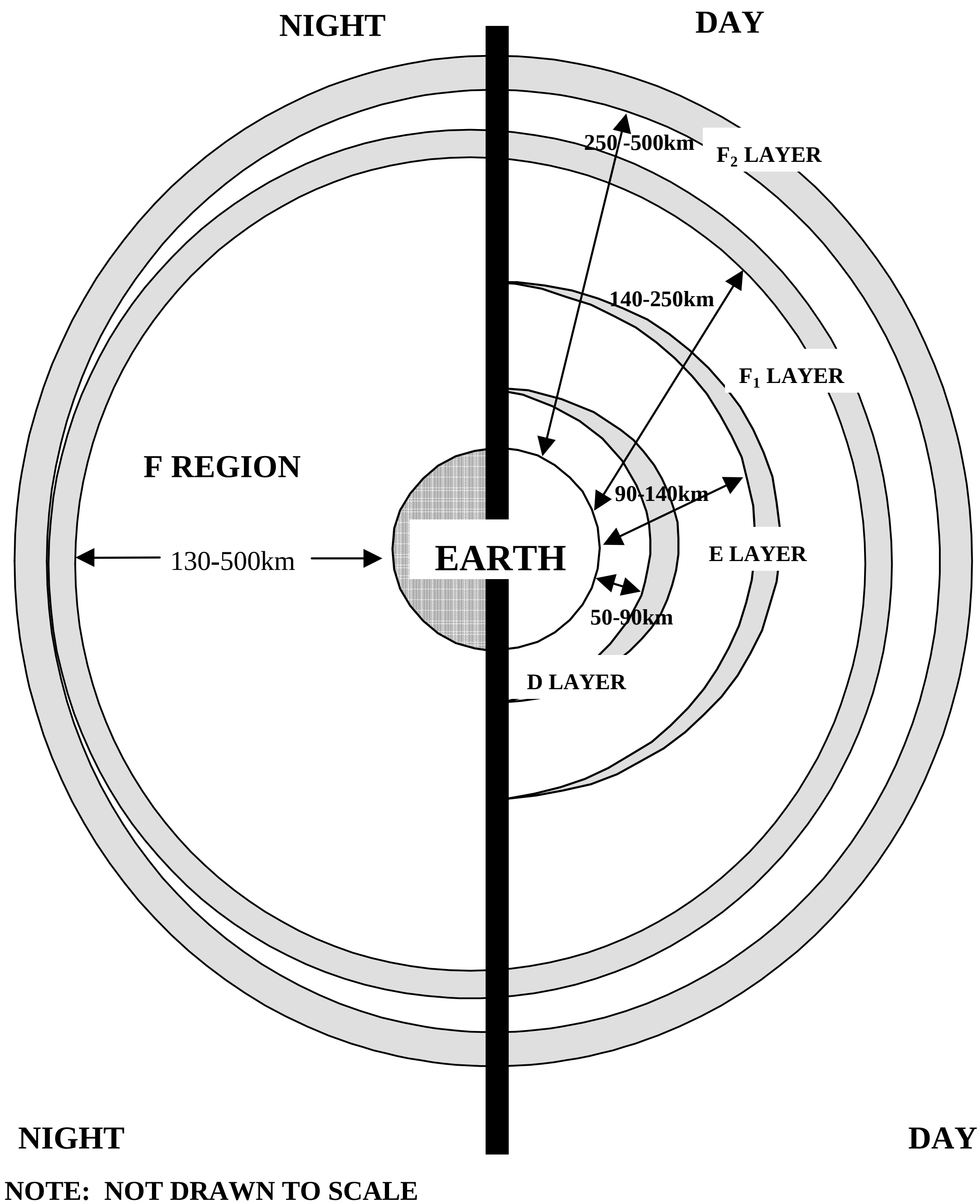


FIGURE A1-3
Earth with ionospheric layers (day and night)

The ionosphere is made up of several ionized regions, which play a most important part in the propagation of radio waves. These regions have an influence on radio waves mainly because of the presence of free electrons, which are arranged in generally horizontal layers.

Ionization is the process of creating free electrically charged particles (ions and free electrons) in the atmosphere, thus establishing the ionosphere. The Sun is the primary “engine” of ionization. The earth’s atmosphere is composed of many different gases. Because the sun emits radiation in a broad spectrum of wavelengths, different wavelengths ionize the various atmospheric gas molecules at different altitudes. This results in the development of a number of ionized layers. Extreme ultraviolet (EUV) radiation from the sun is a primary force in the ionization process. The various types of gas molecules in the upper atmosphere have different susceptibilities to ionization, primarily based on the wavelengths of the ionizing radiation. The short-wavelength solar radiation, including EUV, is sufficiently intense during daylight hours to alter the electronic structure of the various gas molecules above altitudes of about 65 km. In general, the interactions between ions, free electrons, and background neutral molecules in the ionosphere involve chemical, electrodynamic, and kinetic forces. The existence of charged particles in the ionosphere allows electrical forces to affect the motions of the atmospheric gas.

The intensity of solar radiation and therefore ionization varies periodically allowing prediction of solar radiation intensity based on time of day and the season. Ionization is higher during spring and summer because the hours of daylight are longer and conversely lower during the fall and winter because the hours of daylight are shorter. This ionized ionospheric structure also varies widely over the Earth’s surface, since the strength of the sun’s radiation varies considerably with geographic latitude, time of day, season, sunspot activity, and whether or not the ionosphere is disturbed. The intensity of the solar radiation tends to track solar activity, especially the sun spot activity. In addition to ionizing a portion of the neutral gas, solar radiation also breaks down some of the neutral molecules, thereby changing the composition of the upper atmospheric gas. Although the principal source of ionization in the ionosphere is electromagnetic radiation from the sun, there are other important sources of ionization, such as solar particles and galactic cosmic rays. The ionization rate at various altitudes depends upon the intensity of the solar radiation and the ionization efficiency of the neutral atmospheric gases. Collisions in the atmosphere, however, usually result in the recombination of electrons and positive ions, and the reattachment of electrons to neutral gas atoms and molecules, thus decreasing the overall ionization density.

For the purpose of propagation prediction and ionospheric studies, it is frequently useful to separate the environment (especially the ionosphere) into two states, benign and disturbed. The benign ionosphere state is that which is undisturbed by solar flares, large geomagnetic storms, and known manmade (including nuclear) events. Even then, there is still a significant variability, partly due to the effects of such phenomena as traveling ionospheric disturbances (TIDs), sudden ionospheric disturbances (SIDs), sporadic-E, and spread-F, as examples. The disturbed ionosphere is a state that includes the effects of several disturbing influences which occur quite naturally. Solar flares, geomagnetic storms, and nuclear detonations will cause significant ionospheric changes. Disturbances may also be produced by the release of certain chemicals into the ionosphere. The magnitudes of the introduced effects vary widely. Certain regions of the ionosphere, such as the auroral zone and the equatorial region (in certain categories), are always in the disturbed state.

A1-3 Ionospheric layering

Within the ionosphere, there are four layers of varying ionization that have notable effects on communications. As has been noted, solar radiation (EUV, UV, and X-rays) and, to a lesser extent cosmic rays, act on ionospheric gases and cause ionization. Since these ionization sources vary both in energy level and wavelength (frequency), they penetrate to different depths of the atmosphere and cause different ionization effects. The natural grouping of energy levels results in distinct layers being formed at different altitudes.

At altitudes below about 80 km, winds and weather patterns cause a turbulent mixing of the atmospheric gases present at these lower levels. This turbulent mixing diminishes as altitude increases and as the stratification (or layering) of the constituent gases becomes more pronounced. The density of ionized gases and particles increases with altitude to a maximum value, then decreases or remains constant up to the next layer. The higher layers of the ionosphere tend to be more densely ionized and contain the smaller particles, while the lower layers, which are somewhat protected by the higher ones, contain the larger particles and experience less ionization. The different ionospheric gases each have different ionizing wavelengths, recombination times, and collision cross sections, as well as several other characteristics. All of this results in the creation of the ionized atmospheric layers. The boundaries between the various ionospheric layers are not distinct, because of constant motion within the layers and the changeability of the ionizing forces.

The ionospheric layers that most influence HF communications are the D, E, F_1, and F_2 layers, and, when present, the sporadic-E layer. Of these, the D-layer acts as a large rf sponge that absorbs signals passing through it. Depending on frequency and time of day, the remaining four ionized layers are useful (necessary!) to the communicator and HF communications.

Due to the ionization effects of the solar zenith angle (height of the Sun in the sky), the altitudes of the various layers and their relative electron densities at any time depend on the latitude. For mid-latitudes, the following are typical layer (region) altitudes and extent:

D-region -- 70 to 90 km (a bottom level of 50 km is not too unusual)
E-region -- 90 to 140 km
Sporadic-E region -- typically 105 to 110 km
F-region -- from about 140 km to as high as 1000 km

F_1-region -- 140 to over 200 km (during daylight only)
F_2-region -- 200 to about 500 km

The hourly, daily, seasonal, and solar cycle variations in solar activity cause the altitudes of these layers to undergo continual shifting and further substratification.

A1-3.1 D-layer

The D-layer, which normally extends from 70 to 90 km above the Earth, is strongest during daylight hours with its ionization being directly proportional to how high the sun is in the sky. This layer often extends down to about 50 km. The electron concentration and the corresponding ionization density is quite small at the lowest levels, but increases rapidly with altitude. The D-region electron density has a maximum value shortly after local solar noon and a very small value at night because it is ionized only during the day. The D-layer is the lowest region affecting HF radio waves. There is a pronounced seasonal variation in D-region electron densities with a maximum in summer. The relatively high density of the neutral atmosphere in the D-region causes the electron collision frequency to be correspondingly high. The main influence of the D-region on HF systems is absorption. In fact, this region is responsible for most of the absorption encountered by HF signals which use the skywave mode. Because absorption is inversely proportional to frequency, wave energy in the lower end of the HF band is almost completely absorbed by this layer during daylight hours. The rise and fall of the D-layer, and the corresponding amount of radio wave absorption, is the primary determinant of the lowest usable frequency (LUF) over a given path. Due to the greater penetration ability of higher radio frequencies, the D-layer has a smaller effect on frequencies above about 10 MHz. At lower frequencies, however, absorption by the D-layer is significant. Absorption losses of the higher-frequency waves depend on the D-region ionization density, the extent of the region, the incident angle, the radio frequency, and the number of hops, among other factors. (For every hop, the rf wave traverses the D-region twice, once on the way up, and once on the way down.)

A1-3.2 E-layer

The lowest region of the ionosphere useful for returning radio signals to the Earth is the E-layer. Its altitude ranges from about 90 km to about 130 km and includes both the normal and the sporadic-E layers. The average altitude of the layer’s central region is at about 110 km. At this height, the atmosphere is dense enough so that ions and electrons set free by solar radiation do not have to travel far before they meet and recombine to form neutral particles. It is also dense enough to allow rapid de-ionization as solar energy ceases to reach it. Ionization of this layer begins near sunrise, reaches maximum ionization at noon, and ceases shortly after sundown. The layer can maintain its ability to bend radio waves only in the presence of sunlight. At night, only a small residual level of ionization remains in the E-region. The normal E-layer is important for daytime HF propagation at distances of up to about 2000 km. Irregular cloud-like layers of ionization often occur in the region of normal E-layer appearance and are known as sporadic-E (E_S). These areas are highly ionized and are sometimes capable of supporting the propagation of sky waves at the upper end of the HF band and into the lower VHF band.

A1-3.3 Sporadic E

In addition to the relatively regular ionospheric layers (D, E, and F), layers of enhanced ionization often appear in the E (E_S)-region and the lower parts of the F-regions (sporadic F). The significant irregular reflective layer, from the point of view of HF propagation, is the E_S-layer since it occurs in the same altitude region as the regular E-layer. Despite what their name implies, these layers are quite common. A theory is that E_S occurs as a result of ionization from high altitude wind shear in the presence of the magnetic field of the Earth, rather than from ionization by solar and cosmic radiation. Another theory is that E_S-layers are thin patches of long-lived ions (primarily metallic) that are believed to be rubbed off from meteors as they pass through the atmosphere, and then are formed into thin layers by the action of tidal wind systems. Layers of sodium ions produced by similar mechanisms commonly appear in the 90-km altitude range. Because the recombination rates of metallic ions are extremely low in the ionosphere, these thin layers can persist for many hours before being neutralized by recombination and dispersed by diffusion and are most commonly observed at night when the background densities are low.. Areas of E_S generally last only a few hours, and move about rapidly under the influence of high altitude wind patterns. Different forms of E_S, having different characteristics and production mechanisms, are found in the auroral zones and, at an attitude of about 105 km, in the low and middle equatorial latitudes. They share the common characteristics that they are all E-layer phenomena, their occurrence is not predictable, and they all have an effect on HF radio communications. When E_S occurs, it produces a marked effect on the geometry of radio propagation paths which normally involve the higher layers. Their peak densities can sometimes exceed that of the higher altitude F-region. When this occurs, these layers can reflect incident HF waves at much lower altitudes and prevent reflections from the F-layer, thereby greatly reducing the expected range of transmission. Although E_S is difficult to predict, it can be used to advantage when its presence is known. It has been found that close to the equator, E_S occurs primarily during the day and shows little seasonal variation. By contrast, in the auroral zone, E_S is most prevalent during the night but also shows little seasonal variation. In middle latitudes however, E_S occurrence is subject to both seasonal and diurnal variations and is more prevalent in local summer than in winter and during the day rather than at night.

A1-3.4 F-layer

The F-layer is the highest and most heavily ionized of the ionized regions, and usually ranges in altitude from about 140 km to about 500 km. At these altitudes, the air is thin enough that the ions and electrons recombine very slowly, thus allowing the layer to retain its ionized properties even after sunset. The F-layer is the most important one for long-distance HF propagation. If sporadic ionospheric disturbances are ignored, the height and density of this region varies in a predictable manner diurnally, seasonally, and with the 11-year sunspot cycle. Under normal conditions it exists 24 hours a day. The F-layers ionize very rapidly at sunrise and reach peak electron density early in the afternoon at the middle of the propagation path. The ionization decays very slowly after sunset and reaches the minimum value just before sunrise. At night, the layer has a single density peak and is called the F-layer. During the day, the absorption of solar energy results in the formation of two distinct density peaks. The lower peak, the F_1- layer, ranges in height from about 130 km to about 300 km and seldom is predominant in supporting HF radio propagation. Occasionally, this layer is the reflecting region for HF transmission, but in general, obliquely-incident waves that penetrate the E-region also penetrate the F_1-layer and are reflected by the F_2-layer. The F_1-layer, however, does introduce additional absorption of the radio waves. After sunset, the F_1-layer quickly decays and is replaced by a broadened F_2-layer, which is known simply as the F-layer. The F_2-layer, the higher and more important of the two layers, ranges in height from about 200 km to about 500 km. This F_2-layer reaches maximum ionization at noon and remains charged at night, gradually decreasing to a minimum just before sunrise. In addition to being the layer with the maximum electron density, the F_2-layer is also strongly influenced by solar winds, diffusion, magnetospheric events, and other dynamic effects and exhibits considerable variability. Ionization does not completely depend on the solar zenith angle because with such low molecular collision rates, the region can store received solar energy for many hours. In the daytime, the F_2-layer is generally about 80 km thick, centered on about 300 km altitude. At night the F_1-layer merges with the F_2-layer resulting in a combined F-layer with a width of about 150 km, also centered on about 300 km altitude. Due to the Earth/ionospheric geometry, the maximum range of a single hop off of the F_2-region is about 4000 km (2500 miles). The absence of the F_1-layer, the sharp reduction in absorption of the E-region, and absence of the D-layer cause night-time field intensities and noise to be generally higher than during daylight. Near the equator, there are significant latitudinal gradients in the F-region ionization. In the polar regions (high latitudes), there is a region of strongly depressed electron density in the F-layer. These can have important effects upon long-distance radio wave propagation.

A1-4 Ionospheric effects on radio wave propagation

As was noted earlier, the ionosphere is created primarily by solar radiation and affects the area from about 50 to 600 km above the Earth. When radio waves strike the ionized layers, depending on the frequency, some are completely absorbed, others are reflected/refracted so that they return to the earth, and still others pass through the ionosphere into outer space.

A1-4.1 Absorption

Absorption is the power robber and tends to be greater at lower frequencies and of greater effect as the degree of ionization increases. Below about 65-km altitude, the neutral atmosphere generally has very little effect on HF propagation. The sizes of water vapor molecules and other absorptive gases in the medium are insignificant compared to the HF wavelength, so there is very little interaction between the propagating HF radio waves and the components of the medium. In the D-region, however, collision-related absorption is usually the largest ionospheric-caused loss factor encountered in HF propagation. The primary cause of ionospheric absorption is the ionization due to the atmospheric bombardment primarily by X-rays and UV radiation. Absorption also increases markedly during solar flares and auroral disturbances. The D-region organizes at dawn, reaches a maximum at local noon, and dissipates when the Sun sets. Even though only about one tenth of one percent of the layer molecules are ionized, enough free electrons are present in this region to cause significant absorption of propagating HF signal energy. Absorption generally reaches a maximum during local daylight hours when free electrons exist at relatively low altitudes. Since the ionization efficiency within this region is a strong function of the solar zenith angle, the number of electrons available to contribute to the loss process varies with time of day, season, and geographic location. Although the 11-year solar cycle produces changes in solar radiation output, these changes are sufficiently slow that they are associated with the benign ionosphere. By contrast, abrupt changes in solar radiation influence not only the intensity of the ionization, but the distribution in the affected area as well. These disturbances can significantly affect HF propagation modes and disrupt HF communication systems.

A1-4.2 Attenuation

The principal measure of the effects caused by the disturbances is the attenuation of the signal. This attenuation is the result of increased absorption plus the fading and distortion resulting from the delay spread (time dispersion) and Doppler spread (frequency dispersion) which are caused by time-varying multipath propagation. Skywave signals propagated over mildly disturbed ionospheric paths exhibit minimal Doppler spread (about 1 Hz) and moderate delay spread (about 0.1 ms). When the signals are propagated over moderately to severely disturbed channels, the multipath plus scatter from moving irregularities will typically result in Doppler spreads of 5 to 20 Hz and delay spreads of 3 to about 10 ms. The larger spread values are associated with the most disturbed ionospheric conditions in which signal scattering is the primary propagation mechanism. The received signal level from such a scatter propagation path can be as much as 30 dB below the level of signals propagated by the skywave refraction.

A1-4.3 Day/night terminator

Normal day-to-night (sundown) and night-to-day (sunrise) transitions create sharp density irregularities in the ionosphere and form the so-called “day/night terminator.” Ionization increases dramatically as the sun rises at ionospheric altitudes. Along with abrupt increases in absorption, the sunrise transition can create relatively sharp horizontal gradients that refract HF waves in both azimuth and elevation. Path lengths for propagation at a given frequency will often change dramatically as the ionization density and layer heights of the ionosphere are modified by sunrise. For about an hour around the sunrise terminator, propagation conditions can be very unstable and can adversely affect HF communications. As the Sun rises, however, the sharp gradients smooth and very soon have little impact on propagation. After sunset, the fact that some ionization exists is due primarily to the relatively slow recombination of some of the ions and electrons.

Although the effects of the day/night terminator on propagation can be briefly significant, the impact on well-engineered HF systems can be minimized through prediction and mitigation efforts.

A1-5. Radio wave propagation in the ionosphere

The ionosphere is responsible for several conditions that affect HF radio-wave propagation, both for ground wave and for skywave modes.

A1-5.1 Attenuation and absorption

The usability of an HF path is highly dependent on the amount of attenuation the signal undergoes. The greatest attenuation of the skywave-propagated radio wave is usually caused by free-space spreading loss. Attenuation, in addition to the free-space spreading loss, can also be due to ionospheric absorption as well as the absorption effects associated with imperfect ground, foliage, and atmospheric factors. Ionospheric absorption occurs predominately in the D-region where there is little refractive bending at HF. In this region, free electrons, in addition to being influenced by the ionizing and electromagnetic forces, are also influenced by the electromagnetic field of any incident HF wave. As the electrons move under the influence of the applied electric field, they frequently collide with the more abundant neutral particles. Since the mass of an electron is thousands of times less than the mass of a neutral molecule, these collisions result in a significant loss of electron momentum and energy. Because the neutral particles do not oscillate in the applied field, they do not re-radiate the energy gained during these collisions but transform the energy into heat.

The net result is that free electrons in the upper atmosphere effectively absorb energy from the wave and disperse it throughout the neutral gas. Such absorption is greater at lower frequencies because it is proportional to the inverse square of the frequency. It is this absorption that defines the LUF (lowest usable frequency) (see par. 5j, below) of a circuit. If too much energy is absorbed, the signal will be too weak to be heard at the receiving station. A radio signal loses strength every time it passes through the D-region. For this reason, a three-hop signal will have more path loss (or less signal at the destination), than a one-hop signal.

In order to minimize absorption, frequencies as near the MUF (maximum usable frequency) (see par. 5h, below) as possible should be used. To obtain the maximum range for a single-hop propagation mode, the highest possible frequency and the lowest possible elevation angle that will produce an F-region reflection should be used. Moving to higher frequencies is also generally beneficial for increasing the propagated signal strength and therefore the SNR of the received signal. An HF wave is not simply reflected once at a single critical altitude, it is continuously refracted as it traverses the ionosphere.

A1-5.2 Diffraction, reflection, and refraction

Diffraction is a wave property which is associated with the re-radiation of a wave when it encounters a surface or an obstacle. This is of major concern for VHF and higher frequency systems. At HF, diffraction can cause a phase shift and possible destructive multipath.

The relationship between radio frequency, the path incidence angle, and the amount of ionization can lead to skywave effects that range from benign (small additional losses) to severe (no signal refracted back to earth). In the benign ionosphere, the signal is refracted without spending much time in the lower ionosphere, where absorption is substantial. In the severe case, if the frequency is too high or the path incidence angle is too small, the transmitted signal will pass completely through the ionosphere and continue into space. Between these two extremes lies a very wide range of possibilities.

Refraction occurs when the electron concentration changes, so that waves are refracted back towards the Earth if their frequency is not too high. Reflection and refraction are two words that often seem to be used interchangeably, even though they describe quite different phenomena.

Reflection occurs at any boundary between materials with different dielectric constants. Depending on their wavelength (or frequency), radio waves may be reflected by buildings, trees, vehicles, the ground, water, ionized layers in the outer atmosphere, or at boundaries between air masses having different temperatures and moisture content. Some of the radio energy will be absorbed in the medium that the wave hits, and some of it may pass into (or through) the material.

Refraction is the bending of a wave as it passes from one medium into another. This bending occurs because the wave travels at a different speed in the new material. Radio waves bend when they pass from one material into another in the same way that light waves do. The degree of bending depends on the difference in speeds at which the waves move through the two materials. Refraction occurs only when the wave approaches the new medium in an oblique direction. If the whole wave front arrives at the new medium at the same moment, it is slowed up uniformly and no bending occurs. The amount of bending also increases at higher frequencies. On frequencies below 30 MHz, long-distance communications is the result of refraction. Depending on the frequency used and the time of day, the ionosphere can support communications from very short ranges of less than 90 km (called near vertical incidence skywave -- NVIS) to distances of greater than 4000 km on a single hop and up to global distances with multihop propagation.

A1-5.3 Other HF propagation factors

The MF and HF bands use the F-region (F_2-layer in the daytime) for the primary mode of long-distance propagation. The MF band (300-3000 kHz with wavelengths of 1000m to 100m) suffers from extreme daytime D-layer absorption. In this band, only daytime signals which enter the ionosphere at very high angles will escape complete absorption and will be returned to Earth. This limits communications to distances of only up to about 100 km or so. At night, when the D-layer dissipates, lower-angle signals can be propagated for very long distances.

Another general factor affecting propagation in this band is noise, both atmospheric and man-made. Since noise-producing thunderstorms and man-made noise are usually greater in warm weather, this band is generally more effective in winter. The lower part of the HF band has similar characteristics.

Although the ionosphere is multilayered, the F-layer typically has the most electrons and is the most heavily ionized. This F-layer electron dominance, however, does not always correspond on a one-to-one basis with radio-wave propagation effects. Lower layers (D, E, E_S) may have a major impact on HF system operation. As we have seen, the normal D-region acts as a power robbing attenuator to the HF signal. This is especially strong during the daytime when the Sun-caused ionization is at its greatest. Additionally, patches of sporadic-E ionization may blanket the upper ionopheric layers and serve as the primary reflection layer. This can have both favorable and negative implications for HF coverage.

The phase speeds of the various propagating modes are different, and depend on the characteristics of the propagation path as well as on the wave characteristics themselves. As a result, at the receiver, the propagating modes may be out of phase with one another. Because of the dynamic behavior of the ionosphere, the relative phase relationships between the propagating modes are usually in constant change. The received signal is the vector sum of all of the signals received at each moment and, with many propagating modes, generally results in destructive interference. This produces received signal level fading and the limited-bandwidth that is a characteristic of HF circuits.

The radiation from an HF antenna generally covers a rather large area, even for highly directive antennas. In considering the effects of frequency and angle of incidence on propagation, it is usually more convenient to think of several individual rays instead of a large illuminated area. For a fixed frequency, the paths of rays leaving the transmitter are as shown in Figure 3-4. For low angles of elevation, path **A** is long and the range (surface distance) is large. As the elevation angle increases, the range decreases (**B**) until the skip distance is reached at **C**. Note that as the elevation angle increases, the angle of incidence (Figure 3-3) decreases. Skip distance is the distance from the transmitter to the closest point that can be reached by skywave. For still higher angles of elevation, the ranges can increase rapidly (**D** and **E**). The reflection height of a fixed-frequency HF wave increases as the incidence angle decreases until the point is reached where the electron density is not sufficient (for that frequency) for the ray to be totally reflected and the ray (escape ray) penetrates the layer and does not return (**F**). This point is the critical angle of incidence. The small group of rays between the skip ray and the escape ray is dispersed over a great range. These are high-angle rays. The distances, and even the capability of propagation support for these high-angle rays are problematical in that all of the ionospheric variables come into play. Although their signal strengths may be small, workable signals can be received over high-angle paths. The critical angle is a function both of frequency and of ionization density. For any given ionization distribution, the frequency at which the critical angle reaches zero is known as the critical frequency. This is the maximum frequency which can be reflected as vertical incidence. Radiation at angles more than the critical angle above the horizon will not be returned to Earth, while radiation at angles less than the critical angle will be returned, the distance depending on the elevation angle (Figure A1-4). As the elevation angle is lowered, less refraction in the ionosphere is required to bring the radio wave back to Earth, or to maintain useful signal level. This is the basis for the emphasis on low radiation angles for long-distance circuits, although absorption (and thereby attenuation) increases in proportion to the length of the path through the lower (absorption) ionospheric layers. The high angle waves (escape rays) are bent only slightly in the ionosphere, and so pass on through it.

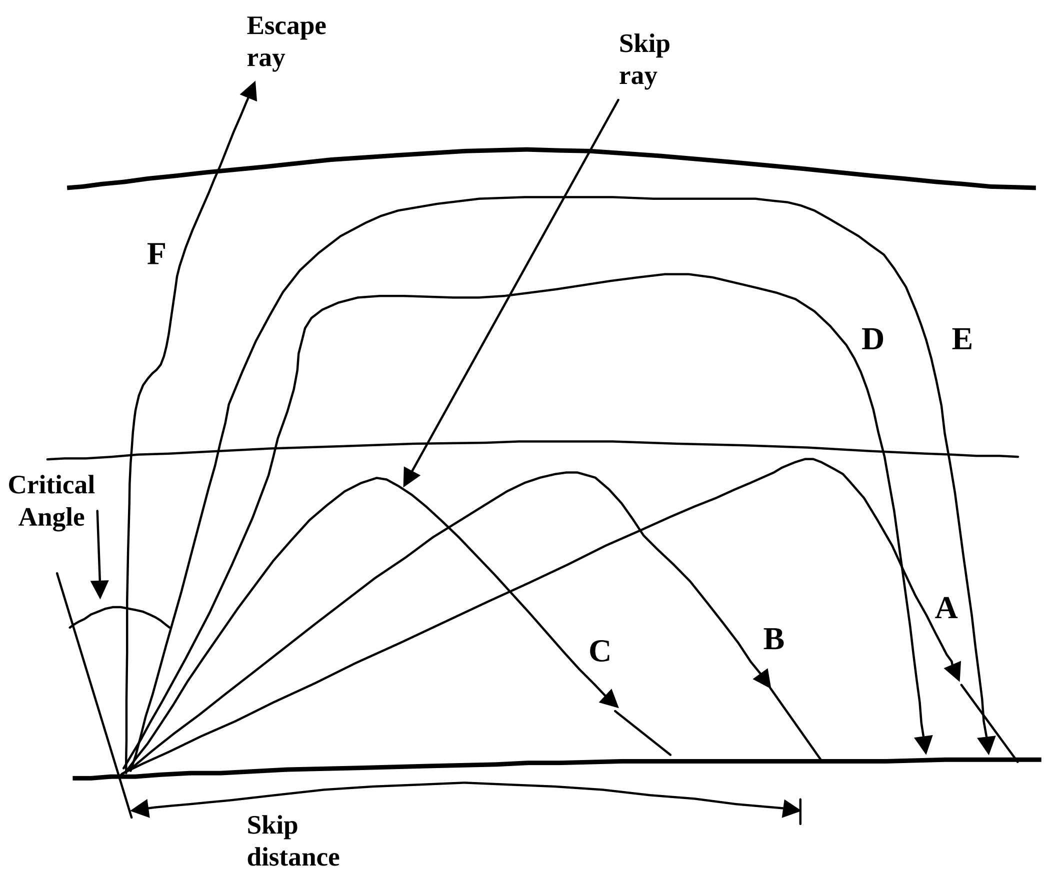


FIGURE A1-4
Ray paths as a function of elevation angle for a fixed frequency

A1-5.4 Maximum usable frequency

The Maximum Usable Frequency (MUF) is the highest frequency at which radio waves are returned to Earth by ionospheric refraction and which can be used to transmit over a particular path under given ionospheric conditions at a specific time. In the theory, frequencies higher than the MUF penetrate the ionosphere and continue on into space, while frequencies lower than the MUF tend to refract in the ionosphere and return back to Earth. Because the ionization of the ionospheric layers is extremely variable, the MUF must be statistically defined based on the intensity of F-region ionization. The accepted working definition of MUF is that it is the highest frequency predicted to occur via a normal reflection from the F_2-layer (F-region at night) on 50 percent of the days of the month at a given time of day on a specified path. This definition depends only on the mode of propagation and the path geometry and is independent of HF radio system parameters and received noise. During a solar maximum, the MUF can rise above 30 MHz during daylight hours, but during solar minima, can be at or below the lower part of the HF band. In practice, the MUF is not a sharp limit and propagation is often possible on frequencies greater than the theoretical MUF.

From an operational perspective, the highest frequency that provides communications between two HF stations at a given time and under specific conditions is defined as the operational MUF. This operational MUF accounts for all HF system parameters such as transmitter power, antenna patterns, and receiver sensitivity and includes actual environmental conditions including the levels of man-made noise at each station. The maximum operational frequency may be appreciably higher than the statistically-predicted MUF. Neither the ground nor the ionosphere are smooth reflectors, as assumed in the simplified theory. Scattering from irregularities will frequently allow signals to propagate to distances beyond the limit of the refracted wave. The received signal characteristics are nearly always optimal for skywave communications when the link operating frequency is chosen at or just below the classical MUF.

Vertical-incidence ionosondes and vertical-incidence sounders are valuable tools for both real time and long-term pictures of the key MUF-determining parameters, such as peak densities and layer heights. The frequency at which the vertical-incidence signal is no longer reflected is the critical frequency at that time and at that location. HF users can interpret the vertical-incidence testers’ data (ionograms) from stations worldwide to help choose the appropriate frequencies and to modify the predicted MUFs with real and near-real time data.

The ionospheric layers, particularly the D- and E-layers, absorb radio-frequency (rf) energy as the radio waves pass through. This absorption is higher at the lower frequencies and is inversely proportional to the square of the frequency. Consequently, it is desirable to use the highest frequency possible -- the MUF. The MUF, as defined, is suitable for reliable communications only 50 percent of the time. The statistical MUF is also unreliable due to the ionospheric irregularities and turbulence as well as to the statistical deviation of day-to-day ionospheric characteristics from the predicted monthly median MUF value. Thus, a lower frequency is chosen to provide a margin for the daily variations in MUF. This frequency, the Frequency of Optimum Traffic (FOT), is usually calculated as 85 percent of the monthly median MUF. Statistically, the FOT so calculated lies below the actual daily MUF 90 percent of the time. It should be noted that the FOT bears this statistical relationship with the MUF and is not calculated as the frequency which will provide the maximum received signal power. Sophisticated propagation prediction programs do not use the 0.85 factor, but instead compute the FOT directly from statistical distributions.

A1-5.5 Lowest useful frequency

The lowest useful frequency (LUF), as statistically calculated, is the lowest frequency at which the field intensity at the receiving antenna is sufficient to provide the required signal-to-noise ratio (SNR) on 90 percent of the undisturbed days of the month. Unlike the MUF and FOT, the LUF, in addition to the amount of absorption on the particular path, is also dependent on the link parameters such as transmitter power output, antenna efficiency, receiver sensitivity, required SNR for the service required, transmission mode, existence of multipath, and the noise levels at the receiving station. As frequency is lowered, the amount of absorption of the signal by the D-layer (and frequently the E-region) increases. This absorption is proportional to the inverse square of the frequency. Eventually, as the frequency is lowered further, the signal becomes completely absorbed by the ionosphere. This is the LUF. The LUF changes in direct correlation to the movement of the Sun over the radio path, and peaks at noon at the midpoint of the path. The “window” of usable frequencies, therefore, lies in the frequency range between the MUF and LUF.

When an ionospherically propagated wave returns to Earth, it can be reflected upward from the ground, travel again to the ionosphere, and again be refracted to Earth. This process, multihop propagation, can be repeated several times under ideal conditions, leading to very long distance communications. Propagation between any two points on the Earth’s surface is usually by the shortest direct route, which is a great-circle path between the two points. A great circle is an imaginary line drawn around the Earth, formed by a plane passing through the center of the Earth. The diameter of a great circle is equal to the diameter of the Earth (12,755 km or 7,926 mi at the equator). The circumference of the Earth -- and the “length” of any global great-circle path is about 40,000 km or 24,900 mi. Due to ionospheric absorption and ground-reflection losses, multiple-hop propagation usually yields lower signal levels and more distorted modulation than single hop signals. There are exceptions, however, and under ideal conditions, communications using long path signals may be possible. The long path is the other (long) route around the great-circle path. The same signal can be propagated over a given path via several different numbers of hops. The success of multihop propagation usually depends on the type of transmitter modulation and type of signal. For interrupted continuous wave (ICW) (also known as CW or Morse code) there is no real problem. On single-sideband (SSB), the signal is somewhat distorted due primarily to time spreading. For radio-teletypewriter (RTTY) or data service using frequency-shift keying (FSK), the distortion may be sufficient to degrade the signal to the point that it cannot be used. Every different point-to-point circuit will have its own mode structure as a function of time of day. This means that every HF propagation problem has a totally unique solution.

A1-6. Anomalous ionospheric propagation and ionospheric disturbances

Deviations from normal ionospheric propagation occur as the result of certain irregularities and transient conditions in the ionosphere. There are also significant disturbances as a result of solar activity. Both the ionospheric disturbances and ionospheric propagation deviations can cause increased absorption, selective fading, signal dispersion and even complete loss of the signal. The most significant of the anomalous propagation mechanisms are sporadic E (previously discussed), spread-E or spread-F (depending upon the ionospheric layer affected), sudden ionospheric disturbances (SIDs), ionospheric storms, and polar cap absorption. Most of these anomalous propagation mechanisms are solar-related. Solar flares are the most frequent and best known solar events. Less common and less known are coronal mass ejection (CME) and significant proton events. These, especially if focused on Earth, can cause severe, even catastrophic, damage to Earth communications throughout the electromagnetic spectrum. Additionally, proton events can be a significant hazard to the safety of orbiting astronauts in addition to the strong threat of equipment damage and communications failures on orbiting communications satellites. It has happened in the past and will happen again in the future.

A1-6.1 Solar flares

Solar flares are explosive releases of solar energy in the form of radiation at wavelengths from x-rays to visible light and mass ejecta ranging from alpha particles to very hot plasma. The radiation reaches the Earth in about 8.3 minutes, but high-energy alpha particles and protons can take from as short as 15 minutes to several hours to reach Earth depending on their energy. It takes about a day and a half for hot plasma to arrive. Although they can occur throughout the solar cycle, solar flares are most frequent during solar maximum. The solar flares, themselves, are relatively short-lived events, but the associated increase in ionizing x-ray and other high-energy radiation can lead to dramatic increases in the ionospheric electron content in the 65- to 90-km altitude range over the entire sunlit hemisphere. During a flare event, the electron density in the D-region may increase by as much as ten times, leading to a sudden and drastic increase of radio-wave absorption. Solar flares and the increased radiation fluxes associated with them also affect the E- and F-layers of the ionosphere, but to a lesser degree.

These solar flare events trigger many of the short duration ionospheric phenomena such as SIDs, and are closely related to other solar-related activity such as geomagnetic substorms, increased auroral activity, and ionospheric storms. Within the HF portion of the radio spectrum, the prediction and analysis of solar flares and specifically the various ionospheric disturbances produced by the flares present difficulties.

A1-6.2 Ionospheric irregularities

There are also ionospheric irregularities which seem to be only indirectly related to the Sun. Such irregularities, including tilts, layer height variations, traveling ionospheric disturbances (TIDs), spread-F, and sporadic-E are difficult if not impossible to predict. There are also sudden frequency deviation (SFD) and short wave fades (SWF), both of which occur within minutes of the appearance of a solar flare. The effects, though, are only on the sunlit hemisphere. Less immediate but near-term phenomena associated with energetic solar protons are also encountered.

Irregularities in ionospheric surfaces scatter, or defocus, radio waves. When this occurs in the F-layer, the disturbance is called spread-F and in the E-layer, spread-E. The surface abnormalities occur as a result of random motion within the ionized layers and changes in ion density profiles. The ionospheric electron density normally varies rather smoothly with height. Spread-F occurs when there are irregularities of electron density embedded within the otherwise benign ionosphere. This causes a distortion of signals which are propagated through that area. It is said that the name spread-F comes from the appearance of the traces on a standard vertical ionogram. Instead of a sharply defined trace, the trace appears to be either spread in frequency, or in delay time. Multipath reflection is a probable cause of frequency spread, while delay spread usually seems to be caused by scattering of the radio wave due to irregular ionization in the signal path. Spread-F, in the middle latitudes, is primarily a sporadically occurring nighttime phenomenon whose production mechanism is not well understood. The resulting signal amplitude will depend on whether the received signals are multipath-reflected or scattered from the irregularities. It has been reported that delay spreads of up to 1 ms have been observed, but Doppler spreads are usually much less than 1 Hz.

Sudden ionospheric disturbances (SIDs) are another group of unpredictable phenomena which can affect HF communications. A SID can totally disrupt HF propagation and usually affects all radio links operating within, or even partially in, the daylight side of the earth. SIDs occur without warning and usually last from a few minutes to several hours, but can disrupt skywave communication for hours or days at a time.. Because the majority of SIDs are associated with solar flares, the frequency of their occurrence is related to the 11-year sunspot cycle. The primary cause of the propagation disruption (fadeout or blackout) is a sudden, abnormal increase in the ionization of the D-region. That region then absorbs all the lower range of HF frequencies and, depending on the intensity of the ionization, partially or completely absorbs the higher HF and sometimes the lower VHF frequencies. A SID can also enhance the field strength of LF and VLF waves.

TIDs are ionospheric disturbances whose signature is a change in the ionospheric density that appears to propagate from the magnetic polar regions to the equatorial regions. TIDs are sometimes associated with solar flares and magnetic disturbances, but at other times they seem independent of such events. In any case, the induced fluctuations in the ionization density and/or layer heights can have noticeable effects on the effective range and received signal strength of HF signals passing through the affected portion of the ionosphere.

A1-6.3 Ionospheric storms

Ionospheric storms are the result of sudden large increases in solar activity, primarily solar flares and CME, which produce streams of charged particles, sometimes called "solar wind". When these particles arrive in the Earth's atmosphere, they tend to be deflected by the Earth's magnetic field towards the auroral zones. In addition to the particle stream, there is an increase in electron density in the D-region and an expansion and diffusion of the F_2-layer. This increased activity can produce large variations in critical frequencies, layer heights, and absorption and may last from several hours to several days. The intensity of the storms varies and the effects usually extend over the entire Earth. The storms typically follow solar-flare-initiated SIDs by anywhere from 15 minutes to 72 hours. During periods of very high sunspot activity, ionospheric storms can occur without initial SIDs. Charged particles from the storms have a scattering effect on the F-layer, temporarily neutralizing its reflective properties. During the storms, ionospheric propagation is characterized by low received signal strengths and flutter-fading, a form of fading that especially affects voice communications. In the first few hours of a severe ionospheric storm, the ionosphere is in a state of turbulence, layer-forming stratification is destroyed, and propagation is, consequently, erratic. In the later stages of severe storms, and throughout more moderate storms, the upper part of the ionosphere is expanded and diffused. As a result, the virtual heights of the layers are much greater and the MUFs much lower. Absorption of radio waves in the D-layer is also increased. These storms can be devastating in the HF band because of the limitation of ionospheric support in the normally-propagating higher frequencies causing nonabsorptive blackout of HF trunks in the affected area. The effects of ionospheric storms are most severe at solar maximum but seem to have more effects on communications at solar minimum.

Ionospheric storms are accompanied by magnetic storms and magnetospheric substorms with subsequent auroral effects. Magnetic storms affect primarily the equatorial and mid-latitude ionospheres, whereas magnetospheric substorms are confined to the high-latitude (auroral and polar) regions.

Magnetic storms often follow the eruption of solar flares within 20 to 40 hours. and are disturbances of the Earth's magnetic field. The earth's magnetic field is an important feature since it generally prevents a direct encounter between the ionosphere and energetic particles of solar origin, and especially solar wind streams. Magnetic storms may last from a few hours to several days and can cause changes in the movement of charged particles in the polar cap, strengthening of electric currents in the ionosphere, equator-ward expansion of the auroral region, and increased ionospheric density in all layers. While the event is occurring, the various components of the Earth's geomagnetic field fluctuate over much wider limits than they normally do.

The geomagnetic field is composed of an internal main field, which very roughly resembles the field resulting from an embedded bar magnet, and an external field generated by currents which flow within the ionosphere and magnetosphere. The geomagnetic field and the solar wind interact like a blunt object in a supersonic flow field. The earth's field is compressed on the Sun-ward side and distended on the opposite (dark) side, giving rise to a characteristic shape resembling a comet. Within the magnetosphere, solar wind particles are generally excluded, due to deflection by the severely distorted geomagnetic field. Although there is a general correlation between long-term averages in magnetic activity and solar activity, the correlation is not precise and is sometimes rather low.

A1-7. Equatorial, mid-latitude, auroral, and polar regions

Skywave communication in equatorial, auroral, and polar regions is generally more of a problem than in mid-latitude regions. Ionization density irregularities that significantly impact HF radio performance are an important, and sometimes dominant, feature of the ionosphere in these regions. In particular, skywave signals received over these paths tend to show large delay and Doppler spreads that result in significant distortion of received signals. This distortion is due primarily to the size, motion, and spatial distribution of electron density irregularities. Even relatively weak irregularities within an otherwise benign ionosphere can cause small but noticeable signal distortion.

A1-7.1 Equatorial region

In the equatorial region, equatorial spread-F (ESF) is a significant recurring irregularity. ESF seems to be primarily caused by an uprising of low electron density globules, or depletion regions, moving upwards from the bottom to the top of the F-region ionosphere. Because of the presence of the geomagnetic field and the conductivity of the lower ionosphere, ESF does not occur until shortly after sunset at low (equatorial) latitudes, where the magnetic field is nearly parallel to the earth's surface. ESF, also known as equatorial clutter, is particularly damaging to HF communications because the typical dimensions of the irregularities of the upwelling globules range from centimeters to hundreds of meters. It has been reported that the largest globules can measure as much as 1000 km from north to south and 100 km from east to west. The upwelling of these globules always follows the sunset and moves in an easterly direction at speeds of several hundred (300-700)km/hr. At HF, ESF produces multipath from both the globules and from normal ionospheric reflection, Doppler shift from the moving irregularities, and dispersion caused by refraction of the incident wave from the globules and the background ionization.

HF propagation at mid-latitudes, as has been shown, can be adversely affected by a number of factors, including the day/night terminator, SIDs, TIDs, sporadic-E, spread-F, solar flares, and magnetic storms.

The auroral ionosphere is the region of greatest particle precipitation from both the earth's outer radiation belt (the magnetosphere) and the interplanetary environment.

A1-7.2 Auroral region

Auroral effects are classified as discrete or diffuse, based on their space and time characteristics. Both the auroral oval (asymmetrically distributed around the magnetic pole) and the diffuse aurora are regions in which particle precipitation (primarily electrons) plays a significant role in ionization production. The various phenomena associated with the auroral region are inherently irregular in both space and time. Based on observations, discrete auroral effects occur most frequently at night, while diffuse effects, although fairly widespread, are primarily a morning phenomenon. The discrete aurora is generally structured, dynamic, and the visual effects are quite bright (the Northern Lights, for example). The diffuse aurora, on the other hand, is much more diffused, slow to change, and the visual effects are only faintly seen. The diffuse aurora is present during both quiet and disturbed magnetic conditions, while the discrete aurora is primarily caused by disturbances. Both types of aurora intensify during magnetospheric substorms. During severe substorms, auroral absorption can be strong enough to cause extended periods of radio blackout.

As in other areas, sunlight fosters an intense ionospheric density in both the auroral and polar areas that tends to hide many possible irregularities. In the absence of nighttime UV ionization in the fall, winter, and early spring, the available ionization is almost wholly dependent on particle precipitation and ion movement from the sunlit ionosphere to the dark (nighttime) areas. During these periods, any HF radio wave passing through or terminating or originating in the auroral and/or polar regions is subject to many forms of density irregularities and frequently shows the effects from the great range of disturbances. (Note: When it is winter in the northern hemisphere, it is summer in the southern hemisphere and vice versa. Spring and fall are also reversed between the two hemispheres.) The effects of ionization and the electron precipitation are the visible aurora, increased electron density at D-, E-, and F-layer heights, heightened auroral radio-wave absorption, and enhanced geomagnetic field perturbations affecting the E-layer.

D-layer ionization, and the accompanying radio-wave absorption, is much like that of the other sunlit latitudes. During an intense solar flare, however, the D-layer ionization region expands sharply upward with the net effect of a sudden and severe increase in radio-wave absorption. This frequently results in an HF radio blackout that can last for the duration of the flare event. This increase in absorption also happens during significant electron precipitation events. During major magnetic storms, communications links that pass through the D-layer in the diffuse auroral absorption zone may be blacked out for the duration of the storm.

Auroral ionization in both the E- and F-layers is a combination of the ionization from direct solar radiation in the sunlit sector and collision-produced ionization from electrons streaming earthward along the geomagnetic field lines. Additionally, the nighttime F-layer is also populated by ionized "blobs" (as contrasted with depleted globules) which are large regions of enhanced ionization that enter the auroral F-region from the midnight sector of the polar cap. Collision-produced ionization and ionized blobs are the dominant factors in the winter nighttime ionosphere and give it its unique character. The amount of electron precipitation and the entry of energetic electrons into the earth's atmosphere is dependent upon a complex interaction between the solar wind magnetic effects and the Earth's magnetosphere. The intensity of this electron precipitation increases with magnetospheric substorm activity.

Collision-generated E-layer ionization is not dependent on solar radiation and is sporadic by nature with sporadic effects on radio wave propagation. During late autumn, winter, and early spring, collision-generated ionization is the dominant production mechanism. At these times, E-layer ionization is quite variable and unpredictable, and sporadic E-layer formation becomes a common phenomenon. Auroral sporadic-E (E_S) differs from mid-latitude E_S in that the irregularities tend to be aligned with the magnetic field. During magnetic storms, the electron precipitation increases greatly. This results in a sharp increase in E-layer electron density and the development of very intense E_S layers. These intense E_S layers usually have a critical reflection frequency that far exceeds that of any higher layers. Once these E_S-layers are formed, they blanket the F-layers, preventing ground-launched HF radio waves from reaching and refracting from the F-layer regions. Any communication link into or out of the auroral ionosphere must then propagate via the E-layer, at least on the initial or final hop of the path. Generally speaking, the E-layer is so irregular and variable during the existence of strong E_S-layers that signals passing through these layers will be subject to significant delay and Doppler spread effects. During magnetically stable daytime conditions, radio signals have about the same characteristics as those in the mid-latitudes. As was reported in earlier reports, during disturbed conditions, multipath signals are observed that are comparable in amplitude to those of the quiet daytime channel, but with considerable more spread in delay time and Doppler frequency. Scatter-type signals, which are about 30-dB less in amplitude than the specular-multipath signals but with somewhat more spread can also be observed.

A1-7.3 Polar region

Radio-wave propagation in the polar region and polar cap absorption can pose significant problems for any radio link originating, terminating, or passing through the polar area.

An important disturbance feature of the polar ionosphere is a solar proton event (SPE). During these events, solar protons are ejected from the sun and arrive in the vicinity of the earth in about 30 minutes. These protons are deflected toward the polar regions by the geomagnetic field where they enter the Earth's atmosphere. The sharply increased D-layer ionization associated with an SPE attenuates, at least to some degree, all radio waves passing through the D-region of the polar ionosphere. This is also known as polar cap absorption (PCA). Attenuation over skywave circuits in excess of 100 dB has been measured. Ionospheric absorption during a PCA event usually occurs in the altitude range of 45 to 80 km (includes the D-layer). The absorption decreases with increasing frequency and increases with increasing propagation path length through the absorbing region and may last for several days, especially when the polar cap is in daylight. SPEs are almost always preceded by a major solar flare and occur most frequently at solar sunspot maximum. Fortunately, SPEs are rare events, which are not typically encountered at solar minimum and are observed approximately once a month at solar maximum.

The dominant ionization irregularities in the polar winter ionosphere are polar arcs and patches. Since the absence of solar radiation (polar winter) results in a weak ambient ionosphere, the appearance of the arcs and patches is much more noticeable than during the rest of the year when the polar area is sunlit. Arcs and patches are areas of enhanced ionization density which generally move quite rapidly in the area. Arcs are narrow, elongated irregularities of enhanced ionization density (up to 1,000 km in length by about 100 km in width) which drift from the dawn to dusk meridians at speeds between 100-250 km/s, and seem to occur most frequently in "quiet" magnetic conditions during solar maximum. Arcs, though, are not considered significant contributors to the polar ionosphere during solar minimum. Patches are large, on the order of 1000 km in diameter, slower (about 1000 m/s), and are believed to originate in a sunlit portion of the subauroral ionosphere. HF propagation via these irregularities generally shows significant delay and Doppler spread values. During polar summer, these and other ionospheric irregularities are usually masked by the dense ionospheric ionization produced by the continuous exposure to solar radiation.

A1-8. Nuclear effects on HF radio

HF radio using ionospheric propagation is more susceptible to the disrupting effects of nuclear explosions in the atmosphere than is any other radio propagation mechanism in any other frequency band. This is due primarily to catastrophic changes in the structure of the ionosphere. Such changes occur minutes after the explosion and last for from several minutes to several days. When explosions occur on the day side of the Earth, continuing ionization by the sun can restore ionospheric layers in as little as ten minutes. When the explosions occur on the night side, this major ionization source is blocked by the Earth and the effects last until daylight. Decaying effects of the explosion, though, may reappear each night for several nights. For nuclear explosions below about 100km in altitude, the predominant effect on radio waves is signal absorption. See Figure 3-5. Above about 100 km, the major effects are refraction and dispersion.

The primary effects on skywaves from the lower level bursts are: (1) greatly increased attenuation through absorption in the D-layer caused primarily by the X-rays and the free electrons from the burst; (2) loss of F-layer propagation paths, due to depletion of electrons in the layer; and (3) anomalous propagation modes caused by irregular ionization enhancements. Reference 4, Section 4, provides a more detailed and illustrated description of the effects of nuclear bursts on HF radio propagation.

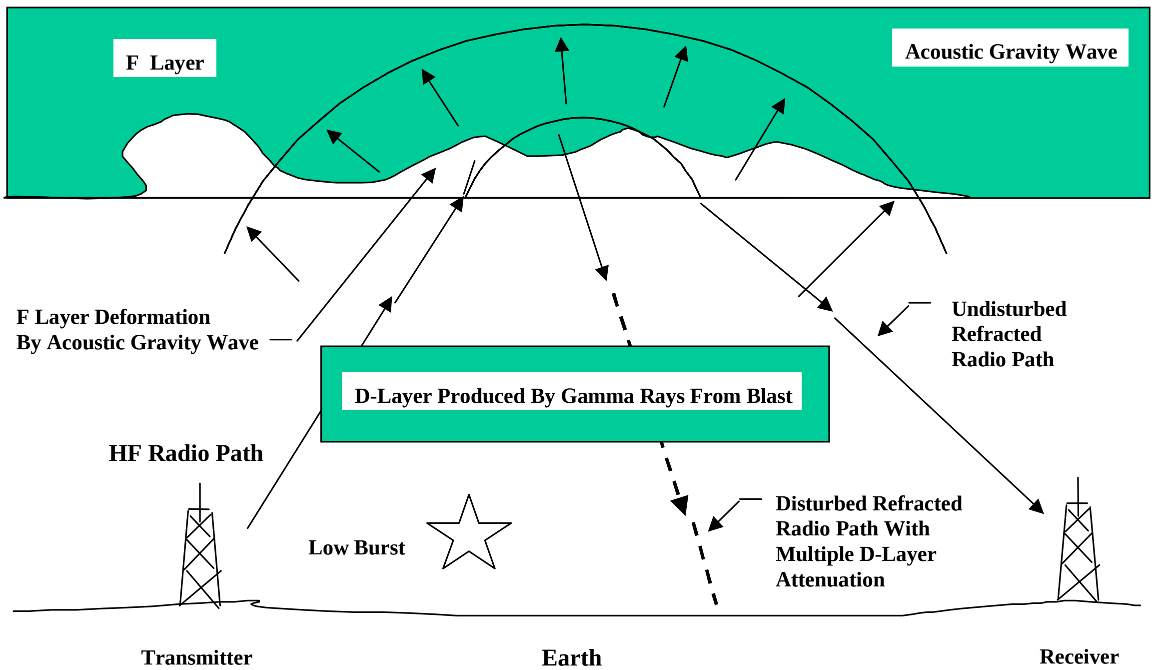


FIGURE A1-5
Nuclear burst effects

A1-9. Multipath propagation

Most HF antennas radiate over a broad vertical angle. As a result, the radiated energy reaches one or more ionospheric layers at different angles of incidence, thus causing the refracted waves to follow different paths. Some paths may involve reflection from the ground and a subsequent return to the ionosphere one or more times before reaching the destination. Other paths may involve refraction from other than the design or preferred layer. The received signal will probably be made up of a number of components arriving via several routes, including one or more skywave paths and a ground-wave path. This is multipath. The arrival times of each of these components differ from each other primarily because of differences in path length.

The multihop paths, being physically longer, substantially delay the waves relative to a single-hop or direct path. This causes the received signal to be dispersed over time. The range, or spread, of multipath propagation times is a function of frequency, path length, geographical location, local time, season and sunspot activity. This range of time differences is called multipath spread. This is particularly a problem for digital transmissions at high data rates, since the multipath spread can cause intersymbol interference. Intersymbol interference is distortion of the received signal by the overlapping of individual pulses to the degree that the receiver cannot reliably distinguish between individual signal elements.

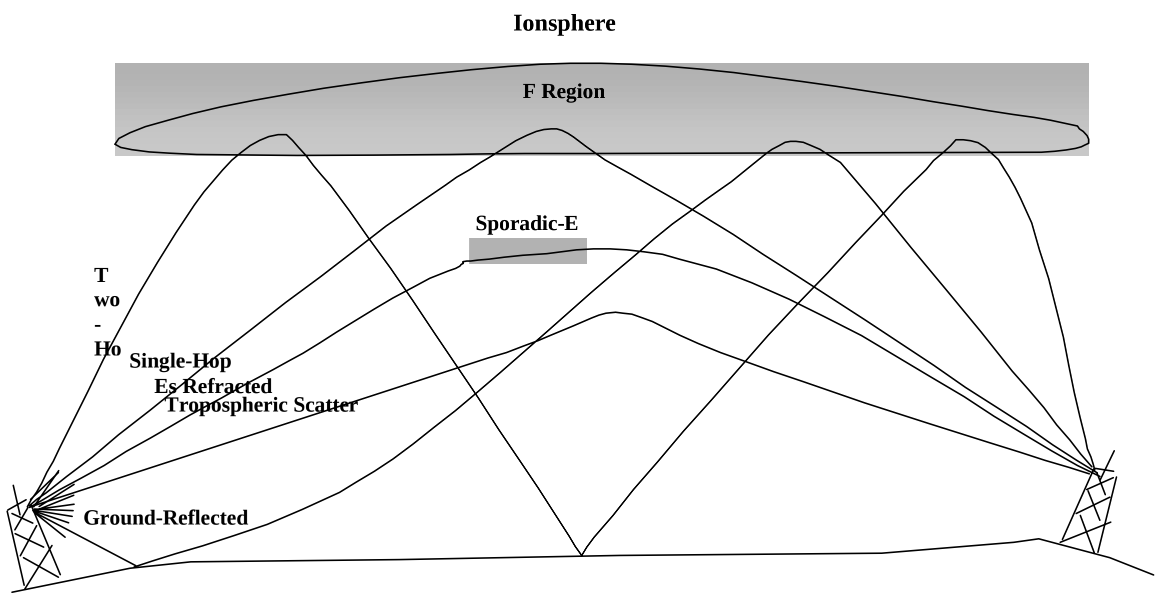


FIGURE A1-5
Multipath propagation

Selecting a frequency as close as possible to the MUF is probably the best way to minimize the effects of multipath spread. As the operating frequency is decreased from the MUF, a frequency is reached at which the multipath spread is a maximum. It is noted that for a 2500 km path, the maximum time dispersion has been shown to be about 3 ms; for 1000 km it increases to 5 ms; and for 200 km, it is about 8 ms. The time dispersion can be much greater when conditions are such that the ionosphere contains many irregularities, like those resulting in spread-F.

The route the radio signal travels must also be considered in optimizing the communications links. Each propagation path or mode has its own characteristic group delay. Multipath spread is basically the difference in group delays between the different modes. The received signal strengths of the different modes will normally show considerable differences, thus allowing the receiver-demodulator chain to be able to reject some of the weaker, distortion-causing signals.

A1-10 Conclusion

In this annex, we have addressed the concepts associated with understanding the propagation media for HF radio communication. We have introduced the various types of radio-wave propagation (*i.e*., skywave, reflected wave, direct wave, surface wave, ground wave, *etc*.). Since this annex dealt specifically with HF radio-wave propagation we have shown which of these is more meaningful for HF, how these waves propagate, how they may be refracted by the ionosphere, and what times of the day or night propagation by these waves will be best. This annex has introduced other HF propagation factors such as the effects on HF communication by noise (atmospheric and man-made), the concepts of fading, and why HF is considered limited bandwidth. The important concepts of maximum usable frequency (MUF) and lowest useable frequency (LUF) are introduced. The annex has also introduced other ionospheric propagation disturbances such as solar flares and storms. The annex shows how HF communication is effected at difference parts of the earth such as equatorial, mid-latitude, auroral and polar regions. The annex concluded with a introduction into how HF communication might react in a nuclear atmosphere as well as introduced the concepts of multipath propagation. The next annex, Annex 2, of this handbook will address prediction techniques used to estimate communication conditions along these unpredictable skywave signal paths. Annex 2 also addresses the need for predictions of HF communication performance and addresses the relationships, between short-term and long-term prediction.

ANNEX 2 [1]
PERFORMANCE PREDICTION METHODS

A2-1 Annex Summary

For those involved in development of communication technology and its applications, variabilities and fluctuations in the HF channel present a serious and formidable task. To these workers, the relatively unpredictable nature of skywave signaling is both imposing and challenging. The excitement of communicating around the world with relatively elementary equipment has not been diminished by the development of satellite communications. The mechanism—ionospheric channeling—that is principally responsible for allowing such communications, is essentially a gift of nature.

In this annex, we address the need for predictions of HF communication performance. We then address the relationships between short-term and long-term predictions. We review extant HF performance prediction models with regard to the errors that arise in a) the ionospheric models and b) the prediction methods used. A secondary issue is the unmistakable principle that HF system performance predictions agree best with reality when the associated prediction models are updated with measured data. This is manifest because ionospheric variability is substantial, and typically only median representations of ionospherically dependent parameters are incorporated into the modeling process. Several techniques for accommodating or tracking variability are possible, but this possibility suggests that the spectrum planning process should be made more flexible. The process of model updating is examined only briefly in this Annex. The Annex addresses principally the unadulterated prediction methods.

Although this Annex stresses mainstream Institute for Telecommunication Sciences (ITS) prediction methods (such as the IONCAP family of programs) and internationally sanctioned CCIR techniques, other models may also furnish helpful results. A general summary of the features of major models is provided in this Annex. The Annex concludes with a section addressing the ongoing work to improve long-term predictions.

A.2-2 Introduction

Predictions of telecommunications performance are an important guide for telecommunications requirements of military and commercial enterprises. Predictions may rely upon natural laws of physics—which are capable of being described in theoretical terms—or they may be founded upon the trends and patterns seen in stored data—in which case, the prediction method can lead to the development of quasi-empirical or climatological models.

Predictions have improved over recent years as a result of two factors:

a) the evolution of computers (along with advanced computational methods) and
b) the development of advanced sensors and telemetry.

[1] Annex 2 is largely based upon Chapter 5 of the book *HF Communications: Science and Technology,* by J.M. Goodman, and published by Van Nostrand Reinhold (VNR, New York, 1991-92. Permission is granted to use this material by the author, by VNR, and the current holder of the copyright, Kluwer Academic Publishers. Dated 9-30-98.

The advent of communication satellites has prompted a significant advance in our global perspective, especially valuable in weather forecasting and its affect on telecommunications. Satellites have provided a unique collection of scientific data that has supplemented our basic understanding of cause and effect. Radio methods for earth-space and terrestrial skywave telecommunications are clearly influenced by ionospheric phenomena in a manner that is dependent upon the frequency used. HF is the most vulnerable to the widest range of ionospheric effects, and the magnitude of HF propagation effects provides a good index of intrinsic ionospheric variability. By allowing for compensations, predictions allow one to cope with the HF vulnerabilities to this ionospheric variability. Since HF is the most vulnerable to the greatest range of ionospheric effects, a major component of ionospheric remote sensing technology has been dominated by HF probes and sounding systems.

One of the elements that can promote relatively accurate short-term predictions of HF system performance involves the process of model updating by incorporating live data from sensors that probe the temporal and spatial regions of the path of concern. In the context of HF skywave propagation, any sensor—including an oblique-incidence-sounder—that permits ionospheric characterization of the critical portions of the path can be a very useful probe. Under disturbed conditions, forecasts can lose significance in less than an hour (corresponding to the period of an atmospheric gravity wave) if probe information is less than complete or if the probe is not in close proximity to the control point (*i.e.,* within a few hundred kilometers)[2]. Other factors may similarly affect forecasts. For instance, the update data from the probe is subject to its own built-in errors in scaling and its own imprecision in converting raw data into useful information. Nevertheless, it is possible, in principle, to prepare forecasts that are accurate and useful.

Long-term predictions of path performance, although they are necessarily inaccurate because of ionospheric variability, do provide helpful information for users of the HF spectrum. The validity of these predictions arises from the fact that short-term variability has been appropriately bounded under the propagation regimes or geophysical conditions for the specific long-term predictions under study.

A2-3 Requirements: predictions and spectrum management guidance

A2-3.1 General broadcast requirements

As discussed above, HF is the most critically influenced of the radiofrequency transmission schemes with regard to skywave propagation effects. This wide variability may result in either positive or negative traits in broadcasting and point-to-point transmissions, and may require much flexibility in choosing the optimum set of system parameters to succeed in

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[2] Control point is a term that flows naturally from the mirror model of HF skywave propagation. In view of the fact that most of the refraction experienced by a *reflected* mode is in the neighborhood of the ray trajectory apogee, exclusive of any high-ray modes, convenience suggests that the *control point* should refer to the midpoint of the (presumed) great circle trajectory. Accordingly, midpath ionospheric properties that are reckoned at some appropriate height are assumed to control the propagation. Factors that will render the *control point* notion invalid include: strong tilts and gradients, dominance of the *high ray,* above-the-MOF modes, non-great-circle modes, and sundry scatter modes. Another difficulty is the azimuthal insensitivity of the control point approach, a fact that certainly affects the capability to associate data derived from nonorganic sounders with operational HF paths. This is especially troublesome when the sounder path and the wanted path are virtually orthogonal, even when the control points are common (*i.e.*, paths form a cross in plan view).

reaching an intended receiver. Of all users, those who are concerned with HF broadcasting may find themselves facing the greatest challenge. Facets contributing to this include:

a) requirement for distended signal *laydown* pattern to cover reception centers that are widely separated geographically,
b) a technique to compensate for skip zone variations for designated receivers even when the diurnal period of transmission is limited.

Skip distance variability may be great. Military broadcast services provide for enhanced performance through incorporation of frequency-management techniques; and spectral use efficiency (as a percent of the MUF-to-LUF envelope) is improved by the use of diversity, which may partially compensate for fading and intersymbol interference. Since the listeners of civilian broadcasts are disadvantaged (they have no access to sophisticated radio equipment and no real-time feedback capability), it is obvious that the broadcasting community needs a credible long-term prediction capability before they can offer (and advertise) a reasonable set of broadcast channels to potential listeners in designated reception areas. The successful transmission of programs using the shortwave band must account for a number of parameters, including:

- location of the source transmitter,
- time and duration of the transmission, and
- the specified reception area for the program.

Also, serious attention should be paid to phenomenological elements of the propagation medium, such as the ionospheric heights and critical frequencies, which, in the end, determine the broadcast coverage for a specified frequency.

While predictions are helpful for other HF spectrum users (including tactical- and strategic-military communication services) federal and state emergency communication networks, military affiliated radio systems, and even the amateur radio service, predictions are almost an imperative for the civilian broadcast community.

Coverage prediction depends on an ability to predict the ionospheric conditions. These ionospheric predictions typically comprise the exploitation of models of ionospheric structure, which are coupled to some appropriate radiowave propagation algorithm. As mentioned above, the ionosphere is typically modeled by spatial and temporal functions and some external parameters reflecting solar and magnetic activity control. Usually, the geography for the prediction problem is known, and the ionospheric conditions are prescribed by the model, after one or more input control parameters have been specified. Such a model places too much weight on a single parameter like the sunspot number, and the result is often unsatisfactory if precision is required. Nevertheless, requirements-driven predictions will rely on some equivalent solar activity index in most applications for some time in the future. Models that have been tailored to the needs of the point-to-point service are not always satisfactory for resolution of broadcast coverage, and most models fall into this category. The VOA (Voice of America)[3] has developed a broadcast coverage mapping capability in connection with a CCIR computer method called "HFBC-84." The Institute for Telecommunication Sciences (ITS) of the U.S. Department of Commerce has packaged three useful programs as part of its Windows®–based "PC-HF Propagation Prediction Programs." These programs may be obtained over the Internet at URL http://elbert.its.bldrdoc.gov/hf.html . Two of these programs, (*i.e.*, VOACAP and ICEPAC) are direct descendents of IONCAP, and the third is an implementation of the ITU Recommendation 533. The development of VOACAP and REC533 were motivated by broadcast applications although

[3] The Voice of America is now organized as a component of the International Bureau of Broadcasting (IBB).

VOACAP allows execution of the complete set of original IONCAP methods. All three programs in the ITS suite include area coverage as well as point-to-point versions.

For guidance in future operations, a measure of ionospheric support variability is also needed. Beyond this, variability in received signal level (or alternatively, the basic transmission loss) is required. Models of ionospheric variability expressed in terms of the upper and lower deciles for both the transmission loss and the MUF are available in CCIR publications such as Report 252-2 [CCIR, 1970] and its supplement [CCIR, 1982a] for specified conditions. Interestingly, the CCIR MUF variability tables are largely based upon data obtained in the early sixties [Barghausen *et al.*, 1969] [Davis and Groome, 1964]. The CCIR [1986a] has published another field-strength variability model specific to the needs of broadcasters. Even so, significant deviations from CCIR *suggestions* have been observed [Gibson and Bradley, 1987] [Fox and Wilkinson, 1986]. The exploitation of existing data banks along with the certification of additional data sets that provide variability information is clearly an important effort in performance predictions.

A2-3.2 Military and related requirements

Operational requirements of military users has often led to simplifications of the established main frame procedures in order to provide spectrum guidance in a more accessible manner. This was especially true for tactical commanders who may not have had access to real-time sounding information. Tactical frequency management systems, while they may allow for incorporation of real-time data for decision-making in the field, typically *default* to predictions which may be derived from the long-term models similar to IONCAP. The tactical user was typically disadvantaged as a result of the severe limitation in speed and accuracy afforded by the microprocessors of the 1970's and 1980's. This constraint led to the development of simplified codes and databases to solve specialized problems, and a cottage industry of simple programs evolved during the adolescence of personal computer development. The PROPHET system [Rose, 1982] is a good example of a resource management tool that originally exploited simplicity to provide tailored products to the user. Steps were eventually taken in recent years to improve the models organic to PROPHET and similar systems while retaining user-friendly features for the tactical user. With the advent of smaller, faster Windows®-based microprocessors, the constraints of form factor, weight, and code complexity have been mitigated. By the late 1990's, the distinction between small, mini/microcomputer programs and large mainframe programs virtually disappeared. In this new environment, there is little need to develop simplified methods.

The U.S. Army has published communication charts and the U.S. Navy has published a document called the NTP 6 Supp-1 [1990] *Recommended Frequency Bands and Frequency Guide.* This guide is based on IONCAP methods and the actual recommendations are based on sunspot number ranges specific to a particular year. The range of sunspot numbers for a specified year are based upon long-term running averages reckoned near the publication date and, therefore, may not precisely match currently required conditions. NTP 6 Supp-1 has two methods that are available for users. Both use look-up tables to retrieve MUF and FOT data. The first method is for users who are communicating over *arbitrary* maritime paths, while the second is tailored for use by communicators terminating at established Communication Stations (COMMSTAs) or Communication Units (COMMUs). The NTP 6 Supp-1 *Guide* has been published by the Naval Electromagnetic Spectrum Center, Washington, DC. It is anticipated that the requirement for this guide will diminish with the incorporation of the publication of ALE systems for frequency management, and with access to Windows®-based versions of the IONCAP family of programs.

The U.S. Air Force has shortwave frequency-management challenges which are quite similar to those of the U.S. Army and the U.S. Navy. Nevertheless, embedded ALE systems, which exploit optimal sounding protocols for frequency management, have eroded the requirement for predictions in a number of applications. By the same token, the U.S. Air Force has taken the lead in solar-terrestrial environment predictions, including ionospheric predictions. Surveys by the U.S. Air Force Space Forecast Center have consistently shown that HF users are the predominant claimants to the predictions services. The National Space Weather Program, sponsored by DoD, the National Science Foundation (NSF), and NOAA Space Environment Laboratory—while geared more toward fundamental understanding of the hierarchy of solar/terrestrial interactions—has proved to be a catalyst for development of improved HF prediction services. Moreover, there is a growth in the number of third-party vendors that are offering forecasting products for application in systems that are sensitive to ionospheric disturbances.

A2-3.3 The spectrum management process

Several methods are used for spectrum planning. The ITU has long recognized that the HF skywave channel is a valuable resource, and one of the ITU's technical arms, the CCIR, has developed methods that can be applied by various administrations for optimization of communication and broadcast performance, while limiting the potential for interference with other users. These methods represent the best the community can achieve in the long-term prediction of ionospheric behavior. The various processes by which radiowaves interact with the ionosphere are not ultimately as critical as is the ionospheric definition in the prediction process.

The ITU, created in 1865 at the Paris International Telegraph Convention, is now composed of 163 nations. Objectives of the ITU are promulgated and maintained through the *International Radio Regulations.* These regulations are updated through agreements reached at the World Administrative Radio Conferences (WARCs). The WARC is one of six major entities constituting the ITU. The period between WARCs is at least 10 years but may be as much as 20 years. The most recent meeting was held in 1997 in Geneva. Another agency within the ITU is the Radio Regulations Board (formerly the International Frequency Registration Board), which serves as the official agency for registering the date, purpose, and technical properties of frequency assignments made by member countries. Technical branches of the ITU include the CCIR (International Radio Consultative Committee) now called the ITU-R and the CCITT (International Telegraph and Telephone Consultative Committee), now called the ITU-T. The ITU-R provides much of the guidance to the ITU for outstanding technical issues. Officially this guidance takes the form of published *Recommendations.* The HF prediction methods suggested by the ITU-R, therefore, are quite significant for establishing *Recommendations* for spectral planning by the ITU. These documents are taken up at the WARCs and may lead to reallocation of the radio spectrum. This is of considerable importance to all member nations.

In the United States, the Federal Communications Commission (FCC) and the National Telecommunications and Information Administration (NTIA) of the U.S. Department of Commerce jointly regulate use of the radiofrequency spectrum. NTIA is responsible for government use and the FCC is responsible for regulation of private use services. Within the government, the Interdepartment Radio Advisory Committee (IRAC) oversees government use of the radio spectrum, and resolves outstanding issues. Each government department, having a member in the IRAC, establishes its own procedures consistent with IRAC decisions. The U.S. Department of Defense, for example, places authority for policy establishment and guidance in the Joint Staff (formerly the Joint Chiefs of Staff, the "JCS"). The U.S. Military Communications Electronics Board (USMCEB) develops procedures for implementing the JS guidance. This includes the assignment of frequencies for areas not appropriate for the Commanders-in-Chief (CINCs), who have their own special frequency assignment responsibilities. All DoD components participate in a record system for all frequency resources, and notification is given when a frequency is no longer required. This will make the frequency available for reassignment to other components. Intracommand frequency requirements are passed from the commander to the USMCEB if new assignments are sought. Outside of the United States and if host countries agree, intracommand frequencies may be locally assigned by the commander under certain conditions.

The whole process is rather cumbersome. It is geared to spectral use based upon 1960s technology. Spread spectrum technology and the concepts of frequency pooling, resource sharing, and networking should influence the process in the future. To examine the impact of new spectrum management schemes, it is necessary to request a suite of frequencies on a temporary basis. It has been the experience of one author that such requests are generally approved if it may be shown that little or no interference will be created by the test or experiment.

A2-4 Relationships between prediction, forecasting, nowcasting, and hindcasting

The term *prediction* has a rather elusive meaning, depending upon the nature of the requirement for knowledge[4] about the future. In the case of the ionosphere, a distinction is made between long-term predictions and short-term predictions. Long-term predictions of ionospheric behavior may typically be based upon climatological models developed from historical records for specified solar and/or magnetic activity levels, season, time of day, geographical area involved, etc. Very often, the ionospheric prediction is itself based upon a prediction of the solar activity level. In short, the long-term prediction process relies upon the recognition of loosely established tendencies as they relate to relatively simple (and extraterrestrial) driving parameters, and the result is usually an estimate of median behavior. Two sources of error occur in long-term predictions, one arising because of an imprecise estimate of the driving parameter, such as sunspot number, and the second arising from ionospheric variability which is not properly accounted for in the model. Given these difficulties, it may appear surprising that the process can yield useful results, and yet it often does. Long-term predictions are necessary in HF broadcast planning and in other spectrum management activities where significant lead times are involved. Short-term predictions involve time scales from minutes to days. The term *forecast* is sometimes used to describe those prediction schemes that are based on established cause-and-effect relationships, rather than upon simple tendencies based upon crude indices. In the limit, a short-term *forecast* becomes a real-time ionospheric assessment or a *nowcast.* In the context of HF communications, real-time-channel-evaluation (or RTCE) systems, such as oblique sounders, may be exercised to provide a *nowcast*. Such procedures are useful in adaptive HF

[4] *Knowledge of the future* appears to be a contradiction in terms. Given the variability of the ionosphere and the observation of the considerable variability in the MUF and field strength, it is anticipated that future values of HF system parameters cannot be predicted with great accuracy. Prediction systems should be evaluated in terms of the success achieved in bounding the parameter variation over selected epochs. In bounding, we imply the *least-upper-bound.*

communication systems. The term *hindcast* is sometimes used to describe an *after-the-fact* analysis of ionospherically dependent system disturbances. Solar control data are usually available for this purpose, and this may be augmented by ionospheric observation data. Figure A2-2 shows the relationship between the various prediction epochs.

The error associated with any prediction method is critically dependent upon the parameter being assessed, the lead-time for the prediction, and other factors. One of the most important parameters in the prediction of the propagation component of HF communication performance is the maximum electron density of the ionosphere, since this determines the communication coverage at a specified broadcast (or transmission) frequency. The ordinary ray critical frequency, given by the term foF2, may be directly related to maximum F2 layer electron density, and foF2, together with the effective ray launch angle, will determine the so-called Maximum Usable Frequency (or MUF) for a specified transmission distance. Thus, the ability to predict foF2 or the maximum electron density of the ionosphere by a specified method is a necessary step in the prediction of HF system performance if skywave propagation is involved.

The next section discusses the general use of ionospheric models in the present-day prediction process.

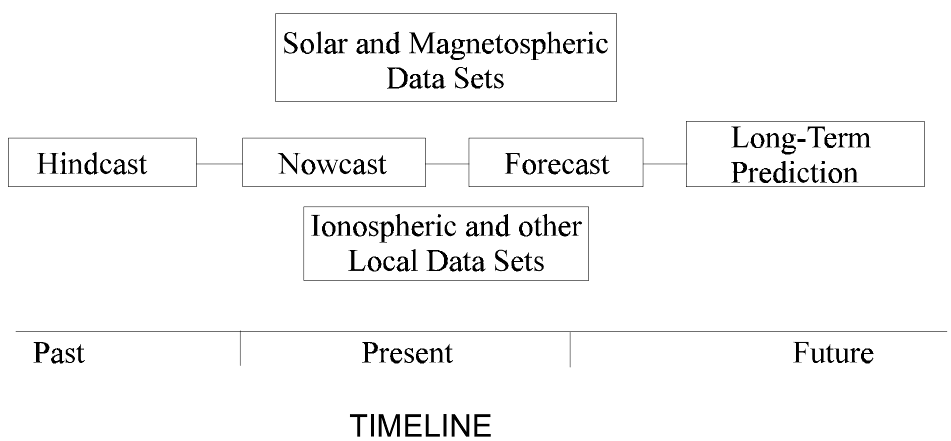


FIGURE A2-1

Relationships among prediction, forecasting, assessment, nowcasting, and hindcasting

Because the sources of ionospheric disturbance cannot be adequately monitored at their points of origin and as they propagate, prediction algorithms are inefficient. An additional complication arises as a result of distortion and attenuation experienced by the propagating disturbance. Moreover, the science that allows us to translate the physical processes in control at the disturbance source to other geographical regimes and times is incomplete. Figure A2-1 depicts the hierarchy of ionospheric disturbances; Table A2-1 provides an estimate of time duration and occurrence frequency for each class of disturbance.

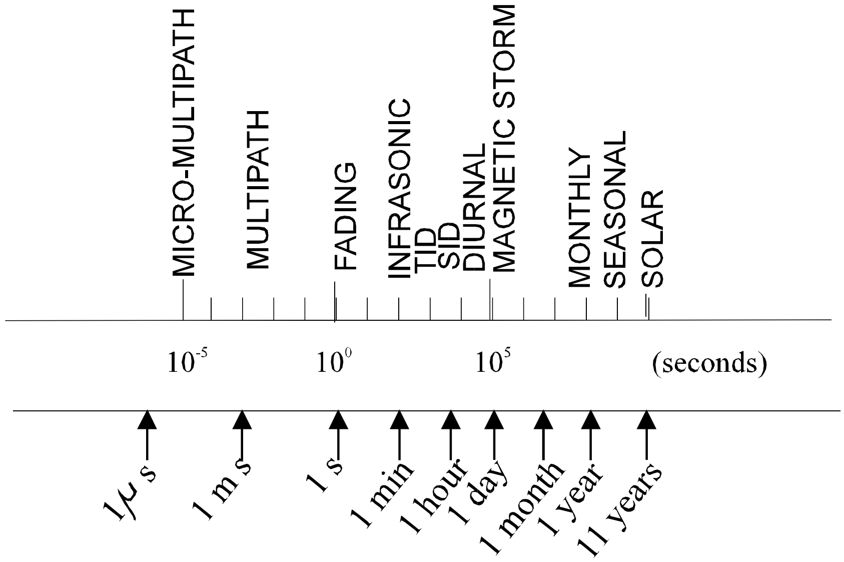


FIGURE A2-2
Hierarchy of ionospheric disturbances

A2-5 The Use of Ionospheric Models for Prediction

The nature of ionospheric variability is quite complex, since it arises from temporal and geographic variabilities in upper atmospheric chemistry, ionization production and loss mechanisms, particle diffusion and electrodynamical phenomena. As indicated earlier, genera. tendencies are fairly well modeled, and much of the variability is understood from a physical point of view. Unfortunately, an understanding of cause and effect does not always translate into a prediction capability.

Several models of varying degrees of complexity have been crafted for the purpose of making ionospheric or propagation predictions, or for use in theoretical studies. The historical development of prediction methods until the middle 1950s is given in an account by Rawer [1975], and post World War II activities are summarized by Lucas [1987]. A survey of ionospheric models has been provided by Goodman [1982], following a review by Kohnlein [1978]. Additional information of a general nature may be found in a report by Bilitza [1990] and further insight may be derived from selected technical surveys [Secan, 1989; CSC, 1985]. Unfortunately, the survey reports have not been distributed widely. A mini-review of models has been published by Rush [1986]. The paper by Rush includes pure ionospheric models but stress is placed on propagation methods that are in current use and under development.

TABLE A2-1

Temporal variations of HF effects†

EFFECT	TIME PERIOD {seconds in ( )}	FREQUENCY {Hertz}
Solar Cycle	11 years (3.5×10^8)	2.9×10^{-9}
Seasonal	3 months (7.9×10^6)	1.3×10^{-7}
Diurnal Cycle	24 hours (8.6×10^4)	1.2×10^{-5}
Large-Scale TID	1 hour (3.6×10^3)	2.8×10^{-4}
Short-Wave Fade	0.5 Hour (1.8×10^3)	5.6×10^{-4}
Small-Scale TID	10 minutes (6×10^2)	1.7×10^{-2}
Faraday Fading	0.1 – 10 seconds	10 - 0.1
Interference Fading	0.01 – 1 second	100 - 1

†The equivalent frequencies are also provided. A spectral decomposition of the effects will demonstrate a rather featureless continuum for periodicities smaller than a day (or frequencies greater than 10^{-5} Hz). Low frequency terms, being related to well-defined source terms, will cause that part of the spectrum to be discrete.

Some of the models that have been used recently include those of Bent, *et al*. [1975], the international Reference Ionosphere (or IRI) [Rawer *et al.,* 1978 and 1981], and the Ching-Chiu model [Ching and Chiu, 1973; Chiu, 1975]. Of more interest to the HF community are models that use the bottomside properties of the ionosphere which influence the skywave propagation model directly. The models that are largely based upon the very substantial database derived from vertical incidence sounders are the ones of choice. For several years much effort has been directed toward the analysis of this database and in the development of suitable mapping techniques and numerical methods for predicting ionospheric properties. Global maps of ionospheric properties have been published, and these data form the basis for many semi-empirical and climatological (statistical) models of the ionosphere. The ionospheric models will play the role of submodels in relative large HF performance prediction codes. We shall return to prediction modeling in Section A2-6.

The U.S. Air Force has developed a class of ionospheric models that are designed to accommodate the insertion of *live* ionospheric data from satellites, terrestrial sensors, and solar observances. The first model was the so-called Air Force 4-D model [Tascione *et al.*, 1979]. The most recent one is the ICED model [Tascione, 1988], which uses an *effective* sunspot number and a geomagnetic Q-index, the latter being associated with in-situ satellite data describing auroral characteristics. The effective sunspot number used in ICED is based on near-real-time ionospheric measurements derived from a worldwide network of vertical-incidence sounders; the effective number being that value which, if it were to have occurred, would provide the best match between data and model. The effective sunspot number used in ICED is reminiscent of the *T-index* developed by the Australians [IPSD, 1968] as a replacement for the running 12-month average sunspot number, but the number is more closely related to the real-time pseudoflux concept developed by NRL workers [Goodman *et al.*, 1983, 1984]. Exploitation of this scheme allows for the incorporation of dynamic ionospheric behavior. The model should therefore be applicable to HF broadcasting predictions, and should be particularly appropriate for the modeling of high latitude effects. The topside profile is modeled rather simplistically in ICED, and improvements could include incorporation of multiple scale heights above the F2 peak and a correction for a plasmaspheric contribution to the TEC at great heights. However, these matters are more relevant to considerations of transionospheric propagation. The manipulation of models to derive forecasting information is covered below in a separate annex that stresses real-time and near-real-time assessment of the propagation path for solution of the *nowcasting* problem.

Work by Anderson *et al*. [1985] has covered the calculation of ionospheric profiles on a global scale in response to physical driving parameters, such as the underlying neutral composition, temperature, and wind; the magnetospheric and equatorial electric field distributions; the auroral precipitation pattern; and the solar EUV spectrum. A subset of these parameters has been used in profile calculations for the development of semi-empirical low-latitude ionospheric model (SLIM) [Anderson *et al.*, 1985, 1987] [Sojka and Schunk, 1985]. This kind of approach is computationally very intensive, but the use of coefficient maps from these calculations, which depend on the appropriate parameter values, appears feasible. The Fully Analytical Ionospheric Model (FAIM) [Anderson *et al.*, 1989] uses the structure and formalism of the Chiu model with coefficients fitted to the SLIM model profiles. The development of such programs is required to eliminate the use of oversimplified driving parameters in prediction models and to describe completely the chain of events involved in the solar wind-magnetosphere-ionosphere-atmosphere system. Brief descriptions of SLIM and FAIM are contained in a report by Bilitza [1990]. As indicated in section 2.3.2, ITS has packaged a triad of programs, two of which are direct descendents of IONCAP. One of these, ICEPAC, was motivated by U.S. Air Force scientists who recognized that most variations in HF were related to variations in the ionosphere. The ITS modified IONCAP to reflect an improved electron-density model as well as an improved representation of the polar region. ICEPAC is quite similar to IONCAP for the user, but employs the ICED model as the electron-density model of choice.

A2-6 The ingredients of skywave prediction programs

The primary purpose of an HF performance prediction model is to provide an estimate of how well a system will work under a given set of circumstances. Typically this translates into some measure of system reliability (see Section 2.9). The components of a complete skywave performance prediction model should include:

- full documentation
  - (including basis in theory,
  - user's guide,
  - I/O interface data, and
  - machine-specific information),
- a *user-friendly* preprocessor routine which enables the analyst to set up a computation strategy efficiently, the underlying ionospheric submodel structure,
- the database or coefficients upon which the ionospheric submodel depends,
- the noise and interference submodels with associated databases,
- the antenna and siting factor submodels and their databases,
- procedures or rules by which propagation is treated, and
- a set of output products (for each method or option). These major components are shown in Figure A2-3.

Models typically require inputs of

- path geometry (terminal locations in geomagnetic and geographic coordinates),
- day of year (or month/season),
- time of day (or some time block), and

- an index set to *drive* the ionospheric personality (*i.e.*, solar and possibly magnetic activity).

In addition,

- certain terrain and siting information,
- antenna configuration/type and
- other forms of system data are necessary.

Because of the well-established diurnal and seasonal variabilities of the ionosphere, it is not surprising that time-of-day and month (or equivalent) are required as input parameters. Moreover, time block and seasonal data inputs along with receiver location are needed to deduce atmospheric noise, galactic noise, and man-made interference levels. Noise considerations are covered briefly in a later section of this Annex.

DOCUMENTATION

Theory Manual with References
User's Guide with Examples
Technical Specifications
Configuration Control Strategy

PRE-PROCESSOR

IONOSPHERIC SUBMODEL

NOISE & INTERFERENCE SUBMODEL

ANTENNA & SITING FACTOR SUBMODELS

PROPAGATION PROCEDURES & ALGORITHMS

PROGRAM DELIVERABLES

ARCHIVAL FUNCTION & POST-PROCESSOR

FIGURE. A2-3
Major Components of a Complete Skywave Prediction Program

A2-7 Brief synopsis of prediction models

Propagation prediction models have been developed over the years, and many have incorporated features shown in Figure A2-3. Table A2-2 is a listing of various models and appropriate references.

TABLE A2-2

Skywave propagation prediction models

Model Name	**Originator**	**Reference**
SPIM method	SPIM: France	Rawer [1952] Halley [1965]
CRPL Method	CRPL: U.S.A.	NBS Circular 462 [1948]
DSIR Method	Appleton Lab Slough, UK	Piggott [1959]
USSR Method	Soviet Acad. Sci.: USSR	Kasantsev [1947, 1956]
FTZ Model	Deutsche Bundespost	Ochs [1970]
REC533 (CCIR)	CCIR	ITU-R Rec. 533[Replaces CCIR 252, 894, & HFBC84]
CCIR-252-2 †	CCIR/ITU	Rpt. 252-2 [CCIR, 1970]
CCIR-252-2 † Supplement	CCIR/ITU	Rpt 252-2 Supplement [CCIR, 1982A]
CCIR-894-1 †	CCIR/ITU	Rpt. 894 [CCIR, 1986a]
HFBC84	WARC/ITU	ITU [1984a]
ITSA-1	ITS-Boulder	Lucas and Haydon [1986]
ITS-78	ITS-Boulder	Barghausen *et al.* [1969]
HFMUFES4	ITS-Boulder	Haydon *et al.* [1976]
IONCAP	ITS-Boulder	Teters *et al.* [1983]
AMBCOM RADARC	SRI ITS-Boulder NRL-Wash.,DC	Hatfield [1980] Lucas *et al.* [1972] Headrick *et al.* [1971] Headrick and Skolnik [1974]
ICEPAC	ITS-Boulder	Hand, http://elbert.its.bldrdoc.gov/f.html
VOACAP	ITS-Boulder, *et al.*	Hand, http://elbert.its.bldrdoc.gov/f.html
REC533	ITS Boulder, *et al.*	Hand, http://elbert.its.bldrdoc.gov/f.html

†The CCIR Secretariat (ITU, Geneva) retains computer codes for CCIR-252 (HFMLOSS for mainframes); CCIR-252 Supplement (SUP252 for mainframes); and CCIR Report 894 (REP894 for mainframes and micros). See Section A2.14 of this annex for a discussion of microcomputer methods.

A2-7.1 Historical development

Current methodologies for HF performance prediction evolved gradually, beginning with uncoordinated studies by workers from many countries and organizations. Serious work to establish prediction methods began in earnest during World War II because of the obvious military communication requirements. The earliest methods by the Allies, Germany, and Japan were of the graphical type to speed analysis, because computer methods were not available. The long-distance methods used by Germany and those used by the Allies [IRPL, 1943] form an interesting contrast. (The Interagency Radio Propagation Laboratory, IRPL, was a forerunner to the Central Radio Propagation Laboratory, CRPL—now the Institute for Telecommunication Sciences—at Boulder, Colorado).

In Germany, long-distance propagation was analyzed by examination of each mode and path independently. According to an account by Rawer [1975], short paths assumed 1E, 2E, 1F and 2F mode possibilities while for long paths multiple F layer modes alone were considered. At each reflection point (or *control point*, see Footnote No. 1 of this annex) the MUF was deduced by extraction of a value of foF2 for that point (from crude maps) and the appropriate MUF factor was applied. The overall MUF was logically determined as the lowest of the set of subhop MUFs for each path to be reckoned. Because of noise extension, scatter effects, and the possibility of ducted or chordal mode propagation, this approach, while intuitively pleasing, was pessimistic. The American long-path approach, influenced by a more global perspective, used modified control point method that accounted for only two *minor points* along the great circle path linking communication terminals. These two control points were 2000 km from the communication terminals. This produced a rather optimistic result.

In the period during World War II and after, sounding *networks* were established to provide a basis for the construction of better maps from which foF2 and MUF variation with latitude (and longitude) could be assessed. As previously indicated, significant equatorial anomalies were discovered through examination of this data [Appleton, 1946]. Following WW II, the French organization SPIM was established, while in the United States the agency IRPL became known as CRPL. Both SPIM and CRPL continued the development of more analytical methods to replace simpler procedures. Significant improvements in mapping resulted from the incorporation of a modified dip latitude concept to account for geomagnetic control of the ionospheric parameters [Rawer, 1963]. By 1950 Gallet of SPIM developed a mapping technique which soon became part of a computerized method for developing MUF maps. By the early 1960s Gallet had moved to the United States where he joined with Jones in formulating a basis for the current method for mapping ionospheric parameters [Jones and Gallet, 1962].

A2-7.2 Commentary on selected models

Models that stem from methods developed by Department of Commerce scientists at Boulder, Colorado, include ITSA-1, ITS-78, HFMUFES-4, IONCAP, RADARC, and, more recently, ICEPAC and VOACAP. These methods have influenced the design of other prediction models. The CCIR (currently the ITU-R) has developed methods for estimating field strength and transmission loss based upon empirical data, and a computer method for propagation prediction was developed for the WARC-HFBC under the aegis of the International Frequency Registration Board (now the Radio Regulations Board), an organ of the ITU. For more information, the reader is referred to the following: Report 252-2 [CCIR, 1970] and its Supplement [CCIR, 1982a] (both previously cited and published separately), as well as Report 894-1 [CCIR, 1986a] and Recommendation 621 [CCIR, 1986b], which are contained in the 1986 "Green Book" [CCIR, 1986c]. Methods have also been developed in the United Kingdom, Canada, France, the USSR, and India. Many of these have been listed in Table A2-2.

It should be noted that the ITU underwent reorganization in the mid 1990’s. As part of this reorganization, the CCIR was abolished and effectively replaced by the Radio Communications Sector (ITU-R). While the ITU-R still develops Recommendations, it seldom produces Reports, as CCIR did in the past. Most of the relevant CCIR Recommendations have been replaced by ITU-R Recommendations, and the ITU-R also publishes special purpose handbooks as necessary. Documentation from the ITU may be obtained through the Internet at the URL

http://WWW.itu.ch/index.html

The appropriate ITU-R Study Groups involved in HF propagation and HF communication issues are SG-3 and SG-9, respectively. Working Party 3L investigates HF modeling. Work on HF broadcasting is carried out within the working parties of Study Group 10. A synopsis of selected computer models follows:

ITSA-1: [Lucas and Haydon, 1966]. This model was developed by the U.S Commerce Department's ITS. At the time it was published it represented one of the first computer methods for exploiting augmentations in the underlying ionospheric and geophysical databases. Probably the first computerized method was a program called MUFLUF, which was developed by the Central Radio Propagation Laboratory, a forerunner to the ITS organization at Boulder. The ITSA-1 model superseded MUFLUF soon after publication. ITSA-1 did not include separate D or F1 layers, and sporadic E was not accounted for. In this program the concepts of circuit reliability and service probability were introduced. MUF variability data were included.

ITS-78 (HFMUFES): [Barghausen *et al.*, 1969] [Haydon *et al.*, 1976]. ITS-78 actually represents a series of codes developed at ITS in Boulder beginning with ITS-78, and culminating with HFMUFES4. These programs did not include an F1 layer but do include sporadic E. Most of the features of ITSA-1 were included, but with revised F-layer ionospheric data.

IONCAP: [Teters *et al*., 1983] [Lucas, 1987]. Now replaced by ICEPAC or VOACAP, this IONCAP was one of a string of *mainframe* programs developed by ITS and its predecessor organizations. The following improvements over previous ITS models are contained in IONCAP:

- a more complete ionospheric description
- modification in loss equations
- empirical adjustment to Martyn's Theorem
- revised loss statistics to account for Es and above-the-MUF-losses
- new methodology for long-distance modeling; and
- revision to antenna gain models.

A *User's Guide* has been distributed.

RADARC: [Lucas *et al.*, 1972] [Headrick *et al.*, 1971] [Headrick and Skolnik, 1974]. This program was promoted by the Naval Research Laboratory for use in analyzing the performance of over-the-horizon radar facilities. It is a close relative of IONCAP and HFMUFES, however, the computational strategy is tailored to provide information along specified radials (and arbitrary distances) from a transmitter rather than for point-to-point communication paths.

FTZ [Ochs, 1970]: This model was developed by the Deutsche Bundespost. It includes an empirical representation of field strength. This method is based upon observations of signal level associated with a large number of circuit-hours and paths, with the majority of the paths terminating in Germany. Since data were obtained without accounting for the individual modes that may have contributed to the result, the model is not fully satisfactory for arbitrary antennas (and patterns). Nevertheless for long-distance communication where elevation angles are minimized, the model is quite useful. Furthermore, computations require a limited amount of machine time, making the FTZ model a valuable method for preliminary screening of a large number of paths.

CCIR 252-2: [CCIR, 1970]. Now replaced by CCIR's "Rec 533," this model, termed "CCIR Interim Method for Estimating Skywave Field Strength and Transmission Loss Between Approximate Limits of 2 and 30 MHz," was initially adopted by CCIR at the 1970 New Delhi plenary. It was the first of three computer methods for field strength prediction that were sanctioned by the CCIR.

CCIR 252-2 Supplement: [CCIR, 1982a]. Now replaced by CCIR's "Rec 533," this Supplement is a field-strength prediction method entitled, "Second CCIR Computer-based Interim Method for Estimating Skywave Field Strength and Transmission Loss at Frequencies Between 2 and 30 MHz." The method is more complex than the method of CCIR 252-2 in a number of respects, and the machine time required reflects this additional complexity. A major change is the consideration of longitudinal gradients for the first time. A computer program was completed in 1987.

CCIR 894-1: [CCIR, 1986a]. Now replaced by CCIR's "Rec 533," this program was developed to assist in the WARC HF Broadcast Conference, a rapid computational method was documented as CCIR Rpt. 894. This document was the result of CCIR Interim Working Party (IWP 6/12) deliberations to produce a prediction program for use in planning by the HF broadcast service. This program is a simplification of CCIR 252-2 (or equivalently IONCAP) but incorporates the FTZ approach for long-distance applications. The IONCAP approach is used for paths less than 7000 km, FTZ is used for paths greater than 9000 km, and a linear interpolation scheme is applied for path lengths between 7000 and 9000 km.

HFBC84: [ITU, 1984a]. Now replaced by CCIR's "Rec 533," this program was a computer code based upon Report 894. An improved estimate of field strength is obtained by taking the antenna gain (of appropriate broadcast antennas) into account when selecting modes to be included in the calculations. HFBC84 provides the analyst with a practical procedure for mapping the coverage of a specified broadcast antenna. Such a coverage pattern is given in Figure A2-5.

AMBCOM: [Hatfield, 1980]. This program was developed by SRI International in connection with work supported by the Defense Nuclear Agency, and it is a companion program to NUCOM, another propagation program specific to the nuclear environment. One difference between the ITS series of programs and AMBCOM is that the latter uses a 2-D raytrace program, while the former programs use virtual methods. In addition, AMBCOM contains within its ionospheric submodel structure a considerable amount of high latitude information including improved auroral absorption models. This should provide for an improved prediction capability for paths through the high-latitude region or within its neighborhood. The model allows insertion of as many as 41 ionospheric data points along the paths of interest. This capability should make AMBCOM highly suitable for a detailed analysis of links or coverage areas in situations in which the underlying ionosphere is well sampled. The 1-D approach used in AMBCOM is a relaxation of the ionospheric specification requirements implicit in the use of full 3-D methods, but provides a more realistic explanation of coverage than simple (and artificial) virtual methods. A major distinction between AMBCOM and virtual methods used by the CCIR is that the ionosphere defines the path of the ensemble of rays in AMBCOM, whereas a predetermined path is used to define the effective part of the ionosphere (*i.e.*, the "control point") in the virtual or "mirror" methods. Because of added complexity, the program is generally slower than simpler models. Because AMBCOM uses raytracing and will operate against large electron density gradients, it will predict asymmetric hops and unconventional modes. AMBCOM documentation is not as widely distributed as IONCAP or the CCIR methods.

VOACAP. This prediction program was developed for use on a PC. The developers— NRL, ITS, and VOA made more than 60 changes to the computer code. Most of the changes improved the computation speed, corrected errors in IONCAP coding and logic, and improved input/output graphics. The program addresses broadcasting predictions. These changes are well documented and the source code of IONCAP was maintained with numerous comment cards for each change.

In 1985, the Voice of America (VOA) adopted the Ionospheric Communications Analysis and Prediction Program (Teters, *et al.*, 1983) as the approved engineering model to be used for broadcast relay station design and antenna specification. As the program was modified for these purposes, the name was changed to the Voice of America Coverage Analysis Program (VOACAP) to distinguish it from the official National Telecommunications and Information Administration (NTIA) IONCAP program. The development of VOACAP was accomplished for VOA by the Naval Research Laboratory and the Institute for Telecommunication Sciences (Department of Commerce, NTIA).

The Voice of America Coverage Analysis Program (VOACAP) predicts the expected performance of high frequency (HF) broadcast systems, and in doing so is useful in the planning and operation of HF transmissions for the four seasons, different sunspot activities, hours of the day, and geographic location.

This current version of VOACAP running on a PC under Windows, incorporates a colorful, user-friendly interface to easily modify input variables and to produce the desired results.

ICEPAC. For many years, numerous organizations have been using the HF spectrum to communicate over long distances. It was recognized in the late 1930's that these communication systems were subject to marked variations in performance. The effective operation of long-distance HF systems increased in proportion to the ability to predict variations in the ionosphere, since such an ability permitted the selection of optimum frequencies, antennas, and other circuit parameters. Research demonstrated that most variations in HF system performance were directly related to changes in the ionosphere, which, in turn, are affected in a complex manner by solar activity, seasonal and diurnal variations, as well as latitude and longitude. Various organizations developed computer models to analyze HF circuit performance. The ionospheric Communications Analysis and Prediction Program (IONCAP) developed by ITS and its predecessor organizations, became one of the more accepted and widely used models for HF propagation predictions. However, IONCAP demonstrated poor performance in the polar region and use some of the older electron density profile structures. To correct these problems, IONCAP was transformed into ICEPAC by adding the ionospheric Conductivity and Electron Density (ICED) profile model described in Tascione *et al.* [1987]. The ICED profile model is a statistical model of the large-scale features of the northern hemisphere. the model recognizes the different physical processes that exist in the different regions of the ionosphere. It contains distinct algorithms for the sub-Auroral trough, Auroral zone, and polar cap.

The Ionospheric Communications Enhanced Profile Analysis and Circuit Prediction Program (ICEPAC) predicts the expected performance of high frequency (HF) broadcast systems, and in do9ing so is useful in the planning and operation of HF transmissions for the four seasons, different sunspot activities, hours of the day, and geographic location.

This current version of ICEPAC (a descendent of IONCAP) running on a PC under Windows, incorporates a colorful, user-friendly interface to easily modify input variables and to produce the desired results.

This general prediction program was designed with a windows front end, and has been modified to provide more graphical results (see Fig. A2.5, for an example).

REC 533: [ITU-R, 1995]. This prediction program—which replaces CCIR 894-1, and HFBC894—improves prediction methods to enhance operational facilities and to improve accuracy. The program deals with basic maximum usable frequencies (MUFs) of the various propagation modes evaluated in terms of the corresponding ionospheric layer critical frequencies and in terms of hop length. Its algorithms are documented in Recommendation ITU-R P.533-5 (1995), and the computer program itself is available from the ITU (see the ITU/BR *Catalogue of Software for Radio Spectrum Management).*

This propagation prediction method is for use in estimating reliability and compatibility between frequencies of about 3 MHz and 30 MHz. REC533 derives from a method first proposed in 1983 by CCIR Interim Working Party 6/12 with later refinements following considerations by WARCs for HF broadcasting, the CCIR, broadcasting, and other organizations. The procedure applies a ray-path analysis for path lengths up to 7000 km, composite mode empirical formulations from the fit to measured data beyond 9000 km, and a smooth transition between these approaches over the 7000-9000 km distance range.

Monthly median basic MUF, incident skywave field strength, and available receiver power from a lossless receiving antenna of given gain are determined. Signal strengths are standardized against a CCIR measurement data bank. The method requires the determination of a number of ionospheric characteristics and propagation parameters at specified “control points”.

The propagation program was made available to the ITU in July 1993 by Working Party 6A (WP6A). Information on the availability of that program is found in Resolution 63. This implementation was simultaneously developed by the U.S. Department of Commerce NTIA/ITS in Boulder, Colorado, under contract from the Voice of America. It includes the point-to-point and area coverage models.

This current version of REC533, running on a PC under Windows®, was developed and is maintained by the United States Department of Commerce, National Telecommunications and Information Administration, Institute for Telecommunication Sciences (NTIA/ITS) located in Boulder, Colorado. It incorporates a colorful, user-friendly interface to easily modify input variables and to produce the desired results.

A2-7.3 Ionospheric data used in prediction models

The parameters used in major prediction models are the same in many instances and the data sets that represent a given parameter may also be the same. Nevertheless, the manner in which the data are used can lead to extraordinary differences in detail. Fortunately, for purposes of deriving an intuitive idea of the various influences on HF propagation/performance, most models are adequate. Indeed, if updating is possible, then many differences may be unimportant, except to the purist.

Table A2-4 is based on a previously unpublished review by Lucas [1987]. It summarizes some of the most important ionospheric parameters, and indicates the models that incorporate the specified data sets.

For convenience, selected ionosonde characteristics and their definitions are listed in Table A2-4. The original papers, indicated in the table, review how each parameter is derived and over what period of time the empirical data were assembled. The references in Table A2-3 indicate the specific usage of parameters in a given model.

Statistical distributions are required for certain ionospheric parameters for at least two reasons. First, parameters such as f_oF2, f_oEs and hF2 fail to follow Chapmanlike rules, a fact that makes prediction of the average behavior of these parameters less successful than it might otherwise be. Secondly, departures from the mean are perceived to be random variables, and not subject to the prediction process, at least in the deterministic sense. The sporadic E layer and the F2 layer are obvious candidates for statistical treatment. Statistical distributions for f_oF2 [Lucas and Haydon, 1966] and Es [Leftin *et al.*, 1968] are available.

The only ionospheric height that is explicitly computed in listed computer prediction models is hF2. Still, the variability in hF2 arising from unpredictable sources, such as traveling ionospheric disturbances (TIDs), is a significant fraction of the mean diurnal variation. Typically Shimazaki's formula (or some derivative) is used for estimating the mean value in hF2, but other approaches may also be used.

TABLE A2-4

Ionospheric parameters, data sources, and models

Models	**Layer Criticals**				**Layer Heights**				**Layer Semi-thickness**			
	foEs	**foE**	**foF1**	**foF2**	**hEs**	**hE**	**hF1**	**hF2**	**yEs**	**yE**	**yF1**	**yF2**
RADARC	1	2	3	4	k	k	e	5	k	k	k	6
IONCAP	1	2	3	4	k	k	k	5	k	k	k	6
ITS-78	1	2	n	13	n	k	n	5	k	k	n	7
ITSA-1	n	8	n	4,12	n	k	n	5	n	k	n	6
HFBC84	n	8	n	4	k	k	n	9	n	n	n	n
CCIR-252	1	2	n	4	k	k	n	5,11	n	k	n	7
AMBCOM	1	2,10	n	13	k	k	n	5	k	k	n	7
ICEPAC												
VOACAP												

Key

1. Leftin, *et al.* [1968]
2. Leftin [1976]
3. Rosich and Jones [1973]
4. CCIR [1966a]
5. Shimazaki [1955]
6. Lucas and Haydon [1966]
7. Leftin, *et al.*, [1967]
8. Knecht [1962]
9. Lockwood [1984]
10. Hatfield [1980]
11. Leftin [1969]
12. Jones and Gallet [1962]
13. CCIR [1970]

e determined empirically
k constant
n not applicable or undefined layer

(Information in this table is based in part upon unpublished material from Lucas [1987].)

TABLE A2-4

Ionosonde parameters and definitions

Ionosonde Parameter	Definition
foE	Critical frequency of the ordinary ray component of the normal E layer. It is the frequency that just penetrates the ionospheric E layer. It is proportional to the square root of Nmax for region E.
h'E	Minimum virtual height of the E layer. This is determined at the point where the ionosonde trace becomes horizontal.
foEs	Critical frequency of the ordinary ray component of the Es (sporadic E) layer.
h'Es	Minimum virtual height of the sporadic E layer, and reckoned at the height where the trace becomes horizontal.
fbEs	The blanketing frequency for the Es layer. This corresponds to the lowest ordinary wave frequency for which the Es layer allows penetration to a higher layer; *i.e.,* begins to become transparent.
foF2	The critical frequency of the ordinary wave component of the F2 layer. It is proportional to the square root of Nmax for the layer. It is the frequency that just penetrates the F2 layer.
foF	Critical frequency of the ordinary wave component of layer F1. The ionosonde frequency that just penetrates the F1 layer.
h'F2	Minimum virtual height of the F2 layer. It is measured at the point where the trace becomes horizontal.
h'F	Minimum virtual height of the night F layer and the day F1 layer. Again, it is measured at the point where the F trace involved becomes horizontal.
h'F1	Minimum virtual height of the F1 layer, measured at the point where the F1 trace becomes horizontal.
h'FF2	Alternative tabulation of the minimum virtual height of the F layer. It corresponds to the minimum virtual height of the night F layer and the day F2 layer. Again, it is measured at the point where the appropriate traces become horizontal.
hpF2	Virtual height of the F2 layer corresponding to the frequency f = 0.834 foF2. Based upon a parabolic layer approximation.
M(3000)F2	Ratio of MUF(3000)F2 to the critical frequency foF2.

A new mirror height method having similarities to the Shimazaki approach has been used in HFBC84 [Lockwood, 1984]. The basis for hF2 estimation in the CCIR-252 model is virtual height data (*i.e.,* h'FF2) from Leftin *et al.* [1967] and Leftin [1969]. Recognizing that hF2 is simply the (nonvirtual) height of the F2 maximum, $h_{max}F2$, the Shimazaki relation says:

$$h_{max}F2 = 1490/M(3000)F2 - 176 \qquad (4.1)$$

We recognize that M(3000)F2 is MUF(3000)F2 ÷ foF2, and that it is proportional to the secant of the ray zenith angle Ø. If the layer descends, it is apparent that the secant of Ø will increase.

Consequently, M(3000)F2 increases as layer height decreases, and vice versa. This fact is reflected in equation 4.1. Taking h_{max}F2 to be a nominal 300 km, then M(3000)F2 is nearly 3.2. Under this condition, dh/dM(3000)F2 ≈ - 150 km. Hence an increase in M(3000)F2 of 0.2 will correspond to a height reduction of 30 km.

Maps of f_oF2 and M(3000)F2 have been of major importance in HF propagation prediction for years. They are used in various ionospheric models to provide a global distribution of electron density and F2 layer height in other applications. The CCIR [1966a] model, documented as CCIR Report 340-1, consists of an *Atlas of Ionospheric Coefficients* defining f_oF2 and M(3000)F2, plus actual maps of the parameters EJF(zero)F2 and EJF(4000)F2,which have been defined above. The CCIR [1970] model, termed *Supplement No. 1*, is an update of the Report 340, which replaces the CCIR [1966a] foF2 *Oslo* coefficients with new ones that better fit the existing database. Improvements included replacement of the linear dependence of foF2 on sunspot number by a polynomial dependence, and a Fourier representation of the annual variation so that any day could be examined in terms of its surrounding monthly median. The CCIR [1970] coefficients were conceived by Jones and Obitts and are sometimes referred to as the *New Delhi* coefficients. Screen or *phantom* points were required over sparsely sounded oceanic areas for both the *Oslo* and *New Delhi* coefficients. Early versions of ITS-78 (HFMUFES) used *Oslo* coefficients that were reproduced on red computer cards. Later versions used the *New Delhi* coefficients reproduced on blue cards. Thus the terms *red deck* and *blue deck* are sometimes used in references.

There have been steps to improve the ionospheric coefficients. Within the URSI community (Working Group G.5) Rush *et al.*, [1983, 1984] developed a new coefficient set based upon more fundamental theory. The extensive database assembled by Rush and his colleagues included *new* data points deduced using a method developed by Anderson [1981]. As pointed out by Rush *et al.* [1989], in order not to depart too significantly from established CCIR recommendations and long-term prediction methods, consistency with the structure of the CCIR [1966a] Jones-Gallet coefficient set was required. Fox and McNamara [1986, 1988] have continued the work and have proposed a final set of coefficients. Fox and McNamara organized their data in terms of the T-index rather than in terms of sunspot number, they included more foF2 data in the analysis, and they sought consistency with independent data derived from the Japanese topside sounder ISS-B. They also used methods in which the coefficients were of higher order at low latitudes than the CCIR/URSI maps. This provides more detail at lower latitudes. The new approach is the basis for a new set of coefficients used by the Australian agency IPS. The improvement over the original set is more than satisfactory. To achieve consistency with the standard format of existing internationally sanctioned maps, the IPS coefficients were transformed by URSI to coincide with the existing number of coefficients. This process had the effect of degrading the output from the IPS approach somewhat, but consistently smaller residual errors have been noted when compared with the CCIR maps. Ultimately Rush *et al.* [1989], including the IPS group, have published an update of the foF2 coefficients. Since this revised set, also termed the *1988 URSI coefficient set*, has the same structure as the earlier *1966 CCIR coefficient set* used in IONCAP, an upgrade of IONCAP climatology is straightforward.

Several terms have been used to describe the various CCIR coefficients. As noted above, the first set to be published as a separate booklet by the CCIR is due to Jones and Gallet [1962], and was approved by the CCIR at its 1966 plenary held in Oslo, Norway. When used in early versions of ITS-78, the coefficient set was reproduced on red cards. The CCIR took note of an alternative coefficient set at its 1970 plenary held in New Delhi, India. This set, developed by Jones and Obitts [1970], and published by the CCIR in 1971, was an improvement in a number of areas over the previous set, was only recommended for use in short-term predictions. Differences in the two sets of coefficients were described in CCIR Report 340 as revised in 1983. A summary of existing coefficient sets is given in Table A2-5.

TABLE A2-5

Various sets of ionospheric coefficients

Coefficients Epoch	Authors	Plenary Session Location	Computer Designation	Usage
CCIR 1966	Jones-Gallet	Oslo	Red Deck	Long-term
CCIR 1971	Jones-Obitts	New Delhi	Blue Deck	Short-term
URSI 1988	Rush *et al.*	N/A	N/A	Long-term

A2-7.4 The System Noise Figure Concept

Note: The noise factor is designated by the letter f in this discussion, and should not be confused with the radio frequency. To avoid the possibility of misinterpretation, f(MHz) is used to denote frequency for instances that appear warranted. This comment is specifically relevant to figure A2-7 and to the next three sections.

To estimate the impact of external noise sources on system operation it is necessary to establish the pre-detection signal-to-noise ratio. Figure A2-4 schematically represents a generic receiver system from input to output, the noise factor and the signal-to-noise ratio associated with the receiver, and the location at which these parameters are reckoned. The system noise factor is given by [Spaulding and Stewart, 1987]:

$$f = f_a + (L_c - 1)(T_c/T_o) + L_c(L_t\text{-}1)(T_t/T_o) - L_cL_t(f_r - 1) \qquad \text{(A2-2)}$$

where f_a is the external noise factor given by P_n/kT_ob, F_a is the external noise figure given by 10 $\log_{10}f_a$, p_n is the available noise power from a lossless antenna, L_c is the antenna circuit loss (input power/output power), T_c is the temperature (^oK) of the antenna and neighboring ground, L5 is the transmission line, T_o is the reference temperature (^oK), and f_r is the noise factor of the receiver (^oK). The noise *figure* in dB is simply $F_r = 10 \log_{10}f_r$. To avoid confusion, capital letters are used when discussing the noise figure as well as other terms that may be expressed in decibels, and lower-case letters are used when dealing with receiver and antenna noise factors. The noise power in watts is simply:

$$n = f\,k\,T_o\,b \qquad \text{(A2-3)}$$

where k is Boltzmann's constant = 1.38 x 10^{-23} J/(^oK), T_o = 288(^oK), and b is the noise power bandwidth of the receiving system. For an antenna and transmission line that may be taken to be lossless, then the overall system noise figure F is approximately the sum of F_a and F_r.

Recognizing that $10 \log_{10} kT_o = -204$, we may rewrite equation 4.3, specifically for the external noise component, in a convenient decibel form:

$$P_n = F_a + B - 204 \tag{A2-4}$$

where P_n is in dBW and F_a and B are expressed in dB (where B is in dB-Hz).

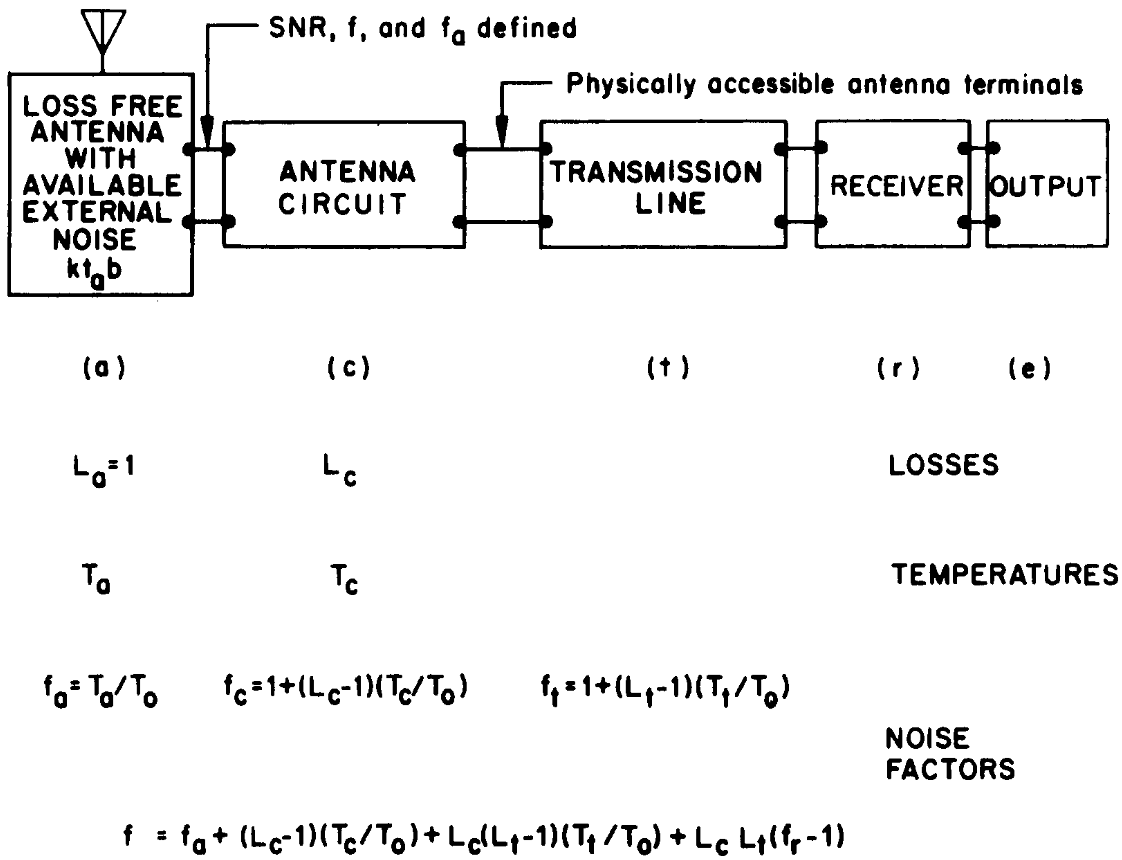


FIGURE A2-4

Generic receiver system concept, illustrating the locations at which signal and noise parameters may be reckoned. [Here, f_a is the external (antenna) noise factor and f_r is the receiver noise factor.] (From Spaulding and Stewart [1987].)

Another way to represent the external noise factor f_a is as a temperature, where f_a is taken to be the ratio of antenna temperature (resulting from external noise) to T_o.

For specified antennas, it is possible to obtain an expression for the field strength in dB (above 1μ V/m). Such expressions take the form:

$$E_n = F_a + 20 \log_{10} f\,(\text{MHz}) + B - \Gamma_A \tag{A2-5}$$

where Γ_A is a constant dependent upon antenna type and configuration. For a short grounded vertical monopole $\Gamma_A = -\ 95.5$ dB. Thus the noise figure (or factor) is a fundamental parameter since it defines for a specified antenna configuration and noise bandwidth the noise level with which the desired signal must compete. We shall now examine the major sources of noise and therefore F_a.

A2-7.5 Noise models and data

Noise at HF has three major components: atmospheric, galactic, and man-made noise. Another category of noise sources are associated with intentional interferers (jammers). These latter sources will not be discussed here. Figure A2-5 gives the range of expected values for noise. Several features in the figure are of interest. First, we see that except for business areas, galactic noise would appear to dominate in the upper half of the HF band. At midband and below, man-made sources become quite important as the galactic component suffers a cutoff because of the high pass filter properties of the ionospheric plasma. Depending upon conditions, atmospheric noise caused by lightning has an enormous range, and may become the dominant noise source, especially in the lower part of the HF band.

A2-7.5.1 Atmospheric

The major cause of atmospheric noise is lightning strokes that produce broadband noise, and that arise during thunderstorms. Clearly this suggests a preferred source and time distribution for the atmospheric noise contribution. Atmospheric noise, like desirable HF signals, obeys the same physical laws, and may propagate over considerable distances beyond the line of sight. Noise originating in the opposite hemisphere or from sources across the day-night terminator are major contributors to F_a. Even though the events are isolated and of short duration, the composite result, as reckoned from a given receiver may be characterized as quasi-constant for any specified hour. The long-distance propagation characteristic of HF has the effect of populating the time domain with signals from the global distribution, but with each individual source being constrained by its own LUF-MUF bandpass filtering operation. Receiver latitude plays an important role at HF. In fact, noise is considerably reduced as the latitude increases commensurate with an average increase in distance from the low latitude source regions. Regions where noise is most severe include the African equatorial zone, the Caribbean area, and the East Indies. No account is provided in existing models for effects from a localized source distribution, and azimuthal information is not available because of the manner in which the database (comprising the CCIR 322 model) was generated. Clearly, local noise is important, and its omission will lead to underestimates for anticipated external noise, especially during the summertime rainy season. On the other hand, actual antennas may have nonuniform patterns in the bearing (and elevation) plane; and this will modify the noise distributions. Highly directive antennas may yield optimistic or pessimistic values for the observed F_a.

Sailors and Brown [1982] have developed a minicomputer atmospheric noise model using simplified methods. With the advance of computer technology, code simplification is no longer a practical necessity.

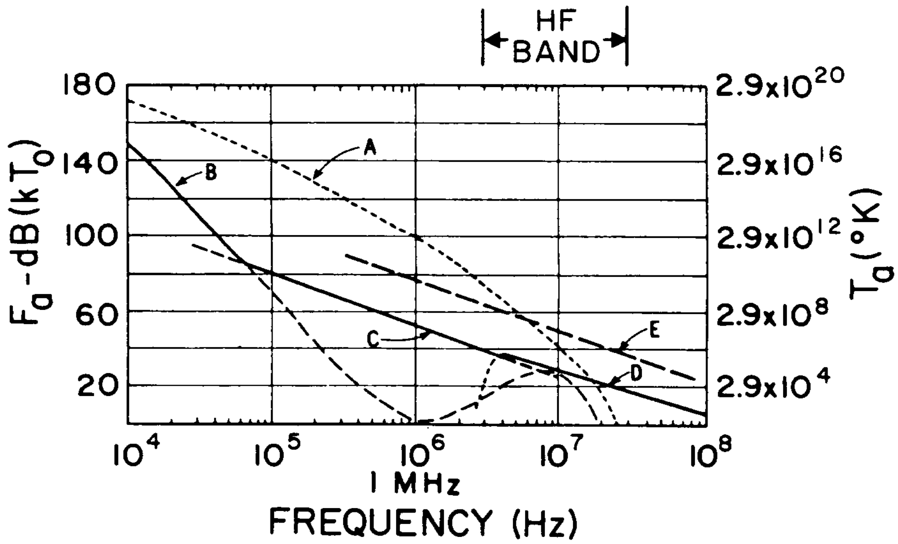


FIGURE A2-5

Noise figure (dB/kTo) (LH-scale), and antenna temperature, °K (RH-scale)

[A: Atmospheric noise from lightning, value exceeded 0.5% of the time; B: Atmospheric noise from lightning exceeded 99.5% of the time; C: Man-made noise at a quiet receiving site; D: Galactic Noise; E: Median business-area, man-made noise.] (From Report 670 [CCIR, 1982c])

A2-7.5.2 Galactic

Figure A2-6 shows the effective temperature of an antenna that is receiving galactic noise. Galactic (or cosmic) noise originates outside the ionosphere, but for signals to be received at an Earth terminal, ionospheric penetration is necessary. Signals in excess of the overhead critical frequency may be received; however, if antennas (such as vertical monopoles) have limited gain in the vertical direction, then available lower frequencies will not effectively contribute. Rules for ionospheric penetration imply that the available cosmic noise distribution will always be confined to a small iris near the zenith direction when operating near the critical frequency. As the radiofrequency f exceeds f_c by a large amount, the iris will become distended being defined by a dimension $\phi \approx \sec^{-1}(f/f_c)$, where ϕ is the ray zenith angle.

A2-7.5.3 Man-made

Man-made noise is not only influenced by the population density, but it also depends upon the technological sophistication of the society. Attempts to relate man-made noise and population density have not been entirely successful, although Lucas and Haydon [1966] have provided an estimate of how population might be used in the prediction of the noise. Propagation may be by either skywave or groundwave methods. Primary sources are local ones, including nearby ignition noise, neon lights, and various electrical equipment.

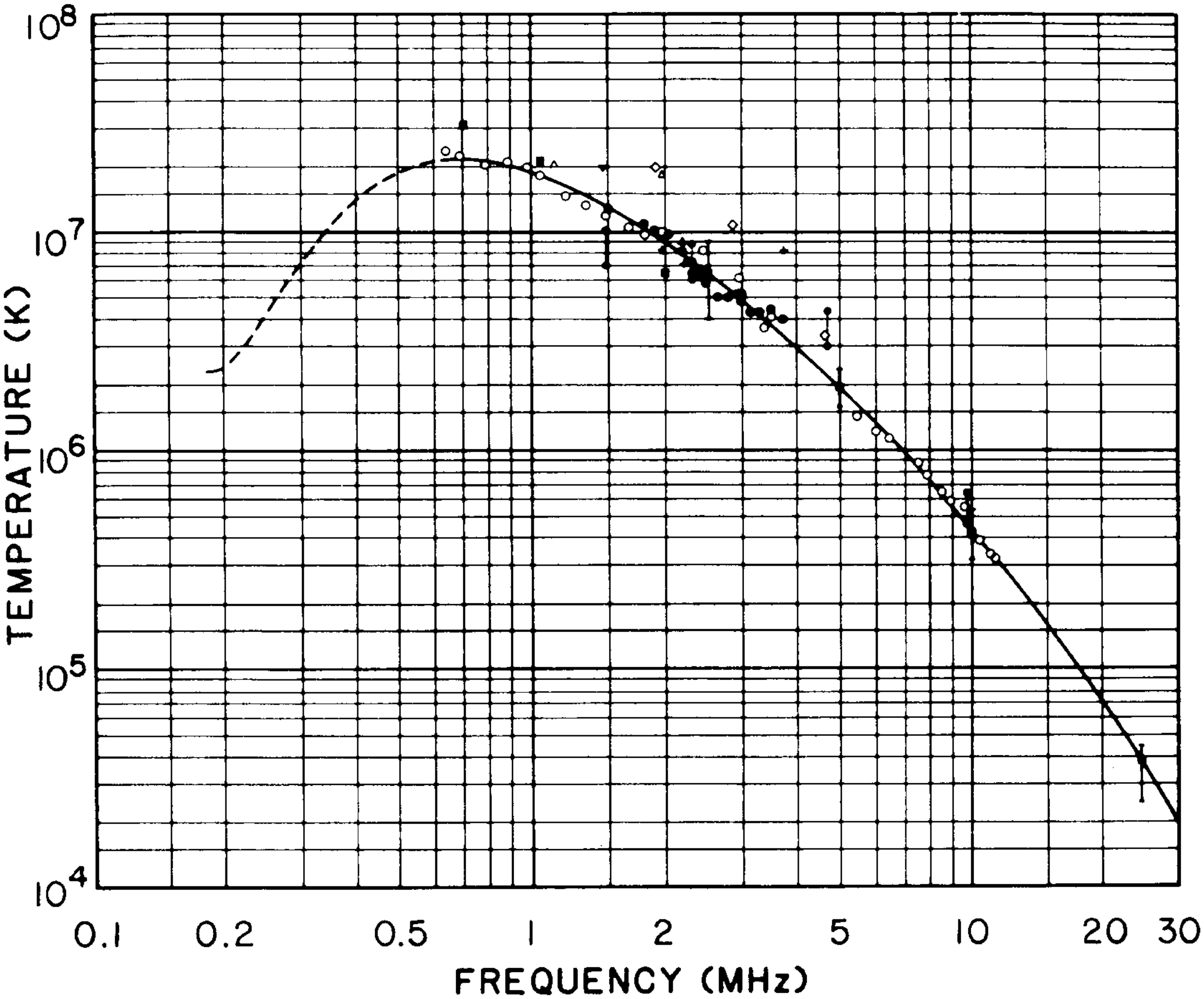


FIGURE A2-6
Galactic noise as a function of frequency

[Data points shown on the plot correspond to experimental results reported by a number of investigators.] (Report 342-5 [CCIR, 1986f])

Figure A2-7 provides a glimpse of residential noise variability across the RF spectrum. We note that the upper and lower deciles differ by approximately 15 to 25 dB throughout, and median values range between roughly 60 dB (at 3 MHz) and 30 dB (at 30 MHz).

A sample man-made noise distribution, expressed in terms of F_a, is given in Figure A2-8 at a frequency of 20 MHz for springtime morning conditions in a residential area. It is seen that the upper-to-lower decile range is about 15 dB. The two log-normal distributions tend to represent the data, one above and one below the median [Spaulding and Disney, 1974]. Galactic and atmospheric noise sources have also been observed to exhibit log-normal distributions.

The man-made noise model described in the earliest versions of CCIR 258 was based upon rf noise measurements originally made by ITS concentrating on sites in the United States. The most recent version of the report, CCIR-258-4 [1982] has been improved by the addition of more modern data, notably data obtained from the Soviet Union. Man-made noise, expressed in terms of F_a, is given in Figure A2-9.

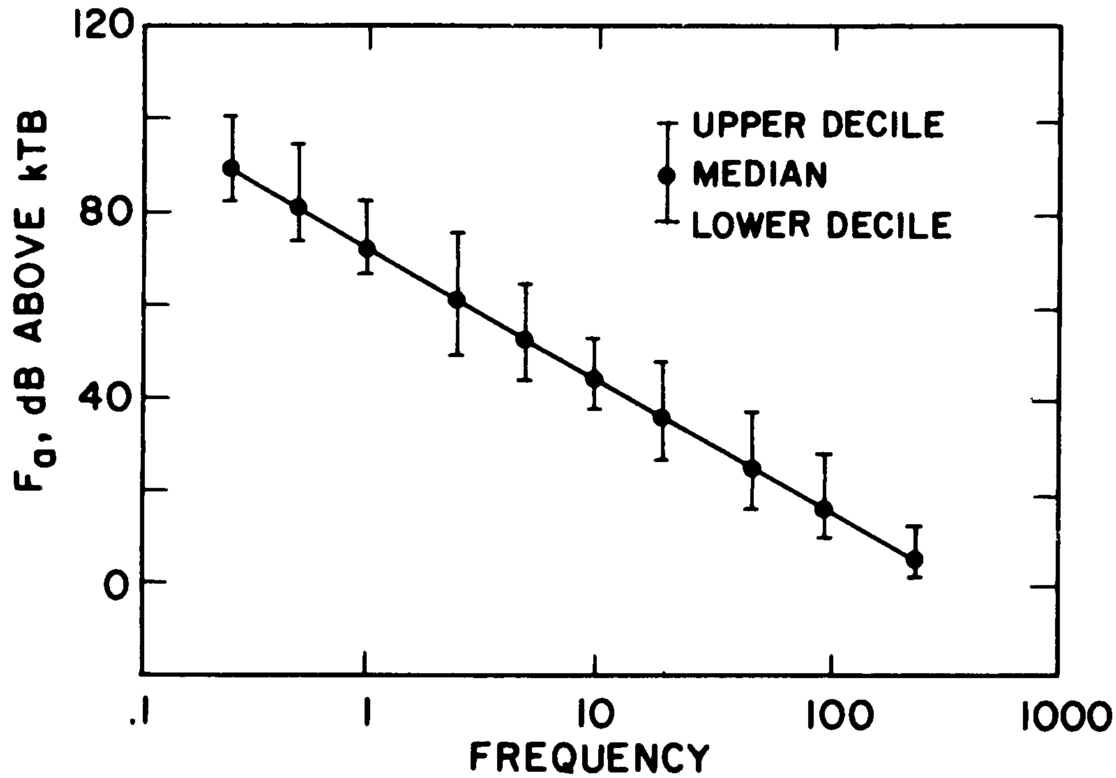


FIGURE A2-7
Man-made noise variability

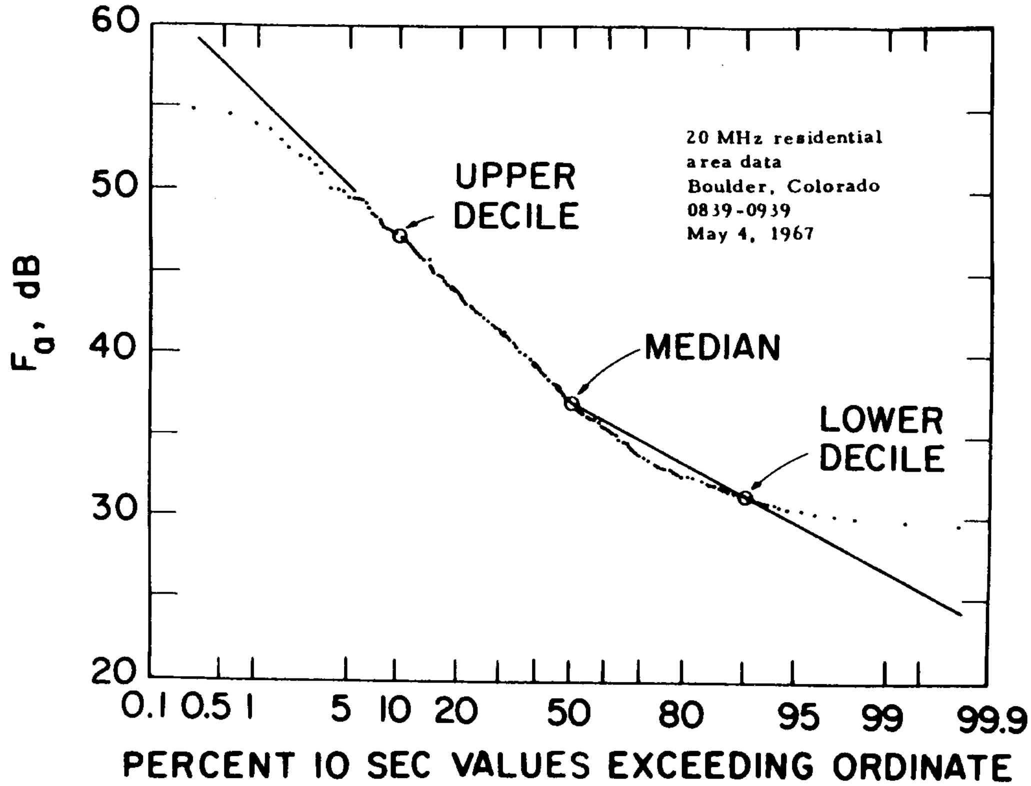


FIGURE A2-8

Noise distribution at 20 MHz, for spring and morning conditions. Residential area near Boulder, Colorado [from Spaulding and Disney [1974]).

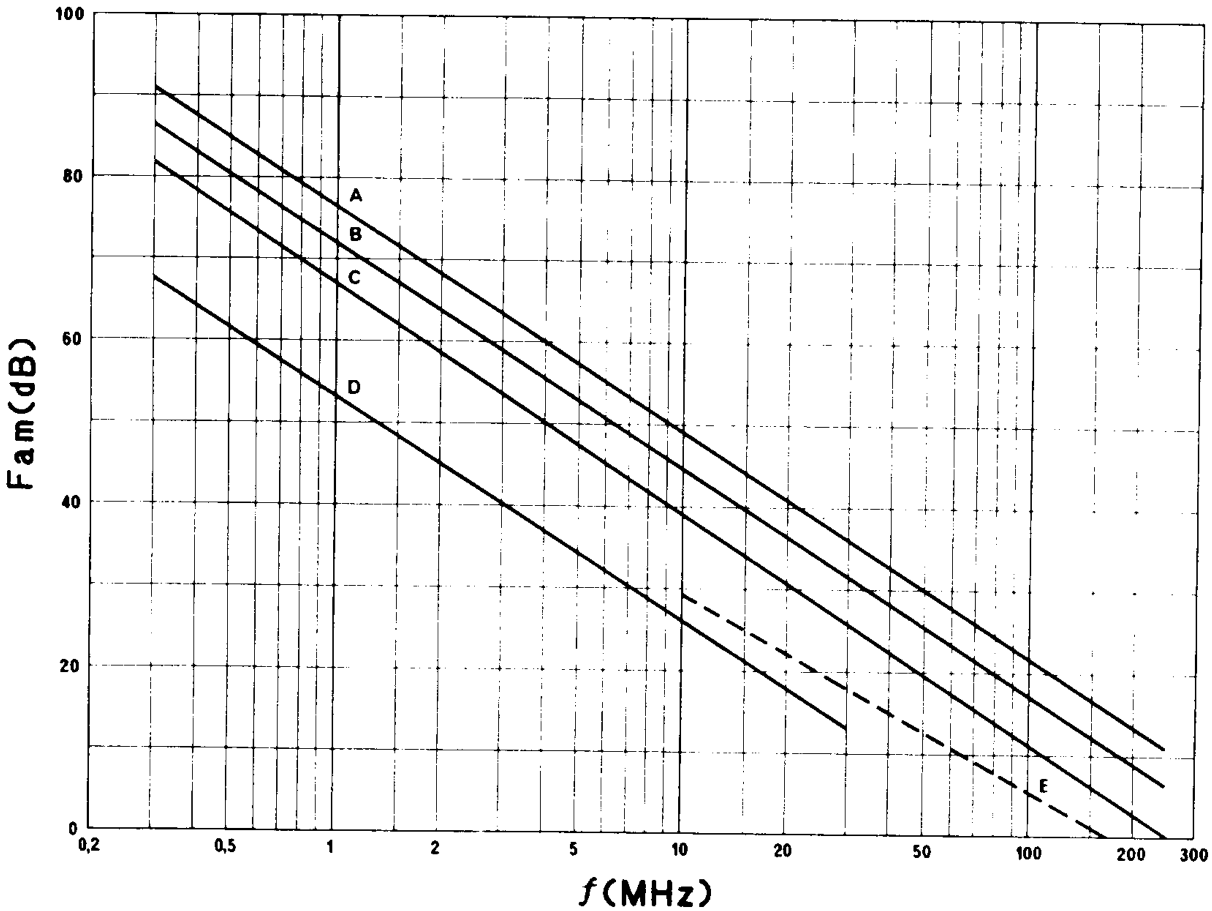


FIGURE A2-9
Man-made noise levels
A: business, B: residential, C: rural, D: Quiet rural, E: Galactic (from Report 258-4 [CCIR, 1982e]).

A2-7.5.4 The CCIR 322 noise model

Implementation of CCIR 322 may be illustrated through the use of three charts. The first chart (actually one of many) shows contours of Fam, the median value of the external noise, for a specified *local time* block at a frequency of 1 MHz. A second chart permits translation of the 1 MHz noise figure medians to the frequency desired. A third chart is used to obtain frequency-dependent statistical information. To obtain an estimate of the atmospheric noise level under specified conditions, we must select an appropriate seasonal map and read the 1 MHz noise estimate for the receiver location dictated.

Figure A2-10 is a CCIR map for the winter season for the 0000-0400 local time block. At Washington, DC, the value of median 1 MHz noise (*i.e.*, F_{am}) is about 70 dB above kT_ob. The next step is to shift this result to the appropriate frequency to be used. We do this with companion Figure A2-11. We see that a family of curves is displayed showing the frequency variation of Fam but parametric in terms of the 1 MHz value (already obtained). Locating the 70-dB curve, we slide to the frequency of interest. Assuming 10 MHz is that frequency, we see that F_{am} is 35 dB above kT_ob. From Figure A2-12 we may deduce noise variability statistics for the frequency of interest.

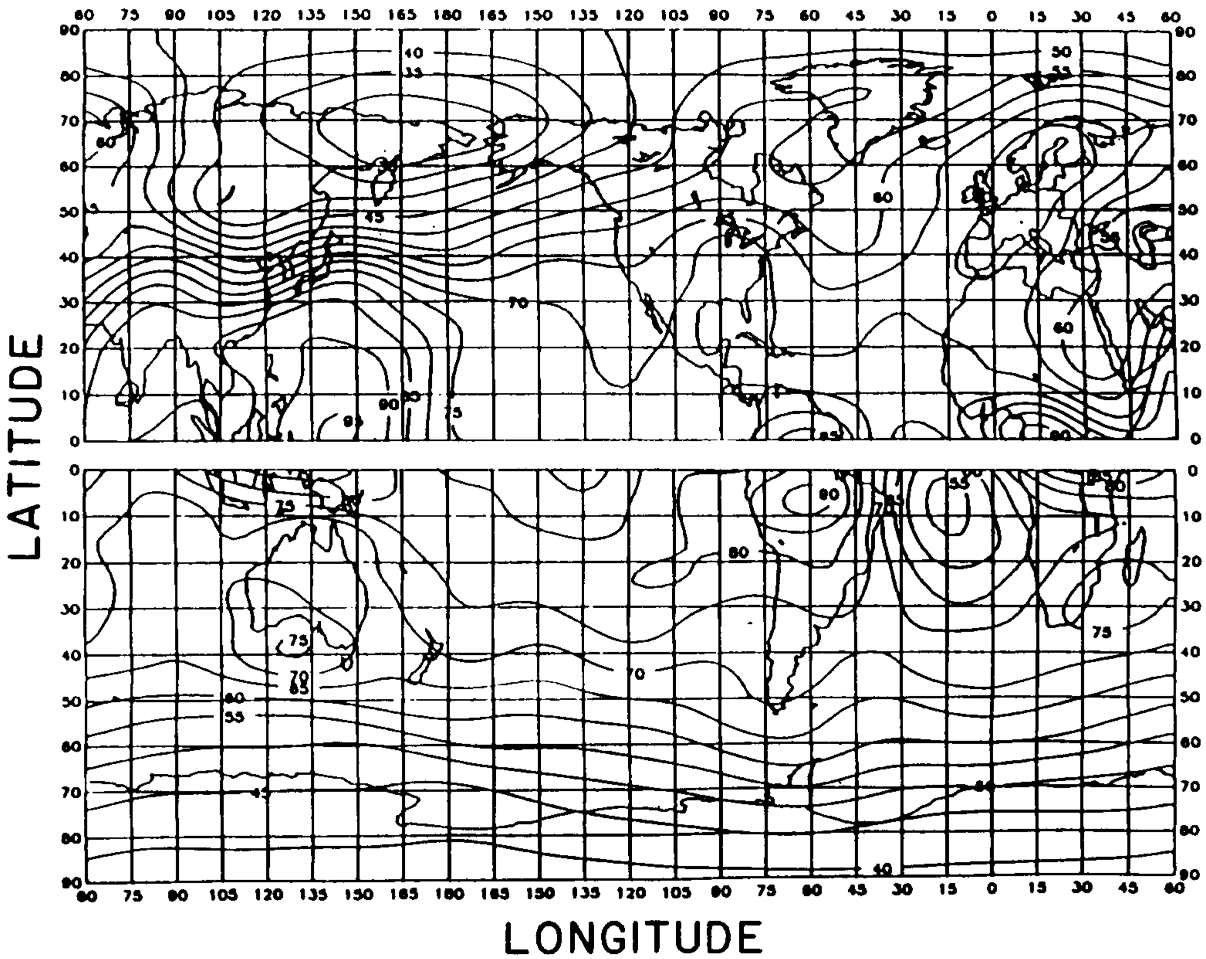


FIGURE A2-10
World map of atmospheric noise at 1 MHz. Winter. Time block: 0000-0400 Lt. Values in dB above kT_0b (from CCIR 322-3 [1966])

With respect to availability of computer codes from the CCIR Secretariat, the set of new noise coefficients associated with Report 322-3 [1966] is termed NOISEDAT and is applicable for microcomputer application. The program NOISY containing the older coefficients is available for mainframe computer versions of CCIR-322-2 [1964]. Understandably, a number of organizations such as NRL and VOA/USIA have modified the existing mainframe code to accommodate the newer coefficients. It should be noted that the way to atmospheric noise, galactic noise, and man-made noise are combined has also been modified.

A2-7.5.5 Combination of noise sources

Spaulding and Stewart [1987] have described how each of the noise sources should be combined to estimate system performance effects. At one time propagation prediction methods simply took as the largest of the atmospheric, man-made, and galactic sources as the composite. Over the years this approach has been modified, and a decidedly more attractive method of combining the three sources and obtaining the composite distribution function has been the result.

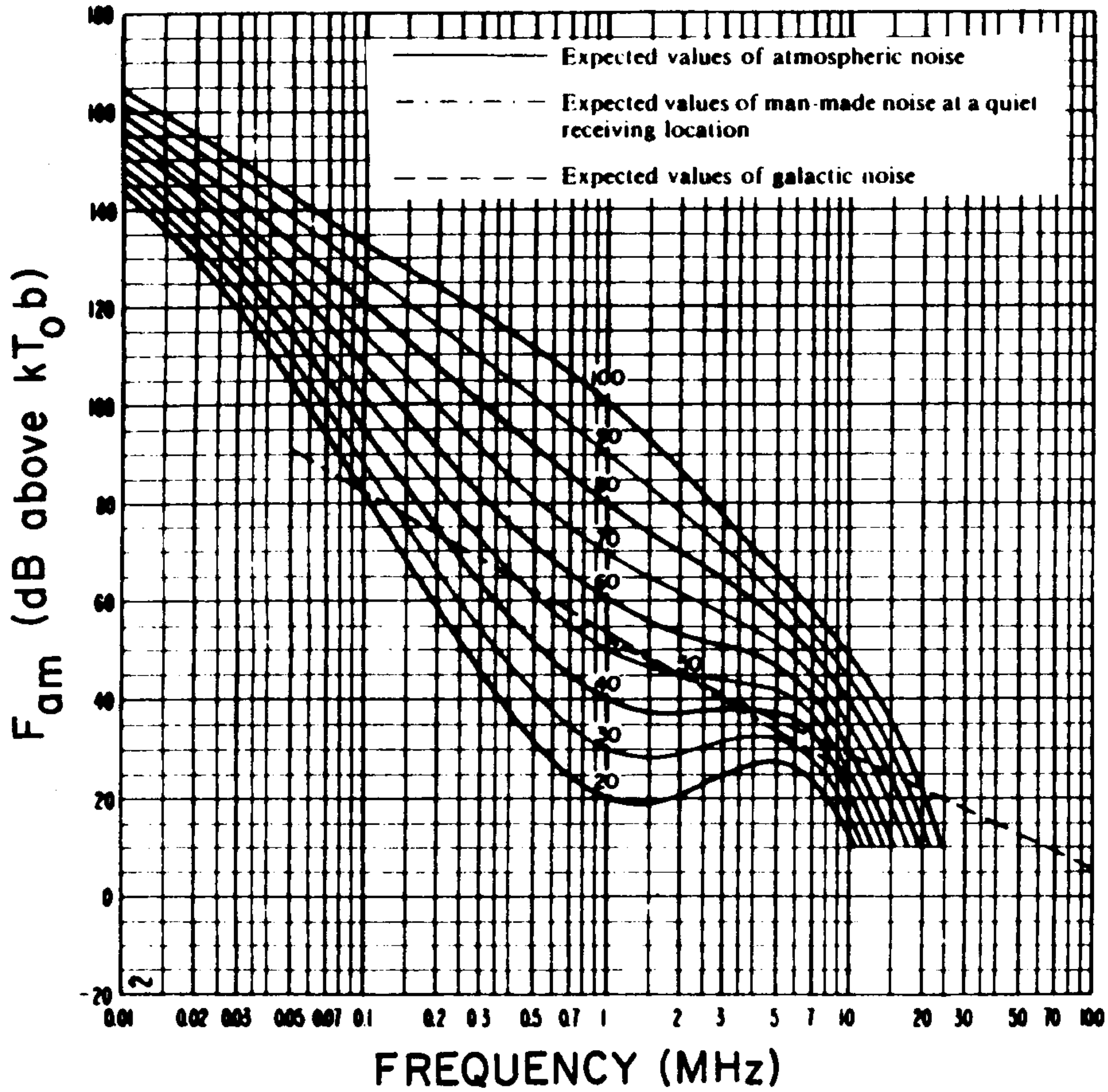


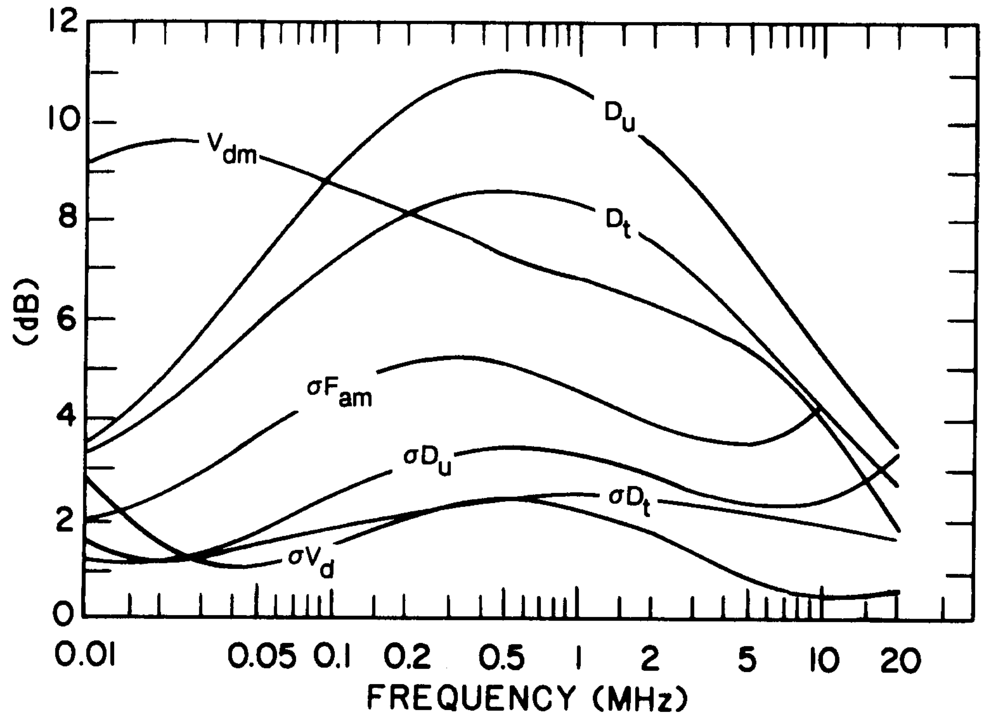
FIGURE A2-11

Variation of radio noise with frequency. Winter, time block: 0000=0400 LT

Values in dB above kT_ob (from CCIR 322-3 [1986])

A2-7.5.6 IONCAP implementations

A version of IONCAP containing the Spaulding-Stewart noise model approach contains the following subroutines: APIS1, which computes the 1 MHz atmospheric noise levels for two adjacent 4-hour time blocks by calling NOISY; NOISY, which uses supplied Fourier coefficients to compute the 1 MHz atmospheric noise value; GENFAM, which computes the atmospheric noise at the appropriate frequency as well as variability data; and GENOIS, which combines all of the sources of noise including atmospheric galactic, and man-made. The subroutine GENOIS has been modified from earlier versions of IONCAP. As indicated in section A2.7.2, ITS has made the PC/Windows® version of VOACAP and ICEPAC available over the Web. These programs also employ the revised Stewart noise model.



KEY

σF_{am}	:	Standard deviation of values of F_{am}
D_u	:	Ratio of upper decile to median value, F_{am}
σD_u	:	Standard deviation of values of D_u
D_t	:	Ratio of the median value, F_{am}, to lower decile
σD_t	:	Standard deviation of value of D_t
V_{dm}	:	Expected value of the median deviation of average voltage. (Values shown are for a bandwidth of 200 Hz.)
σV_d	:	Standard deviation of V_d

FIGURE A2-12

Noise variability. Winter, time block: 0000-0400 LT (from CCIR 322-3 [1986])

A2-7.6 Noise and interference mitigation

It should be obvious that noise and interfer3ence will have a profound influence on the performance of HF systems. Interference, which may be quite severe in the industrialized sections of the world, can dominate other sources. Such domination is not totally unexpected in the upper part of the HF spectrum, and is even consistent with the CCIR 322 and 258 noise models. We anticipate that atmospheric noise will assume a dominant role in the lowest portion of the HF band, certainly at middle latitudes. Nevertheless, high latitude observations have clearly indicated that this expectation is not observed. Within the auroral zone and possibly the cap region, other factors act to limit atmospheric sources relative to local man-made signals. A wideband (WBHF) approach allows the receiver to discriminate naturally against narrowband sources while retaining an intrinsic processing gain. Still it has been found that a few narrow-band and relatively high-power signals may even vulgarize WBHF performance. Interference excision techniques are powerful measures that, when applied in a wideband environment, may enable the maximum advantage of WBHF to be achieved. To determine the advantage that will accrue from such a strategy, it is necessary to model the WBHF channel to determine what might be lost by noise (and elementary frequency band) excision. Remarkably, low power level requirements, of the order of several milliwatts, may be enabled for low data rate transmission (say, 100 bps) for some skywave paths through use of this technique.

One strategy for coping with interference is simply to avoid it. Indeed, spectrum occupancy meters may be monitored by operators, and along with data derived from sounders, it is possible to avoid occupied channels within the LOF to MOF frequency profile. However, operational occupancy monitors may have insufficient bandwidth resolution relative to the spectral “holes,” which are sufficient for some applications. Moreover, manual determination of spectral holes may be inconsistent with the dynamic behavior of channel occupancy. We say “may” because the statement is dependent upon the category of use. Clearly the situation is different in the amateur bands than in the broadcast bands.

Dutta and Gott [1982] have explored the application of congestion information to HF operation and Doany [1981] has examined the impact of congestion on various FSK formats with arbitrary levels of diversity. If M diversity tones are transmitted (with at least a 1 kHz separation between adjacent tones), then the probability that at least two of them will be received free of interference is:

$$P(2,M) = 1 - Q^{M} - M(1 - Q)\, Q^{M-1} \qquad \text{(A2-6)}$$

where Q is the congestion index. The availability of at least two tones will allow a degree of frequency diversity to be accommodated. For Q = 50% and M – 6, then P(2, M) = 0.9. Since Q – 50% implies relatively heavy congestion, it is clear that a sixfold diversity will greatly improve performance under adverse conditions.

Another use that can be made of occupancy measurements is that of passive sounding. Occupancy statistics for skywave signals are strongly dependent upon ionospheric channel behavior. A continuously updated database of channel occupancy, suitably circulated around an HF network, may provide an alternative to active sounding. No operational system has been deployed using this philosophy.

A2-7.7 Effect of noise on system performance

Excision and avoidance strategies are not always possible. In most applications for which an HF system must coexist with the noise background, we simply recognize the error rates and attempt to minimize them by selecting appropriate diversity measures. The vulnerability to noise and interference, like multipath fading, is likewise a function of the modulation format selected.

Figure A2-13 shows how the bit error ratio (BER) depends on the degree of noise impulsiveness and the presence or absence of diversity as a function of SNR. *Waterfall* curves like this have been constructed for various channel conditions and modulation formats. In this case the fading channel was characterized by a Rayleigh distribution and the modulation was non-coherent FSK.

It is noteworthy that noise limits the performance of HF systems for the lower values of SNR, but propagation effects (such as multipath) cause the theoretical improvement in BER for high values of SNR to flatten out. In short, there is a BER floor below which it is not possible to descend since symbol decisions which are corrupted by intersymbol interference and selective fading may be little influenced by increases in the *wanted* signal level. Figure A2-14 bears this out.

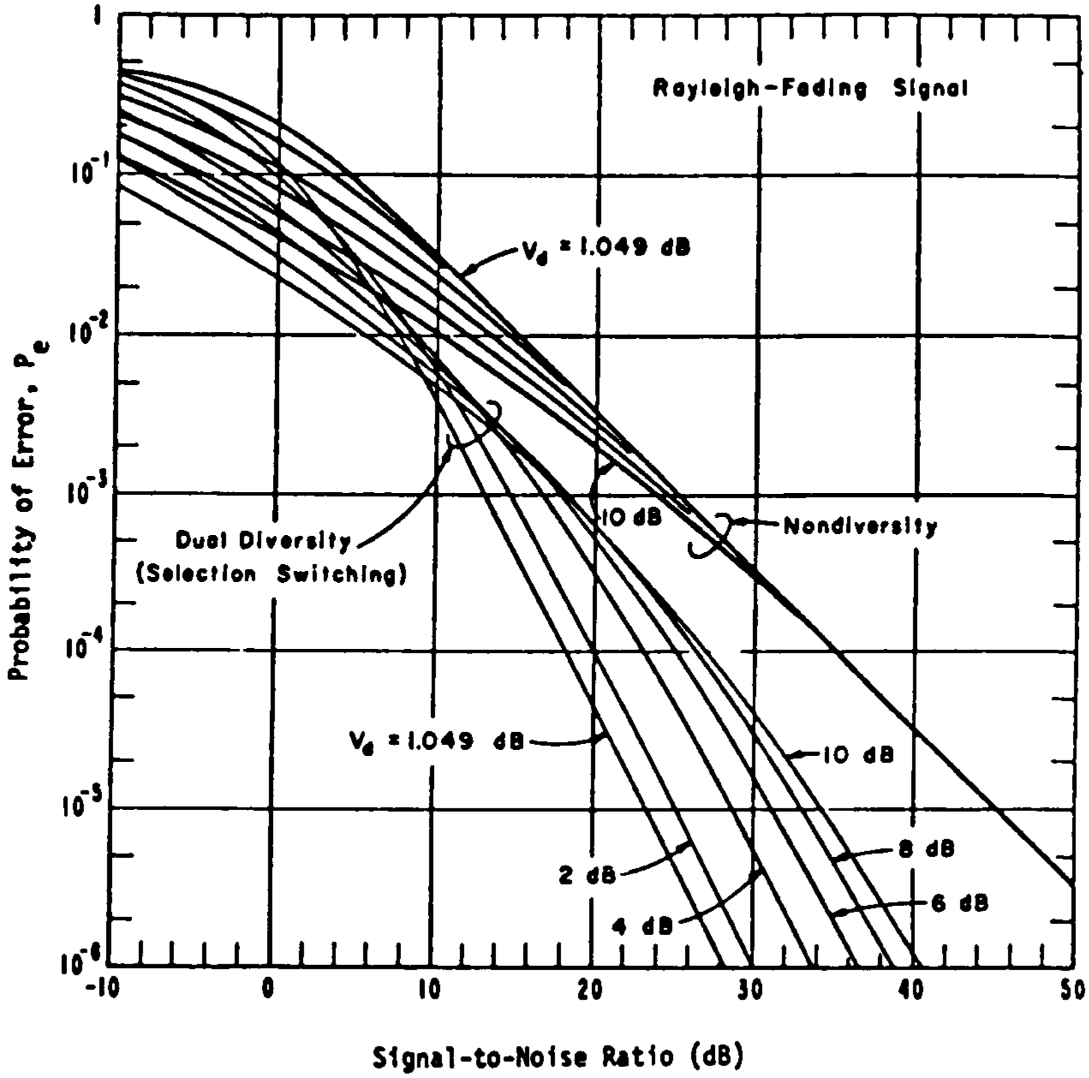


FIGURE A2-13

Probability of bit error for slow flat Rayleigh fading signal for a NCFSK system, for dual diversity and nondiversity reception (Spaulding [1976])

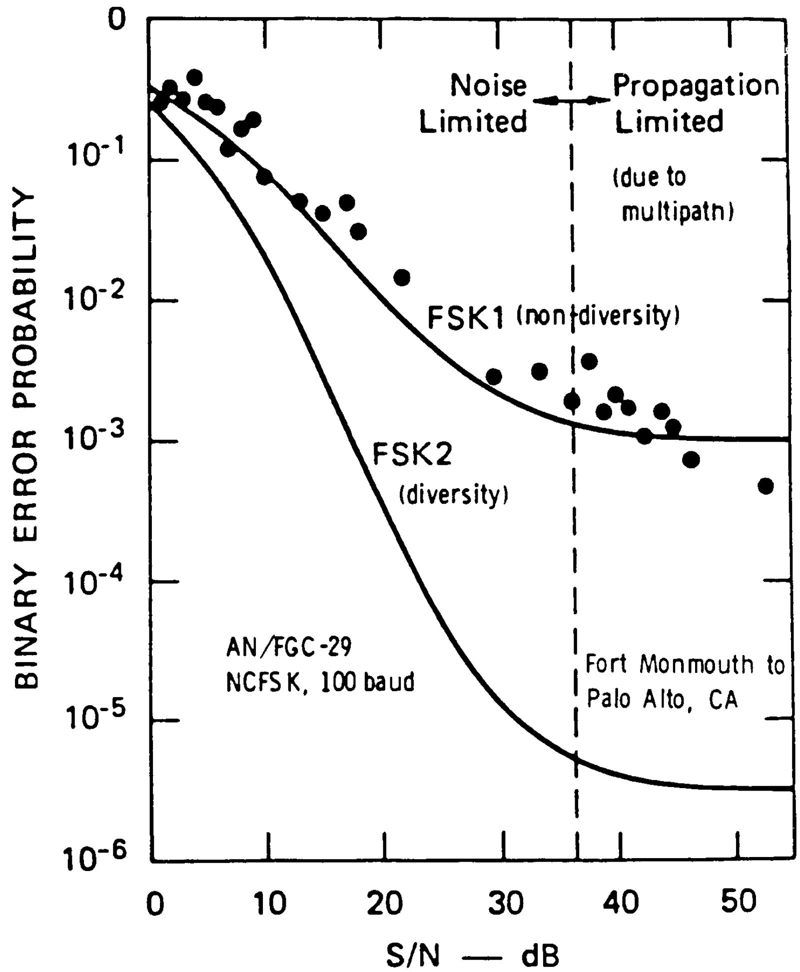


FIGURE A2-14

System performance as a function of signal-to-noise ratio (From Hagn [1988])

A2-8 Publications and computer programs

Publications available through the ITU-R (previously the CCIR) include the *Handbook on High Frequency Directional Antennae* [CCIR, 1965], the *CCIR Book of Antenna Diagrams* [1978], and the *CCIR Atlas of Antenna Diagrams* [1984]. Method-of-Moments (MOM) techniques provide the analyst with a fuller understanding of the complete antenna problem. Programs such as the Numerical Electromagnetics Code (NEC) are used for solution of practical problems, and microcomputer versions of NEC are available (*e.g.,* MININEC and MN as examples). For those interested in additional applications that may be analyzed on a microcomputer, several computer programs are available through the ITU Secretariat. Those programs include HFARRAYS, HFRHOMBS, HFMULSLW, HFDUASLW, and HFDUASLW1. See Resolution 63.2 [CCIR, 1986I] and Circulars 22 [ITU 1984.aA], 23 [ITU, 1984b], and 95 [ITU, 1986a,b]) for more details.

Programs such as HFMUFES, IONCAP, VOACAP, and ICEPAC contain antenna patterns that are used in the HF performance calculations. The antenna packages in the IONCAP family of programs include the ITSA-1 set due to Lucas and Haydon [1966] and an optional ITS-78 set due to Barghausen *et al.* [1969]. Using information extracted from ITS Report No. 74 [Ma and Walters, 1969], the IONCAP "theory manual" describes the evaluation of power gain, radiation resistance, and antenna efficiency for antennas that are included in the program. Methods used are somewhat approximate but are useful in most practical applications. An additional set of broadcast antenna patterns may also be obtained from the International Bureau of Broadcasting (IBB) in Washington, DC.

A2-9 Reliability

The performance of an HF radio system depends on field strength, competing interference, and other factors that may be functions of system configuration, mode of operation, and the type of service indicated. Everything else being equal, performance in transmission of facsimile is far superior to the performance in transmission of high-speed data. Given the same category of communication service, performance will be generally degraded by reduction in EIRP, by increased background noise or by the presence of interference. Reliability is a notion that indicates to the engineer a probability that the system will perform its function under a set of circumstances. Some pertinent definitions are provided below in Annex 8 of this document. Methods for computing reliability are listed in Table 4-11.

A2-9.1 Basic mode reliability

The mode reliability, denoted by the term R_m, is given by:

$$R_m = P_{SNR} \qquad \text{(A2.7)}$$

where Q is the mode availability, and P_{SNR} is a conditional probability that the required signal-to-noise ratio (SNR) is exceeded, under the condition that the mode exists. Equation 4.7 presumes that mode presence is independent of signal strength. This approach is useful for computer methods that contain the median field strength for a specified mode of propagation under the condition that the reflection (or refraction) condition actually exists. (See CCIR method 252-2.) Methods CCIR 252-2 (Supplement) and 894 compute median field strength for all time, irrespective of a special mode availability.

Thus, the mode reliability that is consistent with these latter models is just the fraction of time that the SNR exceeds the required value. An expression for PSNR is given in Report 892-1 [CCIR, 1986h] based upon work by Bradley and Bedford [1976].

A2-9.2 Circuit reliability

As indicated in CCIR Report 892-1 [1986h], Liu and Bradley [1985] have developed a general expression for circuit reliability for the general situation corresponding to an arbitrary number of contributing modes. A practical situation involves only two contributing modes, and the resulting expression for reliability will involve expressions for mode availability and mode performance achievement. We have:

$$R_c = q_1P_1 + q_2P_2 + q_{12}P_{12} \qquad \text{(A2.8)}$$

where R_c is the circuit reliability; q_1 and P_1 are the mode availability and mode performance achievement for the case when mode 1 is present; q_2 and P_2 are the mode availability and mode performance achievement for the case when mode 2 is present; q_{12} is the probability that modes 1 and 2 are present simultaneously; and P_{12} is the probability that the combination of modes 1 and 2 will lead to a signal-to-noise in excess of some required level. Even though equation A2.8 is limited to two contributing modes, its evaluation is not necessarily trivial. Other methods for computing reliability are listed in Table A2-6.

TABLE A2-6

Various reliability methods in use

Name of Method or "System" Use	**Reference**
IONCAP/VOACAP/ICEPAC	Teters *et al*. [1983-1995]
HFMUFES	Barghausen *et al*. [1969]
Liu-Bradley	Liu and Bradley [1985]
CRC-Canada	Petrie [1981]
CCIR Method	CCIR Report 892-1 [1986h]
Maslin Method	Maslin [1978]
Chernov Method	Chernov [1969]
HFBC Method	CCIR Report 892=1 [1986h]
REC533	ITU-R Recommendation PI 842-1

It is of interest to look at some special cases of an approximate method developed by Liu and Bradley [1985] for which correlation between two contributing mode MUFs may be taken into account, whereas correlation between mode SNRs is ignored. The method presumes that the basic MUF is normally distributed and the SNR is log-normal (*i.e.*, the SNR in dB is normally distributed). Taking the correlation between two modes as c_{12}, and $Q_1 = q_1 + q_{12}$, $Q_2 = q_2 + q_{12}$ where q_1 and q_{12} were defined previously, we have:

$$R_c = Q_1P_1 + Q_2P_2 \{1 - [c_{12}^2 + 1 - c_{12}^2) Q_1] P_1\} \qquad \text{(A2-9)}$$

where $Q_1 \geq Q_2$. For $c_{12} = 0$ and $c_{12} = 1$, obvious simplifications in equation 4.14 will result. For purposes of planning, one may take E and F1 modes to be fully correlated (*i.e.*, $c_{12} = 1$), E and F2 modes to be uncorrelated, and F1 and F2 modes to be uncorrelated. Also, correlation between dual modes from the same layer are taken to be highly correlated but not necessarily unity. For example, experience has shown that two F2 modes have a cross correlation coefficient of 0.8 for purposes of reliability calculations. The effect of vanishing correlation between two contributing modes is to limit the maximum reliability that may be achieved.

IONCAP uses another scheme for estimating circuit reliability. The method involves combining the signal power from all modes under the presumption that the relative phase relationships between the contributing modes are random. The SNR is taken to be the difference between the means for both signal and noise (in dB), while the variance of SNR is simply the sum of the respective variances. The circuit reliability is taken to be the fraction of days (over a month) that the SNR ≥ the required value. Clearly, if a specified mode does not propagate efficiently, the algorithm automatically disables any significant contribution of that mode to the overall reliability. There is no need to account for mode support explicitly. It is noteworthy that the ionospheric variability and mode support is accounted for implicitly (in terms of SNR variability, which is part of the IONCAP model). As expected, comparisons of the various methods for circuit reliability show some differences.

Table A2-7 gives the number of methods available within the IONCAP family of programs. The table is representative of VOACAP version 97.0327W. The newest release is 98.0908W. The reader is referred to the following Web site for more details:

http://elbert.its.bldrdoc.gov/hf.html

The descriptors of IONCAP methods listed in Table A2-7 are fairly self-explanatory. The term REL corresponds to reliability, and ANG refers to the elevation angle associated with the specified dominant mode. Methods 1 and 2 allow the user to see the underlying ionospheric data that is used in the other methods. A number of graphical and tabular methods that provide various combinations of propagation data such as HPF, MUF, LUF, FOT, ANG, and foEs are available. However, system performance methods set mainframe models apart from microcomputer models that compute only a limited set of parameters, typically only the propagation parameters and possibly a measure of signal strength. Popular methods in Table A2-12 include numbers 17, 20, and 25. A complete system performance is accommodated in method 20 and a condensed version of this is found in method 17. Method 25 allows the analyst to examine system effects mode-by-mode. The reliability vs. MUF table found in method 24 is also quite useful, while the antenna methods 13-15 are primarily available for reference purposes.

In the computation of reliability, the user must specify a number of system parameters as well as required SNR for a specified modulation format and grade of service. These data are found in various communication handbooks. Tables A2 and 5 in NTIA Report 83-127 give data for an assortment of conditions. The reader should not be surprised to see apparently enormous values in the tables just referenced since they reflect the required SNR for a signal in the occupied bandwidth versus noise in a 1-Hz bandwidth. To compare signal and noise in a common bandwidth, one must subtract the system (*i.e.*, noise) bandwidth in dB from the tabulated value.

TABLE A2-7.

Listing of IONCAP methods*

Method No.	**Method Description**
1	Ionospheric parameters
2	Ionograms
3	MUF-FOT lines (nomogram)
4	MUF-FOT graph (use 11 or 28)
5	HPF-MUF-FOT graph
6	MUF-FOT-Es graph (use 11)
7	FOT-MUF table (full ionosphere)
8	MUF-FOT graph (use 11 or 28)
9	HPF-MUF-FOT graph
10	MUF-FOT-ANG graph
11	MUF-FOT-Es graph—real graph, not line printer
12	MUF by magnetic indices, K (not implemented)
13	Transmitter antenna pattern
14	Receiver antenna pattern
15	Both transmitter and receiver patterns
16	System performance (SP)
17	Condensed system performance, reliability
18	Condenses system performance, service probability
19	Propagation path geometry
20	Complete system performance (C.S.P.)
21	Forced long path model (C.S.P.)
22	Forced short path model (C.S.P.)
23	User selected output (set by TOPLINES & BOTLINES)
24	MUF-REL table
25	All modes table
26	MUF-LUF-FOT table (nomogram)
27	FOT-LUF graph (Use 28)
28	MUF-FOT-LUF graph—real graph, not line printer
29	MUF-LUF graph (Use 28)
30	For VOACAP only—S/L path smoothing (7,000 – 10,000 km)

*The IONCAP documentation consists of a user's guide [Teters *et al.*, 1983] which outlines the various methods that may be selected. A listing of methods within this table is associated with VOACAP ver. 97.0327W. The latest Windows®, NT, and 95/98 32-bit version of ICEPAC/VOACAP/REC533 is 98.0908W. See Teters, 1983, *Estimating the Performance of Telecommunication Systems Using the Ionospheric Transmission Channel: Ionospheric Communications Analysis and Predictions Program (IONCAP) User's Manual,* NTIA Report 83-127.

See http://elbert.its.bldrdoc.gov/hf.html

A2-10 Small programs and personal-computer methods

Over the years, the computer mainframe methods in the IONCAP family have been replaced by PC-based versions that run in a convenient Windows® environment. In fact, the fully capable versions of programs such as VOACAP and ICEPAC made the transitions to the PC environment more directly. While this evolutionary process was taking place, it was necessary to solve practical problems with less capable machines. This gave birth to a class of so-called microcomputer methods in the 1980s. Many of these methods still have validity in special applications and are the subject of this section. See Report 1013 (CCIR 1986L). One of the first microcomputer models to be developed for general use by the public was MINIMUF [Rose, 1982a], which is part of the PROPHET family of programs [Rose, 1982b]. There have been a number of improvements to MINIMUF, the more recent versions being termed MINIMUF 3.5 and MINIMUF85 [Sailors *et al.*, 1986]. Other microprocessor-oriented frequency prediction models have followed: MICROMUF [Bakhuizen, 1984], FTZMUF2 as described by Damboldt and Suessmann [1988a, b], and a series of models based upon algorithms developed by Fricker [SES, 1988]. Daehler [1990] has developed a MUF-LUF-FOT prediction program having a number of simple models as its basis, but admitting to several update options. Table A2-8 is a compilation of microcomputer methods and corresponding references. A review of various microcomputer methods has been published by Davy *et al*. [1987]. Field strength models are represented by MINIFTZ4 and the most complete CCIR-sanctioned microprocessor model is REP894. A microcomputer program, developed in accordance with the specifications provided in CCIR Report 1013 and based upon CCIR 894 methodology, is the program MICROP2 [Dick and Miller, 1987].

The Ionospheric Prediction Service of Australia has developed a user friendly microcomputer program called the Advanced Stand-Alone Prediction System [ASAPS) [IPS, 1991]. This model exploits the T-index, which was developed by IPS investigators, and draws on a previously developed GRAFEX prediction method [Turner, 1980].

Although there is some concern that accuracy may be sacrificed in the development of the microcomputer models, this concern is tempered by the following considerations. First, there have been no in-depth studies as yet which show that the large mainframe prediction models significantly outperform their smaller cousins, at least in the prediction of a simple parameter such as the MUF where there is a common basis for comparison. Secondly, in the world of RTCE and ionospheric assessment technology, which may be used for frequent updating of the model input conditions, small microcomputer models may perform quite adequately. This is because temporal updating procedures typically involve the application of scale factors that effectively suppress the physics that may be contained within the more elegant mainframe model. Thus, more rapid temporal updating leads to a convergence in the performance metric of competing models. The same may also be said of spatial extrapolation using models, although in this case and "update" involves the number and location of ionospheric control points used in the extrapolation process. Naturally, one would prefer the flexibility of the larger more elegant model if the capability to update in either space or time is limited. It should be noted that the IONCAP family of programs and other sophisticated modes have been converted to PC operation, thus making the relative accuracy question moot.

TABLE A2-8

Microcomputer prediction methods and references

Model Name	**Reference**
FTXMUF2 (foF2 and M3000)	Damboldt and Suessmann [1988a, b]
Fricker (foF2 & hF2)	Fricker [1985]
Compact Ionospheric Model	Clarke [1985]
MINIMUF	Rose [1982a, b]
MICROMUF [based on Fricker's algorithms]	SESC [1988] [Bakhuizen, 1984]
MINIPROP [based on Fricker's algorithms]	SESC [1988]
MAXIMUF [based on Fricker's algorithms]	SESC [1988]
KWIKMUF [based on Fricker's algorithms]	SESC [1988]
Gerdes Approach [approach similar to MINIMUF]	Gerdes [1984]
EINMUF (MUF-LUF-FOT) [approach similar to MINIMUF]	Daehler [1990]
Devereux/Wilkinson Method [approach similar to MINIMUF]	Devereux & Wilkinson [1983]
Fricker (Field Strength)	Fricker [1987]
IONOSOND [based on Fricker's algorithms]	W1FM [Lexington, MA]
MINIFTZ4 (Field Strength)	Damboldt & Seussmann [1988a, b]
MICROPREDIC	Petrie *et al.* [1986]
HFBC84 (Micro Version) [Replaced by REC 533]	Pan and Ji [1985]
HFPC85-CNET Method	Davy *et al.* [1987]
REP894 [with CCIR Secretariat: also MICROP2, HFRPC8]	CCIR 894 [1986a]
PC-IONCAP (NTIS)	Teters *et al.* [1983]
ASAPS	IPS [1991]
VOACAP	G. Hand [1993]
REC533	Recommendation ITU-R PI.842-1
ICEPAC/VOACAP/REC533	http://elbert.its.bldrdoc.gov/hf.html
PROPMAN	Roesler of Rockwell Collins

A separate implementation of IONCAP, called PC-IONCAP has been developed by ITS and is available through NTIS along with an early version of IONCAP documentation [Teters *et al.*, 1983]. A number of companies have implemented IONCAP methods to support special-purpose programs. For example, Rockwell Collins has developed PROPMAN, a PC version of IONCAP that incorporates the capability for updating.

A2-11 Commentary on short-term prediction techniques

Short-term prediction methods typically involve the measurement of either an ionospheric or geophysical parameter that is applied to an empirical model or algorithm. We have seen just above that long-term prediction methods provide the system architect and the frequency planner with useful guidance, but that ionospheric variability with time scales of tens of minutes present a considerable challenge. Certainly the ubiquitous median models have no intrinsic short-term forecasting capabilities. One should expect very little correlation between the unfiltered real world and the predictions extracted from a median model. A summary of short-term methods is provided in Report 888-1 [CCIR, 1986m]. Even though long-term models have no capability to assess short-term variability in other than a statistical way, the Achilles heel of short-term forecasting is that there is a danger that long-term models may be used improperly by analysts. Milsom [1987] has listed the outstanding problems associated with short-term forecasting, and Goodman [1991] has examined ways of coping with short-term variability.

The deviation of short-term predictions (which we shall hereafter term forecasts) may entail the process of model update with an external geophysical parameter, an ionospheric parameter, or a combination of both. Forecasts that exploit ionospheric measurements for updating purposes are by far more successful.

A2-12 Toward improvement of long-term predictions

Long-term prediction of ionospheric behavior depends critically upon a reliable representation of past ionospheric data and a known correlation with solar activity, which is the derivative of yet another prediction process. Because of the general lack of a truly accurate representation or model of the ionosphere, which is compounded by the tendency to *drive* these models with a single parameter such as sunspot number, long-term predictions are not dependable. This is because short-term, apparently stochastic disturbance sources or factors, which occur in the actual physical process, are not properly accounted for in the prediction method. Thus, long-term methods for prediction are used to derive coarse guidance. The hope is that they at least reflect the median behavior.

There are long-term tendencies in the solar flux. Recommendation 371 [CCIR, 1986n], dealing with the choice of indices for long-term predictions of ionospheric behavior, recommends that predictions that are for dates more than one year ahead of the current period be treated different from periods that are less. If predictions are for epochs of more than 12 months in the future, the 12-month running mean sunspot number is to be used for the prediction of all ionospheric parameters, including foF2, M(3000)F2, foF1, and FoE. The 12-month average is used to average out the shorter period disturbances, which may disguise the long-term tendency of solar flux and its influence on the median ionospheric parameters. For shorter lead times, several indices, including a measure of the 10.7 cm solar flux, as well as the sunspot number, produce equivalent answers in connection with prediction of the parameters foF2 and M(3000F2. As far as the lower ionospheric parameters foF1 and foE are concerned, it turns out that the 10.7 cm solar flux is the best index for periods up to 6 months into the future, and perhaps even longer. The fact that actual flux (even at 10.7 cm, which does not itself interact with the ionosphere,) best represents the solar ionization flux, which produces the E and F1 regions of the ionosphere, is well-known and is implicit in the CCIR recommendations.

In the design stage, the driving parameters of a prediction model are allowed to take on a range of values, and the system is designed to encompass the results of the calibrations. While sunspot number may be an adequate driving parameter for this purpose, it is not optimum for predicting events that will occur in particular days, weeks, or months in the future. Mounting evidence has accumulated [Sheeley *et al.*, 1985] that shows that coronal holes and particular large sunspot groups on the Sun are the real sources of high-speed solar windstreams, which feed most immediately into high latitude ionospheric effects and are later felt elsewhere. Observed effects are ionospheric storms, shifted and expanded auroral rings, depressed critical frequencies at mid-latitudes, etc. In other words, a sunspot number that totals all the spots is too crude a parameter to predict these effects. Instead, the idea would be to view coronal holes and pertinent sunspot regions from the Earth, account for the correct number of days for solar rotation to carry these solar features to the central meridian, and then add 2-3 days for the solar wind perturbation to reach the Earth. Hence, ionospheric effects could be predicted from solar observations about a week in advance. If one accounts for the fact that several of these solar features last many solar rotations, then corresponding effects can be confidently predicted to occur every 27-28 days. This is the basis for prediction of effects from solar observations with lead times up to several months. These developments point to the redesign of ionospheric models on the basis of correlating synoptic ionospheric parameter data with a different batch of relevant solar parameters. Shorter term forecasts (on the scale of hours) may be related to the class of solar flare-related sudden ionospheric disturbances (SIDs), which are associated with bursts of short-wavelength electromagnetic radiation.

Difficulties associated with HF radio circuit performance predictions are outlined in Report 889-1 [CCIR, 1986o]. They are abbreviated in Table A2-9 below, and the list clearly illustrates why HF predictions have mixed reviews.

TABLE A2-9

Difficulties in making accurate predictions

1	Use of OWF's implies a loss of skywave support 10% of the time (quiet times)
2	Predictions generally ignore storm-time effects.
3	Sporadic E model is not sufficiently accurate.
4	Differences exist between model databases and observations.
5	The SNR is poorly modeled and an incomplete performance metric.
6	Other user interference is not accounted for properly.
7	Deficiencies in mapping ionospheric characteristics, modeling tilts and gradients, *etc.* exist.

A2-13 Web sites for ionospheric prediction programs

There are a number of prediction services and real-time data programs available over the World Wide Web. However, the reader is cautioned that new Internet sites are continually being introduced as the technology advances. Below is a collection of Web sites available at this writing.

Program Name/Resource	**URL Address**
Real-Time Inograms (NGDC)	http://www.NGDC.NOAA.gov/stp/IONO/grams.html
Ionosphere Home Page (NGDC)	http://www.NGDC.NOAA.gov/stp/IONO/ionohome.html
HF Propagation Models (NTIA/ITS)	http://elbert.its.bldrdoc.gov/hf.html
Space Environment Center (SEC) home page	http://www.sec.noaa.gov/
Space Physics Interactive Data Resource (SPIDR) (NGDC)	http://julius.ngdc.noaa.gov:8080/index.html
IPS Radio and Space Services (Australia)	http://www.ips.oz.au/
Space Weather Forecasts	http://nastol.astro.lu.se/~henrik/spwfo.html

A2-14 Conclusion

An overview of prominent ionospheric propagation prediction models was given, and their use for shortwave applications was discussed. The backbone of these programs is a climatological or monthly median ionospheric model, which does not account for short-term variability. Since all such ionospheric models admit to significant errors from this class of disturbance, the choice of prediction model may depend less on the phenomenology embodied in the model and more upon less esoteric matters such as: availability of computer assets, transportability of the model, software maintenance requirements, ease of use, and related issues. This has led to a bifurcation of prediction systems into two classes: one devoted to study of detailed physical processes and long-term planning, and the other driven by short-term tactical requirements. Certain longer period disturbances or features characterized by large geographical scales, may be better described by more detailed models, although a significant empirical component may be involved, and update procedures will be necessitated to improve accuracy significantly. Examples include: day-night transitions, equatorial anomaly regions, high latitude auroral and sub-auroral trough regions, *etc*. Today most of the original, large mainframe models and newly developed models are incorporated into microcomputers and PCs. Thus, we see that the most advanced models and methods are now available to even the most unsophisticated user, and these models have replaced some of the well-known skeletal models that were developed for microcomputers in the 1970s and early 1980s. Moreover, programs such as IONCAP may be incorporated within forecasting systems for near real-time frequency management of HF systems. In addition, similar models may be incorporated within advanced modems that use microprocessors for network management. A method for modifying the IONCAP family of codes to reflect real-time changes in the ionosphere has been developed and described by Goodman, *et al.*, 1997. The basis of the approach found in ITU-R Rec. F.1337 (ITU, 1997) entitled, *Frequency management of adaptive HF radio systems and networks using FMCW oblique incidence sounding.* This method can also be exploited in the context of adaptive HF system protocol structures such as ALE. For example, it may be used to organize ALE scan lists, thereby reducing the need to use in-band channel sounding, the latter being a process which limits the efficiency of networked communications under stressed or disturbed conditions.

Long-term predictions are likely to be required for broadcast planning for some time to come. They are also worthwhile for system studies and planning for military operations. It is unclear to what extent incremental improvements in long-term modeling will provide for anything but small incremental improvements in long-term prediction capability. Computer procedures and display formats may be improved, however, and these cosmetic changes will add value, since they will provide the analyst with a capability to examine the projected data more coherently and in a variety of scenarios. One potential area for long-term performance improvement may arise as the result of a newly developed scheme for mapping the tendencies of high-latitude propagation from 1 week to several months in advance, based upon observation of the evolution of coronal holes and related solar features. There are a number of deficiencies in current modeling approaches and we have identified most of them. Aside from taking more care in representing the ionospheric *personality*, and possible incorporation of 3-D ray-tracing methods, quantum improvements in prediction capability are not anticipated. The future realm is dynamic modeling.

Long-term modeling approaches may be used to benefit short-term predictions. More dynamic approaches, based on ionospheric soundings, have been developed. They may be shown to have viability in updating selected prediction models for short-term use. This approach has been found to be particularly useful for local removal of the DC bias errors in ionospheric models, which result from the use of monthly medians and imprecise driving parameters, such as the sunspot number. Updates are particularly relevant for the effective use of adaptive HF schemes. However, a present ionospheric specification decorrelates rapidly when compared with future reality. The update must be performed rapidly. The best application of update for military or civilian broadcast planning may well be in the context of relay station diversity. Thus, the broadcast planner could envision real-time resource management. The resources available in the future may involve backscatter sounder technology, as well as overhead imagery tailored to provide ionospheric *weather* maps. Ionospheric data extracted from the GPS constellation downlink waveforms may be used to provide a more meaningful spatial sampling. These data sources would be coupled to existing assets, such as conventional vertical and oblique sounders and total electron content sensors activated by GPS transmissions. All of this information could be merged with the real-time solar-terrestrial data available through various data services [Joselyn and Carran, 1984]. Relatively high-quality ionospheric information may result from inserting this data into sophisticated ionospheric models that are presently being developed. The possibility exists for the construction of a real-time ionosphere to serve a number of users, not unlike that which has been envisioned by the U.S. Air Force to serve its customers.

Finally, it must be stated that a substantial effort has gone into the general area of ionospheric modeling. From this investment, a considerable amount of insight has been derived, and a number of very interesting methods for performance assessment have evolved. Some of these models include a full range of ionospheric and propagation effects, while others stress simplicity. The modern era allows for selection of the more complex (and complete) models for use in microcomputers as system controllers. Further, these models will have *hooks* allowing real-time update methods to be used as the newer sensors become available. In short, prediction methods based on the evolution of long-term median models, and have been an essential catalyst in the development of more dynamic models.

ANNEX 3

ELEMENTS IN AN HF RADIO SYSTEM

A3-1 Introduction

Now that you have an overview of how radio waves propagate, let's take a look at how they are generated. The primary components in an HF radio system fall into three groups: transmitters, receivers, and antennas. In many modern radio sets, the transmitter and receiver are contained in a single unit called a *transceiver*. In large, fixed systems, transmitting stations and receiving stations are customarily at separate locations, often controlled from a remote third site.

A3-2 Transmitter group

Although transmitters may vary widely in their configuration, they all consist of an *exciter* and *power amplifier*. A simplified diagram of a typical HF transmitter is shown in Figure A3-1.

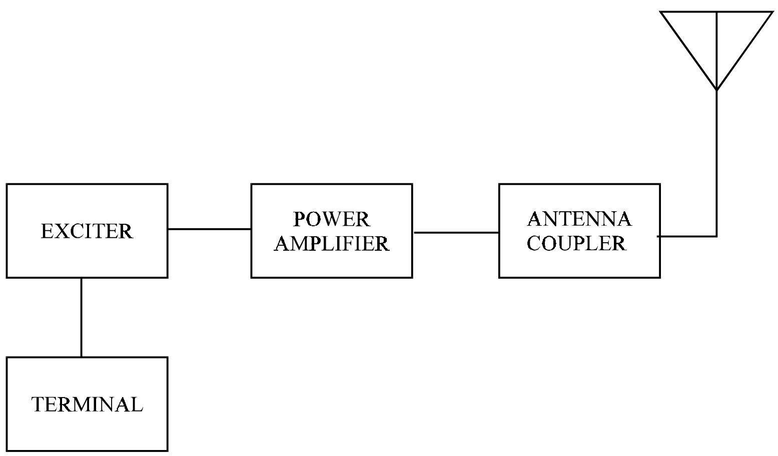


FIGURE A3-1
Simplified diagram of a typical HF transmitter

The exciter synthesizes a carrier, which has one of its properties — modified (modulated) by a lower frequency signal derived from a source of information such as a microphone. The resulting signal is converted to the frequency that is to be transmitted. The power amplifier boosts the output power of the signal to the desired wattage for transmission before sending it through a cable to the transmitting antenna.

The transmitter may also contain filters that are used to "clean up" its output. A *bandpass filter* removes noise, spurious signals, and harmonics generated in the exciter, or output frequency harmonics coming from the power amplifier. This process reduces interference with adjacent communications channels.

A3-3 Receiver rroup

All modern HF receiving systems include an rf input filter/amplifier, a series of frequency converters and intermediate frequency (IF) amplifiers, a demodulator, and a local oscillator frequency synthesizer (see Figure A3-2). To function, the receiver selects a desired signal, amplifies it to a suitable level, and recovers the information through the process of *demodulation*, in which the original modulating signal is recovered from a modulating carrier. With contemporary radio equipment, many of these functions are performed digitally.

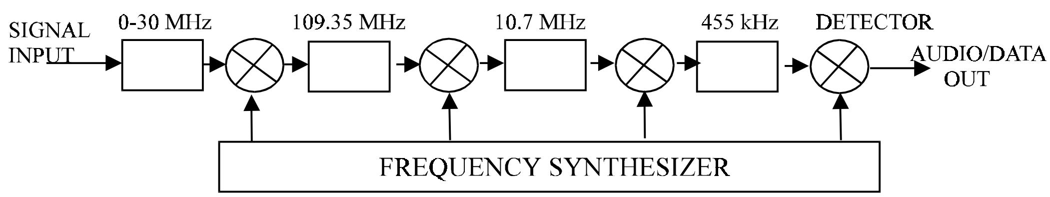


FIGURE A3-2
Simplified diagram of an HF receiver

In order to filter out noise and undesired signals, the rf input states sometimes incorporates a tunable preselector (a bandpass filter). The filtered signal is then amplified and converted to another frequency for further processing.

But the filtering process does not end here. Typically, the received signal is filtered and amplified again at several different intermediate frequencies. The amplification provided in these stages is a variable that depends on the strength of the received signal.

In order to output voice or data, for example, the demodulator produces an audio-frequency *(baseband*) signal that interfaces with additional equipment. Also, because the strength of the input signal may not be constant, the demodulator stage produces a voltage proportional to the level of the rf input signal. To compensate for changes in the signal, the voltage is fed back to the rf and IF amplifiers for automatic gain control (*AGC*), to maintain a constant input to the demodulator.

A3-4 The antenna group

The antenna is one of the most critical elements in a radio circuit. Here, we will look at typical antenna types and their applications.

A3-4.1 Antenna characteristics and parameters

Some of the most commonly used terms to describe antennas are *impedance, gain, radiation pattern, take-off angle,* and *polarization.*

Every antenna has an input impedance, which represents the load to be applied to the transmitter. This impedance depends upon many factors, such as antenna design, frequency of operation, and location of the antenna with respect to surrounding objects.

The basic challenge in radio communications is finding ways to get the most power possible, where and when you need it, to generate and transmit signals. Most transmitters are designed to provide maximum output power and efficiency into a 50-ohm load. (*Ohm* is a unit of measurement of resistance. Its symbol is Ω.) Some antennas, such as log periodic antennas, can provide a 50-ohm load to the transmitter over a wide range of frequencies. These antennas can generally be connected directly to the transmitter. Other antennas, such as dipoles, whips, and long-wire antennas, have impedances that vary widely with frequency and the surrounding environment. In these cases, an *antenna turner* or *coupler* is used. This device is inserted between the transmitter and antenna to modify the characteristics of the load presented to the transmitter so that maximum power may be transferred from the transmitter to the antenna.

The *gain* of an antenna is a measure of its directivity — its ability to focus the energy it radiates in a particular direction. The gain may be determined by comparing the level of signal received from it against the level that would be received from an isotropic antenna, which radiates equally in all directions. Gain can be expressed in dBi; the higher this number, the greater the directivity of the antenna. Transmitting antenna gain directly affects transmitter power requirements. If, for example, an omnidirectional antenna were replaced by a directional antenna with a gain of 10 dBi, a 100-watt transmitter would produce the same effective radiated power as a 1 – kW transmitter and omnidirectional antenna.

In addition to gain, radio users must understand the radiation pattern of an antenna for optimal signal transmission. Radiation pattern is determined by an antenna's design and is strongly influenced by its location with respect to the ground. It may also be affected by its proximity to nearby objects such as buildings and trees. In most antennas, the pattern is not uniform, but is characterized by plots in the vertical and horizontal planes (Figure A3-3), which show antenna gain as a function of elevation angle (vertical pattern) and azimuth angle (horizontal plot). The radiation patterns and frequency dependent, so plots at different frequencies are required to fully characterize the radiation pattern of an antenna.

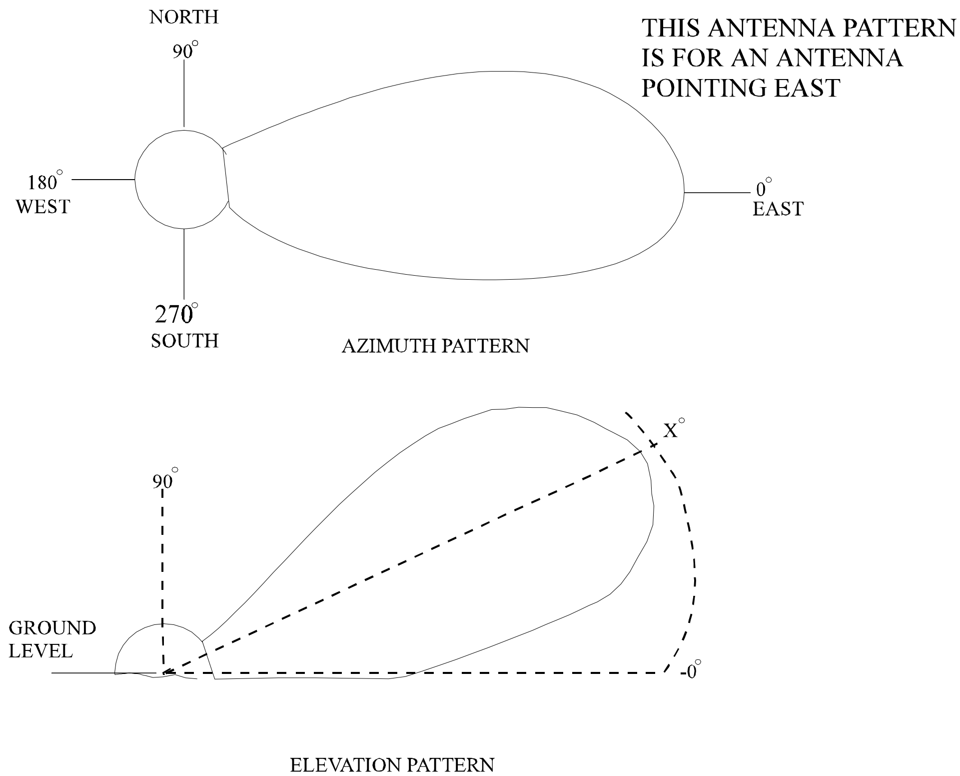


FIGURE A3-3
Antenna radiation patterns

In determining communications range, it is important to factor in the *take-off angle,* which is the angle between the *main lobe* of an antenna pattern and the horizontal plane of the transmitting antenna. Low take-off angles are generally used for long-haul communications; high take-off angles are used for shorter-range communications.

The orientation of an antenna with respect to the ground determines its *polarization.* Most HF antennas are either vertically or horizontally polarized. A vertically polarized antenna produces low take-off angles and is therefore suitable for ground waves and for long-haul sky wave links. The main drawback of vertical antennas is their sensitivity to ground conductivity and locally generated noise. It is necessary to use a grounding screen to get the best results.

A horizontally polarized antenna radiates the higher take-off angles and is suitable for shorter range communications, out to about 400 miles. By adjusting the height of the antenna above ground, it is possible to increase gain at lower take-off angles for longer-range sky wave performance. Horizontally polarized antennas are largely independent of ground conductivity, and are less affected by local noise than vertical antennas.

For ground wave propagation, the transmitting and receiving antennas should have the same polarization for best results. For sky wave propagation, the polarization of the antennas need not be the same, since the polarization of the signal will change during ionospheric refraction.

A3-4.2 Types of antennas

There is a countless variety of antennas used in HF communication. We'll focus here on just some of the more common types.

The *vertical whip* antenna is usually adequate for ground wave circuits, since it is *omnidirectional*, has low take-off angles, and is vertically polarized. A typical vertical whip radiation pattern is shown in Figure A3-4. A reflector, consisting of a second vertical whip, can add directivity to the radiation pattern of a whip.

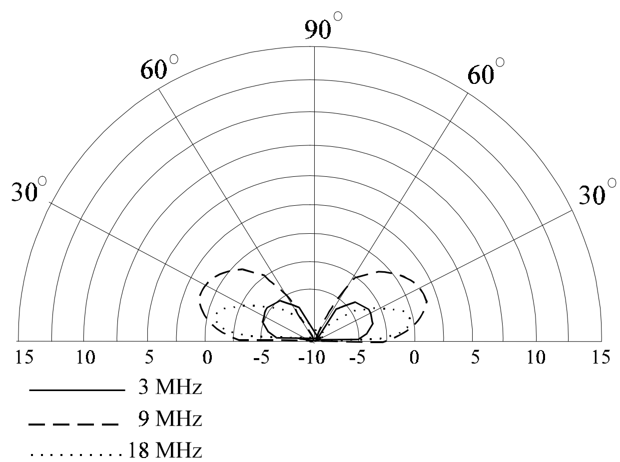


FIGURE A3-4
A typical vertical whip radiation pattern

One of the most versatile types of HF antenna is the half-wave *dipole*, which is basically a length of wire equal to one-half the transmitting wavelength. The dipole can be oriented to provide either horizontal or vertical (center-fed) polarization. Figure A3-5 shows a center-fed horizontal dipole antenna. The radiation pattern can change dramatically as a function of its distance above the ground Figure A3-6 shows the vertical radiation pattern of a horizontal dipole for several values of its height (in terms of transmitting wavelength) above the ground.

A vertical dipole can often be used effectively on ships or vehicles. An inverted vee (sometimes called a "drooping dipole") produces a combination of horizontal and vertical radiation with omnidirectional coverage. See Figure A3-7.

Directional antennas range from simple single-wire configuration like the inverted vee to elaborate multi-wire arrays, including horizontal and vertical log periodic systems; see Figure A3-8. Directional antennas are often used in point-to-point links. In systems requiring point-to-point communications to widely dispersed stations, rotatable directional antennas may be used.

Skywave communications between relatively closely spaced stations may require antennas specially designed for this purpose. These near vertical incidences sky wave (*NVIS)* antennas have a very high take-off angle, radiating rf energy nearly straight up. The radio waves refract downward to the earth in a circular pattern. NVIS antennas provide omnidirectional coverage out to about 600 km.

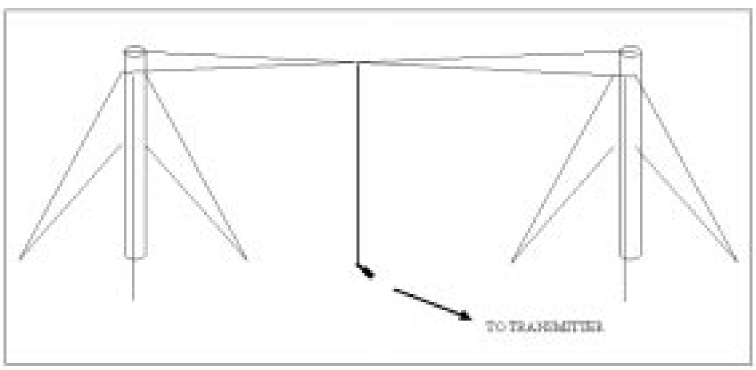


Figure 3-5. Center-Fed Horizontal Dipole Antenna

FIGURE A3-7
Center-fed horizontal dipole antenna

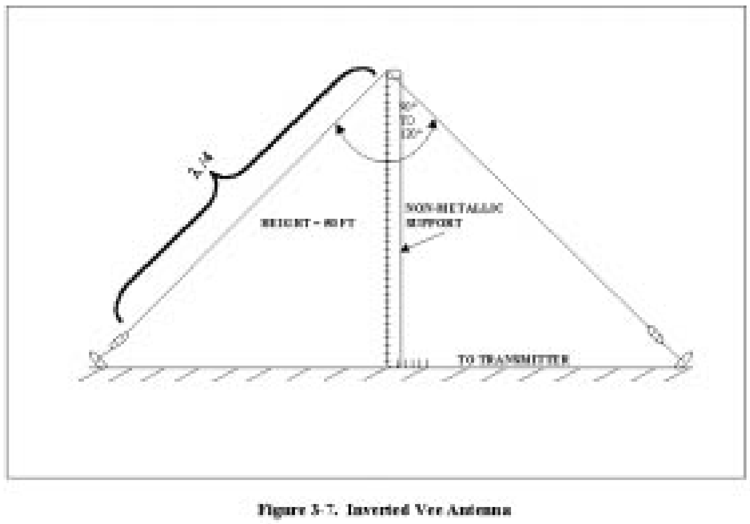


FIGURE A3-7
Inverted Vee antenna

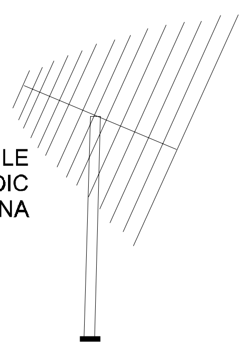


FIGURE A3-8
Horizontal log-periodic antenna

A3-5 Summary

- A radio system consists of a transmitter, receiver, and antenna group.
- The transmitter group consists of an exciter and power amplifier. The exciter includes a modulator, carrier generator, and frequency translator.
- The receiver group consists of an RF input filter/amplifier, frequency converters/IF amplifiers, demodulator, and local oscillator.
- Antenna selection is critical to successful HF communications. Antenna types include vertical whip, dipole, and directional.
- An antenna coupler matches the impedance of the antenna to that of the transmitter, transferring maximum power to the antenna.
- The gain of an antenna is a measure of its directivity — its ability to focus the energy it radiates in a particular direction.
- Antenna radiation patterns are characterized by nulls (areas of weak radiation) and lobes (areas of strong radiation).
- Low antenna take-off angles are generally used for long-haul communications; high take-off angles are used for shorter-range communications.

ANNEX 4
EXAMPLES OF HF ALE RADIO NETWORKS

A4-1 Introduction

This section contains examples of actual working, large-size networks to illustrate the variety of uses HF ALE radio serves each day. The examples are as follows:

1. The Air Force - *HF Global Communications System Air/Ground/Air Network.* This network was begun as a standardization project with the goal to develop standardized calling procedures throughout all DoD agencies. Later this network is scheduled to become a integral part of the Air Force's communication system.
2. A second example network is associated with the organization known as *Shares*. This organization is volunteer association of radio amateurs, private companies, and government agencies that have a common goal to developed a HF radio network that will serve as a backbone communication link in times of emergency. This network is a true test of the interoperability of equipment since all equipment is owned by the participants and varies greatly in brand and operation.
3. The U.S. Federal Emergency Management Agency (FEMA) has developed the *FEMA National Radio System (FNARS)* radio network. This network is another example of a emergency preparedness network that becomes significantly important in case of a national emergency. This network uses, in addition to its own extensive equipment base, all possible residual communications capacity that may be available during emergencies, it is planned to accommodate the vast resources associated with radio amateurs, including RACES and the Military Affiliated Radio System (MARS). Again this FEMA network can be said to be a true test of interoperability standards for radio equipment, operation, and addressing.
4. A fourth example would be the U.S. Customs Service's *Customs Over-the-Horizon Network (COTHEN)*. The Customs Service with military and civilian law-enforcement agencies, and in concert with a number of federal governments in the American zone, have developed a communication system which has proven to be useful in the *war on drugs*. This network serves a number of fixed and mobile users as they attempt to communicate with fellow officers and base stations engaged in law enforcement duties.

The important attributes that make these networks good examples are:

1. Diversity – These networks use multivendor equipment (rather than building the entire network from equipment supplied by a single vendor).
2. Addressing - A significant item in building a large network is how the network accommodates addressing individual stations within the network. A good addressing scheme contributes to a smoothly functioning network. A poor scheme can lead to difficulties such as interference, missed and delayed calls, *etc*.
3. Mission—The network size, equipment, *etc*. fit the mission of the individual networks.

As we analyze each of these networks we should keep these items in mind.

A4-2 The HF global communications system air/ground/air network

The HF global communications system air/ground/air network is a network established by the Air Force Frequency Management Agency (AFFMA) for use by the National Command Authority (NCA), the DoD, Federal Departments, and Allied users equipped with HF ALE radio technology in support of Command and Control (C2) between aircraft/ships and associated ground stations.[HFALECoO, 1996]

The Federal Telecommunications Standards Committee (FTSC) tasked the AFFMA to develop a Federal HF ALE Concept of Operations (CONOPS) to be used in the development of a Federal Standard for HF ALE addressing. The purpose of the CONOPS document is to provide standardized operational instructions for DoD users of HF ALE networks and to provide interoperability between users. Standardized procedures for addressing protocols, ALE sounding rates, and management are all essential to ensure interoperability throughout DoD. [HFALECoO, 1996]

The AFFMA is tasked by HQ USAF to develop initial operating procedures to include addressing protocols, sounding rates, and all technical parameters that affect interoperability for USAF HF ALE Networks. The AFFMA, acting in concert with members of the working groups, is developing and using the Interim A/G/A network to do the following:

1. develop procedures that will ensure interoperability between DoD HF ALE users,
2. establish a training and testing environment for HF ALE users,
3. establish operational procedures that will ensure interoperability with other Federal agencies and connectivity to and from National Command Authority,
4. develop experience and generate an operational database for introducing HF ALE radio operations into the DoD.

HF ALE users of the HF Global Communications System Network must use the addressing protocol procedures developed in the CONOPS to communicate with Global HF stations. As a minimum, each agency must appoint an HF ALE network manager who will work with AFFMA to ensure that scan lists, ALE address elements, and equipment parameters are standardized. The HF ALE Network Manager shall build and maintain a database of all their HF ALE stations, their configurations, ALE addresses, frequency lists, and system parameters. The manager must build databases and disseminate this information to all agencies supporting mission operation. The manager must work closely with frequency managers and their agency's tasking offices in order to build HF ALE networks. [HFALECoO, 1996]

The interim network will be operated in a "live test" manner until the USAF declares the network as "operational". Once the USAF declares the network operational, only aircraft/ships of the United States, Allies, and authorized ground stations will be permitted to operate routinely in the network. When the network is declared to be in an "operational" status, the previous unofficial

Global HF A/G/A Network may then move to the **HF Global Communications System Point-To-Point US&P Network.** The US&P Network is designated as the "National Emergency/Contingency Network." A Federal entity or the Director of SHARES Network, acting upon proper authority and in response to a national emergency, contingency, or disaster, may declare this network to be for "official use only" and may exercise network control. All Federal departments and civil organizations participating in the situation should designate one or more of their HF ALE stations to represent their department or organization. [HFALECoO, 1996]

A4-3 SHARES.

The SHARES network, whose name stands for *Shared Resources*, was developed in a program sponsored by the National Communication System (NCS) to provide backup capability to the Federal government to pass/exchange emergency information. SHARES uses existing HF assets, including radio amateurs, to extend HF coverage for all Federal agencies. Purposes of SHARES include: 1. enduring backup to vulnerable leased systems, 2. providing for extended HF coverage for use by all agencies, 3. providing the flagword SHARES to identify critical message traffic, 4. standardizing framework for operational procedures and message formatting, and 5. providing for a "work around" for jamming by providing more frequency availability to circumvent a threat. Participation in SHARES is open to all Federal agencies, and the responsibilities include the maintenance of a SHARES Directory, and participation in readiness training exercises. [Goodman, 1992]

A4-4 FEMA National Radio System (FNARS)

The FNARS Radio system came into being under a U.S. Presidential mandate (*viz*., Executive Order 12742). FNARS is an Single Side Band (SSB) radio system that can transmit both voice and data, and that has the capability to operate in both secure and non-secure modes. The system must be interoperable with HF radio systems utilized by state and local public safety/health networks such as the FEMA Switched Network (FSN), and the Mobile Air Transportable Telecommunications System (MATTS). Also, in order to exploit all possible residual communications capacity which may be available during emergencies, it is planned to accommodate the vast resources associated with radio amateurs, including Radio Amateur Civil Emergency Services (RACES) and the Military Affiliated Radio System (MARS). [Goodman, 1992]

The FNARS network architecture is hierarchical in nature. FEMA manages, operates, and maintains the FNARS network, which consists of systems located in Washington, DC, (Headquarters); Sperryville, VA; 10 Federal/Regional Centers, and 59 State/Territory Emergency Operation Centers. During emergency and crisis situations, all of these specified sites will be interconnected. Additional connectivity will be achieved with the Armed Services, the Coast Guard, and local communication centers (*viz*., police, fire departments, hospitals, *etc*.). FNARS transmitter power ratings range from 1 kW to 10 kW.[Goodman, 1992]

Figure A4-1 shows all of the stations in the highest level of the network (*i.e*., from the special facility headquarters to each regional headquarters). Then, as an example of the second level of networking, this figure shows an expansion of one of 10 FEMA Federal Regions. We have shown the nodes and branches associated with Region VIII. [FEMA, 1993] Other first-level nodes have a similar fan-out configuration, but to preserve simplicity on this diagram, they are not shown here.

FNARS radios will include both fixed site and mobile versions, and will have ALE capabilities incorporating LQA and preset scanning. Users of the system will be able to make selective calls (*i.e.*, individual or group) and broadcasts. [Goodman, 1992]

A4-5 Customs Over-the-Horizon Network (COTHEN)

The U.S. Customs Service, together with military and civilian law enforcement agencies, and in concert with a number of federal governments in the American zone, have developed a communication system which has proven to be useful in the *war on drugs*. The system includes the Over-The-Horizon Network or COTHEN. [Goodman, 1992] The communications capabilities of this network includes a network of HF SSB radios (*i.e.*, approximately 18 bases and 60 remote units) possessing ALE and Selective Calling (selcall) capability. The system also uses a gateway to enter a larger, mother network, the ATLAS Network. The network is a good example of the capabilities of HF ALE radio since many of the remote radio systems must be operated at the same time the operator is piloting a vehicle (boat, truck, auto, *etc*.), thus the radio must be capable of doing the procedural HF tuning allowing hands-free operation.

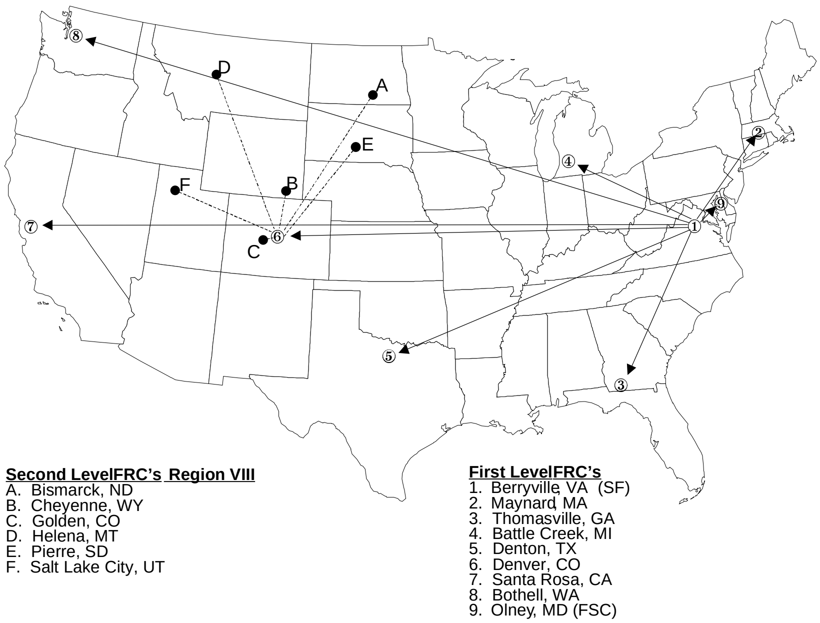


FIGURE A4-1

FNARS HF radio network with expansion for Region VIII

ANNEX 5
LINKING PROTECTION FOR HF ALE RADIO NETWORKS

High Frequency (HF) radio communication has been important to the radio communicator for many decades. Automatic Link Establishment (ALE) is a modern addition to HF communication that is benefiting operators with ease of use. The HF ALE radio has added the automation of the connectivity or linking process to reduce the workload of the typical operator. HF ALE Radios have the ability to selectively call and link with one or more similarly equipped stations via the HF range of frequencies. Link establishment is the ability of an HF radio station to make contact, or to initiate a circuit between itself and another radio station, without operator assistance and usually under processor control. This feature has made the connectivity process more reliable and in some cases, links are made that formerly might have been impossible for the typical operator. All this automation has come with a small but sometimes troublesome price to pay. ALE automation has added *vulnerability of the station to disruption* as a possible cause of operational interference. This disruption can be by adversaries such as pranksters and other hostile parties. Linking protection (LP) is an optional feature that can be added to HF ALE radios to reduce or eliminate the threat that can be introduced by unauthorized users.

Data link sublayers

The FED-STD-1045A (1993) data link layer comprises three sublayers: (a) a lower sublayer concerned with error correction and detection (FEC sublayer), (b) an upper sublayer containing the ALE protocol (ALE sublayer), and (c) an optional protection sublayer between these FEC and ALE sublayers, as shown on Figure A5-1. In the FEC sublayer, redundancy with majority voting, interleaving, de-interleaving, and Golay coding (encoding, decoding) are applied to the 24-bit ALE words that constitute the (FEC sublayer) service-data-unit, in terms of the OSI Reference Model. The ALE sublayer includes protocols for link establishment, data communications, network management, and LQA, based on the capability of exchanging ALE words. Linking protection (LP) is placed in the intermediate "protection" sublayer, so that it may make full use of the error correcting power of the FEC sublayer while intercepting unauthorized attempts to communicate with the local ALE protocol entity to establish links (FED-STD-1049/1, 1993).

Linking protection

Linking protection (LP) is intended to prevent the establishment of unauthorized links or the unauthorized manipulation of legitimate links, and does this through an authentication process. Block diagrams of the data flow through unprotected and protected radios are shown on Figure 2. The blocks on the figure represent logical operations only, and do not necessarily represent distinct hardware modules. LP is achieved by scrambling ALE words under a private key which is changed at daily or longer intervals, and by using known "randomization" information (frequency, time, date, etc.) to vary the scrambled ALE words on a shorter basis (a "protection interval" or PI). The private key is entered directly into the scrambler via an appropriately protected circuit, and is protected during use by the design of the scrambler. The addition of LP to a radio involves adding the functions of a linking protection control module (LPCM), which implements the LP protocol, and a scrambler, which scrambles ALE words under the control of the LPCM. The security of the system is based upon the inability of an adversary to "spoof" the LPCM, and relies on the difficulty of discovering the key used to scramble the ALE words. Because of the wide range of applications for LP, several different scramblers are specified, but the LPCM is common to all LP applications, and includes a common denominator scrambler for assured interoperability of all protected radios. Note that the LPCM handles unclassified ALE words only (though these may be sensitive orderwire commands). Any classified traffic must be encrypted by a higher level cryptographic device. The resulting BLACK data may then be sent through the ALE controller or via a separate data modem (FED-STD-1049/1, 1993).

Protocol transparency

A principal consideration in implementing LP is that the presence of an LP module in a radio (or its controller) should have no impact on any protocols outside of the protection sublayer in the data link layer. In particular, this means that achieving and maintaining LP sync must occur transparently to the ALE waveform and protocols, and that scanning radios must be able to acquire LP sync at any point in the scanning call portion of a protected transmission if this transmission was scrambled under the key in use by the receiving station. Thus, LP modules may not insert sync bits into the data stream, and must acquire LP sync without the use of synchronization preambles or message indicator bits (FED-STD-1049/1, 1993).

Transmit processing

The LP module, in a sending station, scrambles each 24-bit ALE word to be sent using the seed data then in use (frequency, PI number, word number, etc.) and delivers the scrambled word to the FEC module (FED-STD-1049/1, 1993).

Receive processing

The receiver side of an LP module is responsible for achieving LP sync with transmitting stations, and for descrambling protected ALE words produced by the Golay decoder. In operation, when a scanning receiver arrives on a channel carrying valid tones and timing, the FEC sublayer (majority voter, de-interleaver, and Golay decoder) will process the output of the ALE modem and alert the LP receive module when an acceptable candidate word has been received. This occurs roughly once every 8 ms when the Golay decoders are correcting three errors or once every 78 ms when correcting one error per Golay word. The receive LP module must then descramble the candidate word and pass it to the receive ALE module, which will determine whether word sync has been achieved by checking for acceptable preamble and American Standard Code for Information Interchange (ASCII) subset. This task is complicated by the possibility that the received word (even if properly aligned) may have been scrambled using a different PI than that current at the receiver, requiring the receiving LP module to descramble each candidate word under several seeds. A further complication is the possibility, though small, that a word may satisfy the preamble and character set checks under multiple seeds. When that occurs, the valid successors to all seeds which produced valid words are used to descramble the next word and each result is evaluated in the context of the corresponding first word. The probability is extremely small that multiple PI possibilities will exist after this second word is checked. For example, if during a scanning call (or sound), a received word descrambles to TO SAM using seed **A**, and to DATA SNV using seed **B**, the next word is descrambled using the successors to those seeds, such as **A'** and **B'**. If the result of descrambling this next word under **A'** is not TO SAM, the first descrambling under seed **A** was invalid since the word following a TO word in a scanning call must be the same TO word. To be valid in a scanning call or sound, a word following DATA SNV must have three basic 38-ASCII subset characters (FED-STD-1045) and a THRU, REPEAT, THIS IS, or THIS WAS preamble (FED-STD-1049/1, 1993).

Time of day synchronization

Because LP employs protection intervals which are time-based, all stations must maintain accurate time of day (TOD) clocks. Practical considerations suggest that station local times may differ by significant fractions of a minute unless some means is employed to maintain tighter synchronization. Because the effectiveness of LP increases as the length of the PI decreases, there is a trade-off between security (or protection) and the cost of implementing and employing a time synchronization protocol. The approach taken here is to rely on operators to get station times synchronized to a common time source within one minute (± 30 seconds), and then to employ a protocol to synchronize stations to within one or two seconds (fine sync) for full linking protection. While it is possible to operate networks with only coarse (one-minute) time synchronization, this reduces the protection offered by this system against playback (tape recorder) attacks. Synchronization of local times for LP requires some cooperation between the protocol entity and the LP time base. For this reason, the LP module, which already has access to the time base for its normal operations, may appear to be the logical entity to execute the synchronization protocols, although these protocols are logically at a higher level in the protocol stack than the LP procedure. In this case, the LP module would need to examine the contents of received transmissions to extract relevant message sections. If, instead, the synchronization protocols are executed by the ALE entity, the division of function by level of abstraction is cleaner. One concept of how the coordination across the ALE-LP sublayer boundary may be effected in this case is as follows.

a. The transmit ALE entity informs the transmit LP entity of the anticipated time that each transmission will start, so that an appropriate seed will be used for LP.

b. The receive ALE entity informs the receive LP entity of the LP levels and key(s) valid on the current channel, and what combination of fine sync, coarse sync and non-protected transmissions are to be accepted. The first word of a new transmission delivered by the LP entity to the ALE entity is tagged to indicate the LP level, key, and sync mode used to descramble it.

c. For authentication of clear mode time exchanges, the ALE module must be able to call upon the LP module to scramble and descramble individual ALE words "off line."

d. The ALE module must have access to the LP time and time uncertainty values. This time may be kept in the ALE entity, but it must always be available to the LP module (FED-STD-1049/1, 1993).

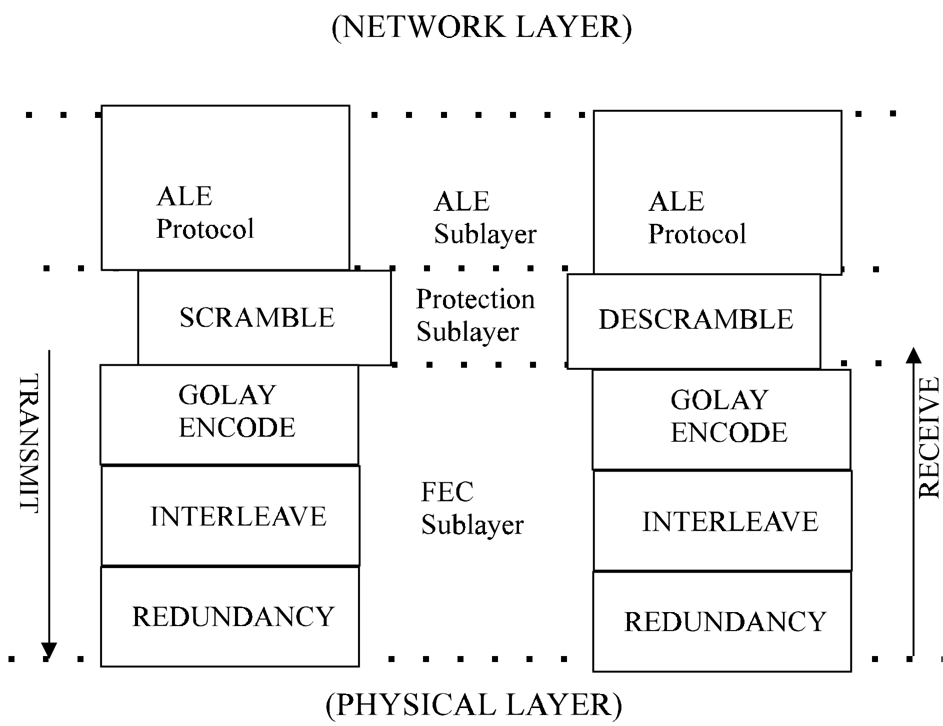
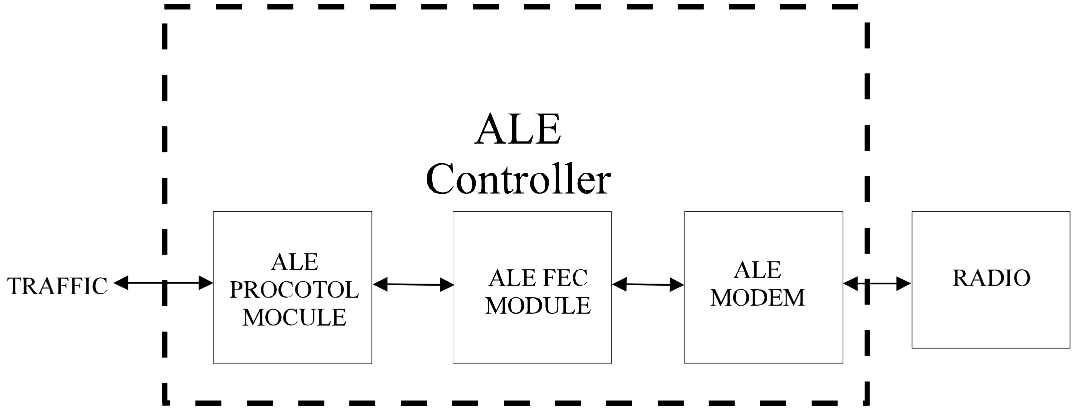
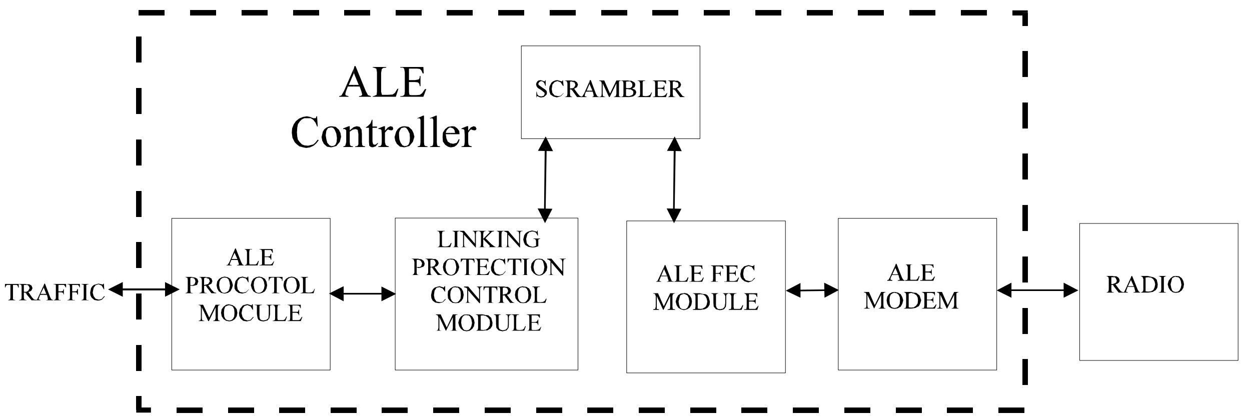


FIGURE A5-1

Conceptual model of data link layer protocols in FED-STD-1045



A. DATA FLOW IN A RADIO WITHOUT LINKING PROTECTION



B. DATA FLOW IN A PROTECTED RADIO

FIGURE A5-2

Data flow in a system without and with linking protection

ANNEX 6
HF E-MAIL

A6-1 Introduction

This annex describes "Battle Force Electronic Mail" (e-mail) that is in widespread use within the United States Navy for administrative and logistics messaging, formerly transmitted via satellite. The standard described here is used for U.S. Navy e-mail communications by approximately 50 ships and with approximately 100 Corps of Engineers stations established by DISA.

This BF e-mail system grew from a Navy modification of e-mail for use in HF radio ground-wave propagation paths between ships in a battle group (an aircraft carrier and as many as 20 ships within a defined area), hence the name: *Battle Force Electronic Mail*. This e-mail system has a gateway capability for connection with the Internet. Security concerns associated with such connections are addressed by the Navy's use of a crypto system with e-mail transmissions. The Internet connection allows Navy personnel at sea to use e-mail to communicate with their families at home via AOL and other ISPs (Internet Service Providers).

A6-1.1 System description—general

This section describes the general operating protocols and parameters required to support the Battle Force (BF) e-mail system operation. Features supported by the system include: user-friendly menu-driven client operation, the ability to transfer imagery as well as text messages, error-free file delivery via an ARQ protocol, message return receipt acknowledgment and minimal operator intervention.

The BF e-mail system was intended for use in a half-duplex network configuration over HF ground-wave distances, but it will support skywave long-haul exchanges with proper frequency and data rate selection. System performance has been tested over VHF and UHF line-of-sight (LOS) channels, UHF DAMA satellite channels, cellular channels and land-line telephone connections. The basic shipboard system installation supports HF and UHF LOS channels. The system supports data rates up to 2400 bits per second (b/s) coded.

HF channel selection should be based on surface wave (ground wave) and Near Vertical Incidence Skywave (NVIS) propagation modes. These modes propagate most efficiently in the 2-10 MHz frequency range.

The basic operation of the BF e-mail system simply consists of preparing messages on a client PC using the Eudora® mail software program, transferring them to a server for transmission, and retrieving new mail from the server. The server acts as the HF equipment controller and electronic "mailbox" as it stores messages intended for off-ship delivery and receives messages delivered from other ships. The synchronous board provides the control signals required to key and unkey the transmitter and initiate modem and crypto synchronization preambles.

A6-2 System components

The levels of the ISO 7-layer model accommodating the various elements of this e-mail system are shown in Figure A6-1.

7 APPLICATION	Eudora Pro mailer
6 PRESENTATION	SMTP
5 SESSION	JNOS Session Mgr (multi-tasking)
4 TRANSPORT	TCP
3 NETWORK	IP
2 DATA LINK	AX.25 (HDLC)
1 PHYSICAL	MIL 110A modem

FIGURE A6-1
The ISO 7-layer model as it relates to BF e-mail

A6-2.1 Computer hardware

Variations of the systems computer configurations exist. Currently, the server and client PC's are Pentium 100 MHz PC's with 8 MB RAM and 1.44 MB 3-1/2" floppy drive. They each have an Ethernet board, two communications ports (COM 1 and 2) and one parallel port (LPT1). However, the server/client combined PC consists of a single 100 MHz Pentium "lunchbox" PC with 8-MB RAM, one synchronous board, two Ethernet boards, two communications ports (COM 1 and 2) and a parallel 1 (LPT1) port. The server and client Ethernet boards are connected via coaxial cable with the end points terminated with a 50-ohm terminator.

The server hosts a synchronous communications board for synchronous half-duplex exchanges and uses the two asynchronous communications ports for asynchronous full-duplex exchanges. Thus, it functions as the radio frequency (rf) equipment and gateway controller. The client is used to compose and retrieve e-mail messages.

a. Ethernet Board

(1) 3Com Ethernet boards and driver software are installed in the server and client PC's to allow the computers to communicate and share devices on the network.

(2) Server and client Ethernet boards are normally connected via RG-58 (Thinnet/10BASE2) 50-ohm coaxial cable using BNC connectors.

(3) If the LAN is extended and connected via coaxial cable (Thinnet), the total length of the LAN should not exceed 606 feet and a maximum of 30 client PC's. The end points on the LAN must also be terminated with a 50-ohm terminator.

b. Synchronous Board

(1) A printed circuit board installed on the server PC that provides the system's half-duplex communication functions.

(2) The synchronous board provides the control signals required to key and unkey the transmitter and initiate modem and crypto synchronization preambles.

(3) The synchronous board is connected to the level converter via an RS-232 cable.

A6-2.2 Peripheral equipment

a. Keyboard/Monitor A/B Switch, if installed.

Used to share a single keyboard and monitor between the client and server PC's. (Limited shipboard space is the main reason for sharing a single keyboard and monitor between the two PC's.)

b. Level Converter.

A black box RS-232 to MIL-STD-188-114 synchronous level converter is used for maintaining correct signal levels between the server's synchronous board's RS-232 port and the KG-84C's MIL-STD-188-114 "red" port.

- Provides the capability of a balanced interface to the KG-84C and/or KIV-7 crypto, which permits greater cable distances between the crypto and the server.
- The RS-232 port is configured as a data communications equipment (DCE) and the MIL-188 port is configured as a data terminal equipment (DTE).
- The level converter is usually connected to the KG-84C via the ship's "red" communication patch panel (except in cases of a dedicated KG-84C and/or KIV-7) and directly to the synchronous board, on the server PC.

A6-2.3 Cryptographic Equipment

Provides encryption/decryption for off-ship e-mail communications. Although TSEC/KG-84A and KIV 7 cryptos can be used to support BF e-mail operations, TSEC/KG-84C is the preferred crypto due to its HF synchronous mode and wide availability.

a. TSEC/KG-84C and/or KIV-7

(1) Provides data encryption for rf off-ship half-duplex e-mail communications via the server's synchronous board.

(2) Normally configured 2400 b/s simplex synchronous operation with external clocks.
(3) Uses the HF serial-tone modem's internal clock for timing.
(4) The KG-84C is usually connected to the HF serial-tone modem via the "black" communication patch panel and to the level converter via the "red" communication patch panel. The KIV-7 is connected directly to the HF serial-tone modem.

b. STU-III (Note: Not backward compatible with TSEC/KG-84C or KIV-7)
(1) Provides data encryption for off-ship e-mail communications via landline (telephone), SHF SATCOM, or Battle Group cellular channels.
(2) Configured for 1200-9600 b/s full-duplex asynchronous protocol, using the server's asynchronous serial communication port (COM 2).

A6-2.4 Modem

a. MIL-STD-188-110A HF Serial-Tone Modem
(1) The HF modems used for this effort are the Rockwell-Collins MDM-3001 stand-alone modem.
(2) These HF modems use coding and redundancy techniques that allow the receiving modem to recover the original data in the case of errors caused by hits and fading throughout the HF path.
(3) Provides forward error correction (FEC), bit redundancy, bit interleaving, and is capable of synchronous or asynchronous data transmission at speeds up to 4800 b/s (unencoded).
(4) Uses a phase-shift key (PSK) modulation scheme specifically designed for operation over HF transmission media.
(5) Provides the external clock for the system.
(6) The MDM-3001 HF serial-tone modem is connected to the radio(s) via the transmit and receive switchboards or the Black Analog Switch and to the crypto via the "black" communication patch panel.

b. STU-III modem.
(1) Capable of data rates of 1200-9600 b/s, full-duplex and asynchronous data.
(2) The STU-III modem's DTE port is connected to the server PC's COM 2 (asynchronous) port via a computer serial cable.

- Note: For details of configuration of equipment and software, see the Appendix, "E-mail via a Slip Connection," which is appended to *General Battle Force Electronic Mail System Manual, Ver. 1.0*, January 1997, prepared by Navy Command, Control, and Ocean Surveillance Center Research, Development, Test and Evaluation Division Terrestrial Link Implementation Branch, Code 846,San Diego,CA 92152-5000.

A6-2.5 Shipboard equipment used

a. Communication patch panels - provides circuit interconnections between the level converter, crypto, and HF serial-tone modem.
b. Crypto
c. Transmit and receive switchboards or the black analog switch - provides circuit interconnections between the HF serial-tone modem, transmitters, receivers, and remote equipment.
d. Transmitter and receiver
e. Antenna coupler and antenna
f. Loudspeaker - used for over-the-air (OTA) monitoring.

A6-2.6 Computer software

Common software used on both the server and client PC's and the Server/Client combined PC includes MS-DOS 6.22, Windows for Workgroups, and the 3COM Ethernet LAN Driver (3c5x9) software. MS-DOS is the Disk Operating System (DOS) that acts as an interface between the computer's hardware, the application program(s), and the user. Microsoft Windows for Workgroups is the user interface built on DOS that offers a Graphical User Interface (GUI) for application software. This allows for the use of icons and menus to perform tasks instead of complex commands. The 3COM Ethernet LAN Driver (3c5x9) software activates and controls the computer's network board. It also serves as the connection between the Client PC's application software and the network components.

A6-2.6.1 Unique server PC software

a. JNOS
   (1) JNOS is a network operating system that runs on top of DOS and provides overall control and management of the network.
   (2) JNOS is designed to operate the TCP/IP protocol stack over a variety of interfaces such as Ethernet, serial ports, and packet radio cards.
   (3) It performs TCP/IP traffic management for the PC.
   (4) It allows transfer of single PC mail (via Ethernet) or multi-station mail (via a LAN)
   (5) It allows the computers attached to the local network to communicate with each other and to access remote host servers to communicate with its computers.

b. BERT.
   This is a bit error ratio test (BERT) that runs on the server PC's N: drive and provides testing for:
   - Checking through the crypto to the modem and back **(Modem Loopback)**
   - Checking the circuit locally over-the-air by transmitting a BERT signal and then receiving the same BERT signal back on board via the ship's radio **(RF Loopback).**
   - Checking circuit connectivity between ships/stations **(OTA BERT).**

A6-2.6.2 Unique client PC software

a. TCP/IP networking software.

(1) A program designed to interface Windows with network boards.

(2) Acts as a virtual packet driver wrapper which enables the packet drivers to function correctly within Windows by making sure that packets get directed to the correct network board.

(3) An Application Programming Interface (API) designed to let Windows applications (*i.e.,* Eudora Pro) run over a TCP/IP network.

(4) Facilitates the initial connection through dial-up scripts and then continues to manage the connection for other programs.

b. Eudora PRO by QUALCOMM.

(1) A Microsoft Windows menu-driven e-mail application.

(2) Used to create, modify, send, and receive e-mail messages.

(3) Provides the capability to attach text and binary files to e-mail messages, therefore allowing for text and imagery transfer throughout the net.

(4) Provides for message return-receipt (RR) acknowledgment (ACK).

- This function forces the remote client's server to acknowledge the received message by sending a receipt message back to the originator.

A6-3 BF e-mail addressing scheme

A6-3.1 Addressing scheme

Addressing is the means by which the originator or control station selects the unit to which it is going to send a message. Each ship/unit is assigned a unique Class C Internet Protocol (IP) address. IP addresses are 32-bit binary numbers that contain sufficient information to uniquely identify a network and a specific host on the network, *i.e.,* 205.253.70.1. The first 24 bits will always represent the network portion of the address and the final 8 bits will always represent the host portion of the address. Thus, "205.253.70" would be the Network Address and "1" would be the host on that network. An IP address is assigned to the server and a sub-address is assigned for the client(s) PC's on the ship's LAN.

Note: IP addresses and domain names must not be changed after installation unless the change is requested and coordinated by the ship's/units network manager.

A6-3.2 Server address

An assigned IP address and domain name that identifies a destination.

(1) IP address is a 32-bit, four-part number that uniquely identifies a machine on the network. For example, "205.253.70.1" could be the IP address for USS NAVY SHIP.

(2) Domain Name is an addressing scheme for associating numeric IP addresses into strings of word segments denoting user names and locations. All domain and user names must start with an alphabetic character (numerics are allowed within names). In the case of ships named for individuals, only the last name of the individual will be used. In the case of ships with multiple word names, a hyphen ("-") will replace all spaces between words. For submarines, hull type and number without a space or hyphen will be used. The unique server address name convention used with BF e-mail is associated with the name of the ship/unit. For example, "navy-ship.navy.mil" is the domain name associated with USS NAVY SHIP's IP address.

A6-3.3 Client address

An IP address and domain name associated with the host server's IP address.

(1) Client IP address consists of the first three parts of the host server's IP address, with the fourth part being modified to include an additional number to identify each client PC on that host server. For example, "205.253.70.11" is attached to host server IP address "205.253.70.1".

(2) Clients' sub-address name convention is the SMTP server's POP Account name mail@"shipname".navy.smil.mil. For example, "mail@navy-ship.navy.mil".

A6-3.4 User's address

a. The user address is the login name or user's name associated with the SMTP server's POP3 account. For example, "como@navy-ship.navy.mil".

(1) "Como" is the login name or user's name. Remember, all domain and user names must start with an alphabetic character (numerics are allowed within names).

(2) The @ symbol is the separator between user name or system name and commands domain name.

(3) "navy-ship" refers to the actual name of the command. The "-" (hyphen) symbol is used within all user and ship/mobile activity domain names instead of spaces. Spaces or blanks are not allowed in any part of the user/domain name. The underscore symbol "_" is also not permitted in domain names.

(4) The "." (dot or period) symbol is the separator between elements of the domain name.

(5) "navy" indicates the host computer's (server) domain name.

(6) "mil" indicates the type of organization (*i.e.*, mil, gov, edu, com) of the network.

b. While awaiting X.500 standard address guidance, it is recommended that user names be based upon existing Navy billet names or functions, *e.g.*, xo, ops, como, n00, n3 or cic, radio, flag.

A6-3.5 SMTP gateway

The BF e-mail server onboard the Flagship/Ground Unit Command Post can provide the small ships/unit's in the group with SHF e-mail connectivity to shore by using an existing domain name mail server (previously installed) which handles the SHF connection. The domain name mail server will determine if the message is for onboard LAN delivery or for transmission to a shore secure gateway over super high frequency (SHF) channels.

(1) Messages from ships/units in the battle group destined for shore/headquarters connectivity will be received by the respective BF e-mail server onboard the Flagship/Ground Unit's Command Post via HF or UHF channels and re-routed to the respective shore or unit's headquarter's domain name mail server via the shipboard/ground unit's LAN. The mail server will transmit the messages to the shore net gateway via SHF channels.

(2) Messages from shore/headquarter's destined for ships/units in the battle group will be received by the Flagship/Command Post via SHF and routed by the Flagship's/Command Post, respective domain name mail server. Mail for ships in the battle group will be re-routed to the Flagship's/Command Post's BF e-mail server via the shipboard/unit LAN. The BF e-mail server will, in turn, re-route the messages for transmission over HF or UHF channels to the appropriated ships/units.

(3) Messages from ships/units in the battle group destined for an embarked Flagship or unit command will be received by the BF e-mail server onboard the Flagship/Command Post via HF or UHF channels and re-routed to the domain name mail server via the shipboard/unit's LAN.

A6-4 Basic information flow

The user turns on the client PC, activates the Windows program, and selects the Eudora Pro application program. Once the Eudora Pro program is loaded, the user logs into the e-mail system by typing in the user's password. The password could be the pre-installed password or one supplied by the ship's/unit's LAN coordinator or Automated Data Processing (ADP) officer to meet the commands security requirements. At this point, the user can either create a new message or modify an existing message, send pending messages to the server, and/or check for incoming mail. Eudora provides the capability to attach text and binary files to e-mail messages, therefore allowing for text and imagery transfer throughout the system.

A6-4.1 Sending mail

To send mail, the user composes the message, addresses the message to its appropriate destination and then selects "Send". The message is sent to the server using the Simple Mail Transport Protocol (SMTP) via Ethernet boards that connect the server and client. Messages sent from the client will be stored on the server's hard disk and queued for delivery at a later time.

To send queued mail, the server raises the "Request To Send" (RTS) line on the RS-232 communications port provided by the PC's synchronous board. This keys the transmitter and initiates the modem synchronization preamble transmission. When the modem has completed this 0.6 second transmission, it the provides a "Clear-to-Send" (CTS) back to the crypto causing it to send its synchronization preamble. When the crypto has completed its preamble transmission, it passes the CTS to the server which in turn starts a connection attempt. At this point the server will call up the remote station server to whom the message is addressed. Once an acknowledgment is received, the server will start transmitting the message.

The message goes from the "mailbox" on the server, to the synchronous board, to the level converter, through the "red" communications patch panel (if used), to the KG-84C and/or KIV-7 crypto, through the "black" communications patch panel (if used) to the HF high-speed serial-tone modem. The modem's audio and keyline interface goes to the radio equipment (this connection is made via the Transmit/Receive switchboards or the Black Analog Switch). When the HF radio equipment is online, the server will call the distant station(s), handshake, connect, and start transmitting its mail. If a remote station does not answer, then the sending server will continue to the next station which it has mail for, and will attempt to make a connection. If that station does not respond either, then the server will move on to the next station. A server can receive calls from other stations while it is waiting for a particular remote station to reply.

Ship-to-ship e-mail transfers are performed as point-to-point exchanges. In order to avoid net interference, the server JNOS software monitors the "data carrier detect" (DCD) line provided by the modem. The modem detects transmissions from other units, and inhibits own-ship transmissions until the circuit is clear. This provides signal collision control so that any particular unit will not normally try to establish a link in the middle of an exchange between two other units. If a called unit does not respond, the server will retain the message in its memory and try again later.

A6-4.2 To Receive Mail from a Remote Server

Since the e-mail system operates on a single net frequency, all active units will listen in on e-mail exchanges between the servers on other ships.

Note: A ship's and/or unit's HF modem and KG-84C and/or KIV-7 crypto will synchronize to all incoming transmissions; however, its respective server will not respond to any call which does not include its unique IP address.

The ship's receiver will pick up the signal and interface directly to the HF modem's audio line (this connection is made via the Transmit/Receive switchboards or the black analog switch). The modem and crypto will synchronize to the incoming transmission, and pass it to the server. If the server recognizes its IP address, it will respond to the calling station with an acknowledgement that it is ready to receive mail addressed to it. once the calling server receives the acknowledgement, it will initiate a handshake, connect, and will start transmitting the mail. After the ship's server receives the transmission data, it will acknowledge receipt back to the sending party and will store the mail in its electronic "mailbox" for retrieval by the addressed user via the client.

A6-4.3 Checking for received mail

To receive mail on the client, the user selects "Check Mail" from the file menu on EudoraPro. The client will then link to the server and will retrieve the mail from the server's electronic "mailbox" using the Post Office Protocol 3 (POP3). The user will see a progress window showing the logging in to the server's POP account and retrieval of mail that it finds addressed to the user. The user will then see a message stating that there is new mail or a message stating, "Sorry, you don't have any mail."

A6-5 Testing and Test Results—Summary

In an NTIA report (Redding and McLean, in press, 1998), data are presented that characterize the performance of the subject HF E-mail system in a controlled environment using HF channel simulators. The objective of these tests by Redding and McLean were to evaluate E-mail throughput over degraded HF channels using the JNOS software and configurations similar to those used in the NraD implementation (*i.e.*, as TCP/IP settings, AX.25 card, and HF modem). HF propagation conditions were simulated through the use of a digital signal processor (DSP)-based Watterson model HF channel simulator using degraded conditions defined by the International Telecommunications Union Radiocommunications Sector (ITU-R) Recommendation F.520-2. In the course of testing, optimum settings and anomalies were reported as they affected performance.

There are many variable parameters in the HF e-mail system, but only a few variables were used so as to limit the testing to a reasonable length. Table 1 shows the parameters that were used. For all tests, the MSS, MTU, and compression were fixed while the window, maxwait, and IRTT were varied. Other variables were the HF modem data rate, e-mail attachment size, and channel simulator conditions. Several experimental changes to the MSS, MTU, window, and maxwait were also made to show their affect on the performance.

TABLE 6A-1

Parameters and associated conditions

Parameter	**Set of Conditions**
Channel Conditions	ITU-R Good[1] @ 0-15 dB SNR in 5 dB steps
	ITU-4 Poor[2] @0-25 dB SNR in 5 dB steps
Modem Data Rate	300 bps
	1200 bps
Modem Interleaver Length	0.6 s (short)
Attached Message size	1 kByte text file
	50 kByte text file
TCP/IP: MSS/MTU/Window	216/256/1024
	216/256/3072
TCP/IP maxwait	90 s for 300 bps, 360 s for 1200 bps

[1]ITU-4 Good channel consists of a multipath of 0.5 ms and a doppler spread (fading) of 0.1 Hz
[2]ITU-4 Poor channel consists of a multipath of 2 ms and a doppler spread (fading) of 1 Hz.

The configuration used for this test is shown in Figure A6-2. The JNOS software ran on a PC-compatible computer, which also interfaced to the AX.25 card. Output from the AX.25 card was fed into the HF modem, which was connected back-to-back with another modem via the simulator. The transmit audio paths passed through the independent paths of the simulator, and into the HF modem receive line. Radios were not used because the simulators operate at baseband.

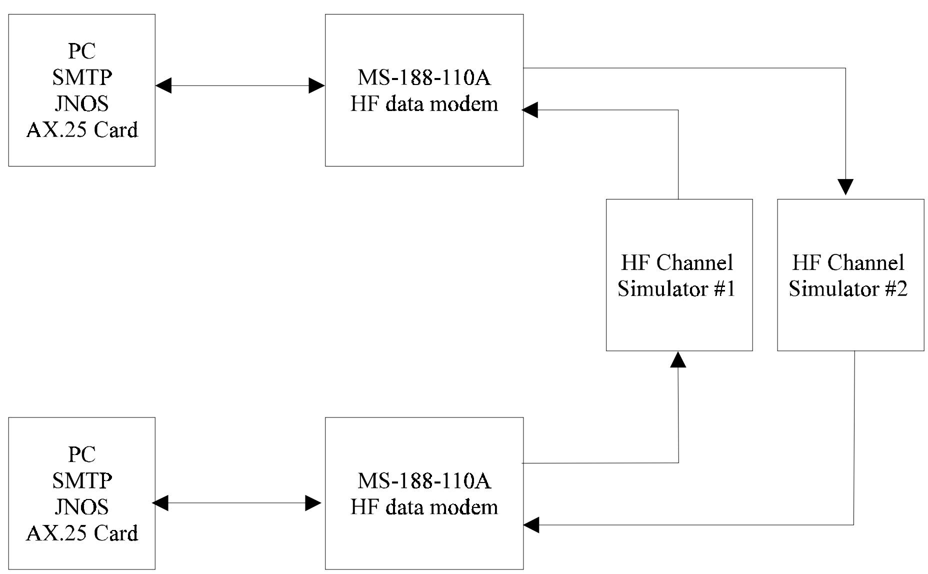


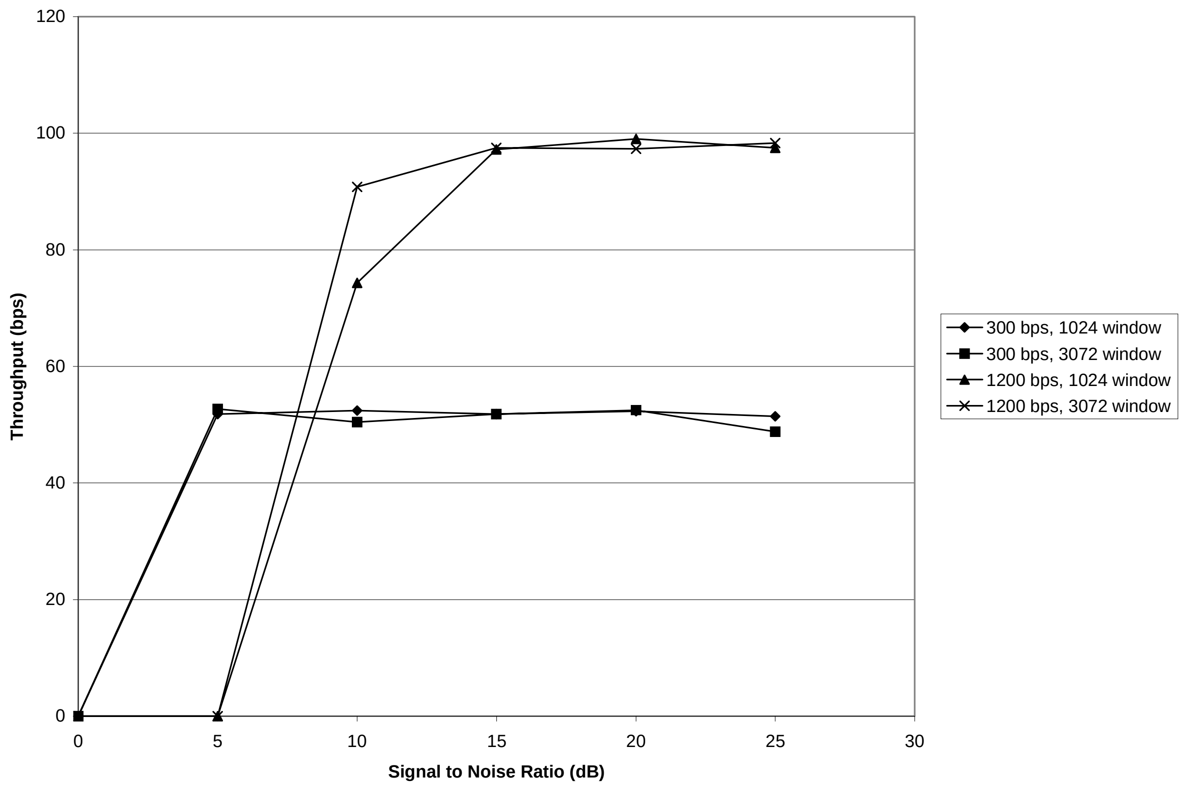
FIGURE A6-2

Configuration used for e-mail tests reported above

A6-5 Test Results

Plots of throughput versus channel conditions all exhibited the same type of pattern, notably: throughput increased from a minimum of 0 bps to a plateau. See Figures A6-3 through A6-6 for an illustration of this pattern. Depending on file size and modem data rate, the plateaus occurred at different maximum data rates and SNRs. Minor differences in throughput occurred as the window varied from 4 times the MTU to 12 times the MTU for a particular modem data rate, indicating that a larger window has no significant affect on performance. In the cases where there is a difference in throughput, the larger window almost always produced the better results. Contributing to the variances was the small number of trials performed.

FIGURE A6-3



Throughput vs. CCIR Good channel with short file attachment

It was observed that as the SNR decreased, a lower data rate was required to pass traffic, as shown by the 75 b/s test performed at 0 dB. This was expected since there is increased error correction coding applied at lower data rates. Conversely, higher modem data rates could be used as the channel SNR increased. This effect occurred with the 3 data rates that were used. The difference in maximum throughput between the 1200 and 2400 b/s data rates was not that significant, although optimization of the data rate should be made if the channel supports higher rates. The test results showed that throughput increased from a minimum of 0 b/s to a data-rate dependent plateau. The knee of the curve moves right, or occurs at a higher SNR, as the data rate increases. Optimization of the data rate versus channel SNR could be accomplished with an adaptive data-rate modem, such as the data link protocol specified in FED-STD-1052.

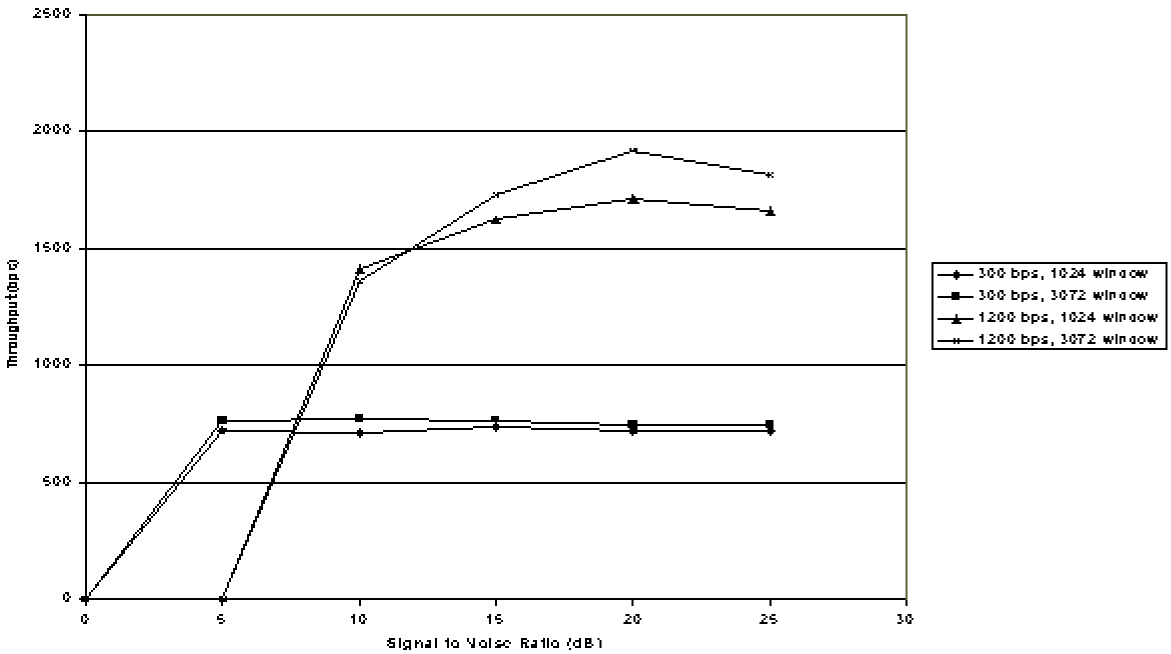


FIGURE A6-4
Throughput vs. CCIR Good channel with long file attachment

Another conclusion of the tests is that users should choose the compression method with regard to the processing power of their computers, since compression is performed in real time. The actual compression level used will be a result of a negotiation between the two stations involved in the transmission. Users should be aware that the JNOS documentation erroneously states that the compact compression is the default. To be sure that the compact compression is being used, autoexec.net should contain the statement "`lzw bits = 16`."

Other than the effect of compression, the tests showed the best performance occurred when a large file attachment was sent. There are two reasons for this result: 1) because the overhead is relatively constant, the ratio of message size to total transmission increases significantly; 2) with longer messages, the TCP window can be used more efficiently, which allows transmission up to the maximum window size before an acknowledgment is expected. Comparing the differences in throughput between the long files and the short files sent shows a 15 to 1 increase in throughput. Although this was not tested, mailers that support SMTP service extensions for command pipelining theoretically would increase throughput since short packets are combined and sent, reducing the number of link turnarounds.

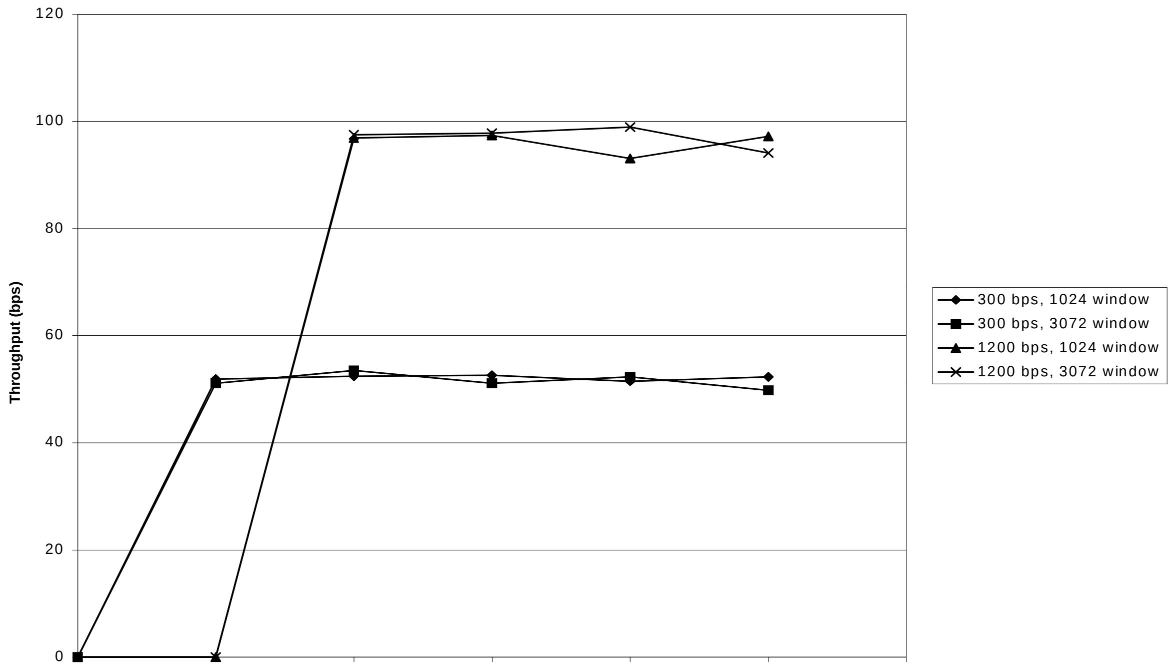


FIGURE A6-5

Throughput vs. CCIR Poor channel with short file attachment

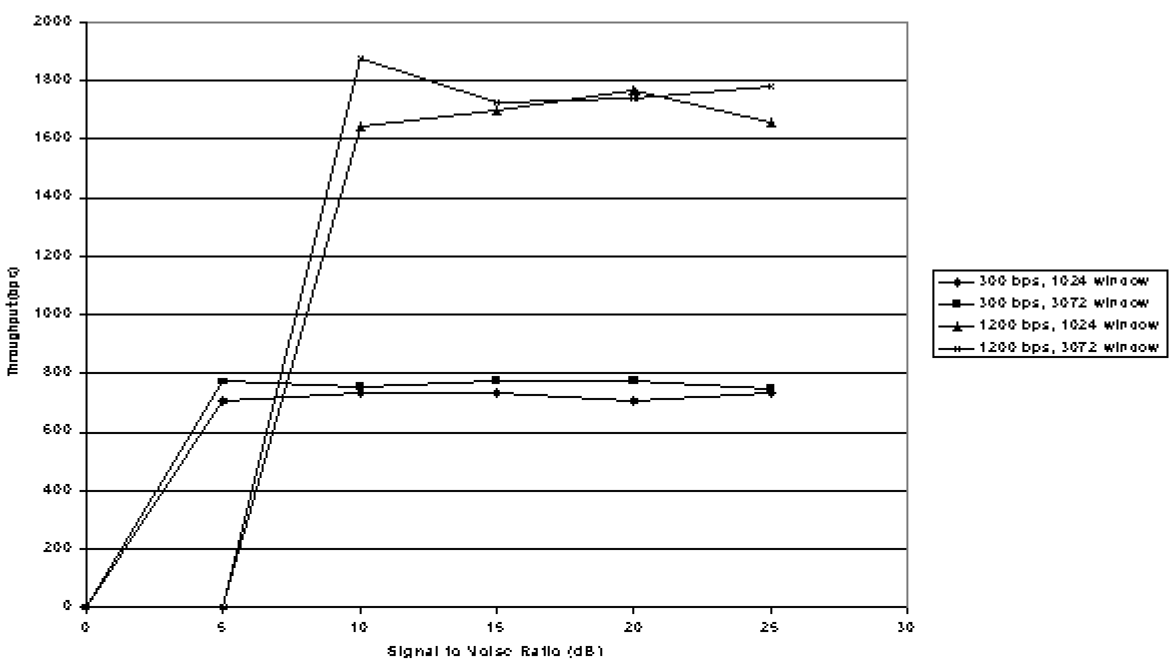


FIGURE A6-6

Throughput vs. CCIR Poor channel with long file attachment

ANNEX 7

HF Radio in the Global Information Infrastructure

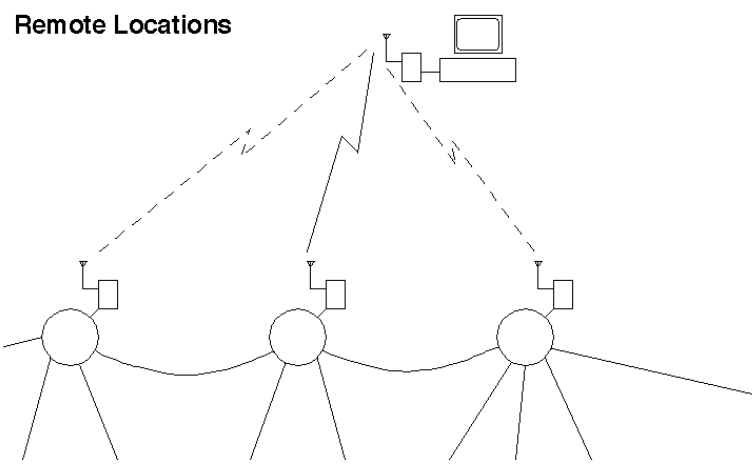
A7-1 Introduction

Advancements in the international information infrastructure daily bring concepts from science fiction into the everyday fabric of society. Only a few years ago, the rapid, asynchronous communication provided by electronic mail became a compelling argument for buying a computer for the home. Today, home computer users contemplate personal “agents” that will nightly scour information sources to produce a customized electronic “newspaper” in time for breakfast.

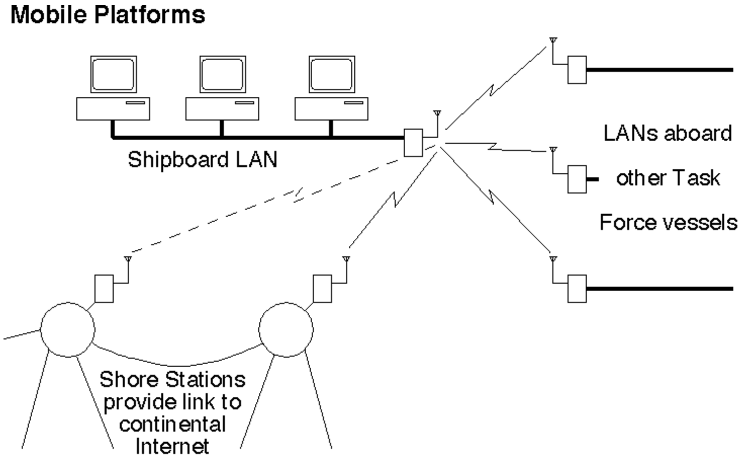
Underlying this explosion in new capabilities is a dense web of networks including the global telephone network and the Internet (the latter relying largely upon the services of the former). However, some communities of potential users of these information resources are not well served by the existing networks. Many of these users could make good use of HF radio technology for “on ramps” to or “bridges” in the “information superhighway.”

Due to the relatively low bandwidth available from HF data channels, however, most scenarios for routing Internet traffic through HF subnetworks involve special circumstances:

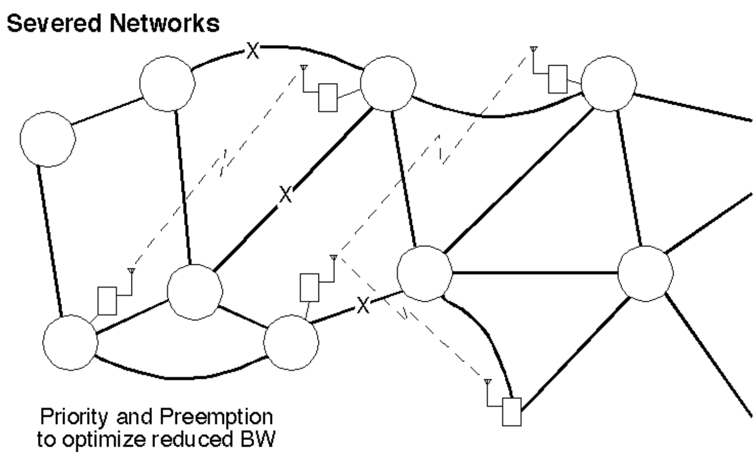
a) *Voice or data to remote locations*. HF is currently in use to provide relatively low-cost voice service to locations too remote for economical landline or line-of-sight radio service. With the addition of modern HF automation, such remote sites can be linked together into HF subnetworks, with multiple gateways into the information infrastructure to improve the robustness of connectivity to these sites.



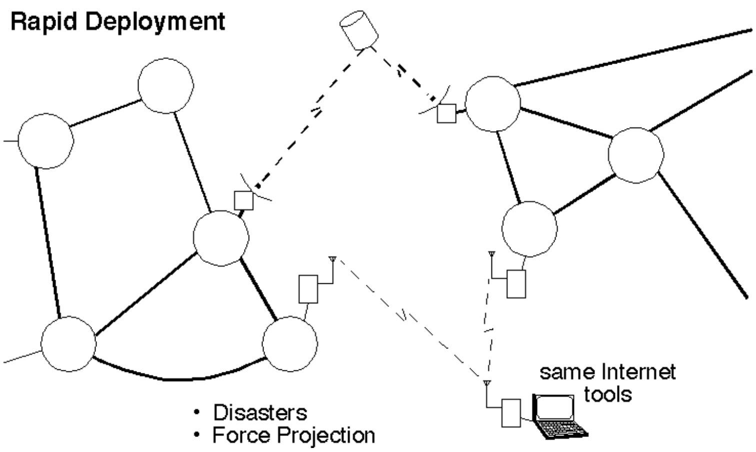
b) *Voice or data to mobile platforms*. For communications to mobile platforms beyond line of sight, HF provides an economical alternative to satellite communications. Automatic Link Establishment (ALE) has been shown to largely alleviate the link-level connectivity problems that formerly plagued HF. Automated HF Node Controllers (HFNCs) will integrate individual voice and data terminals, as well as the networks aboard larger platforms, into the high-bandwidth, low-cost stationary infrastructure. For example, shipboard LANs may be linked within a task force using UHF, VHF, and HF radio (as appropriate for each link), with long-haul trunks carried by an optimized mix of satellite and HF radio.



c) *Emergency connection to severed networks*. Natural or man-made disasters can sever segments of our backbone networks. A backup network of automated HF radio stations can quickly detect and bridge such faults to carry high-precedence traffic into and out of emergency areas. Bandwidth limitations will require priority and preemption mechanisms to optimize use of the HF links.



d) *Connection to rapid deployment networks*. From disaster areas to combat theaters, the transportability, low cost, and long range of HF radio make it a primary quick-response medium. With an automated capability to link HF subnetworks into the Internet, deployed teams can use familiar communication tools such as electronic mail to ease the transition to operations in the field.



A7-2 Joining the Internet

A7-2.1 Compatibility

If HF radio is to be used to transparently extend the information infrastructure to these new user communities, we need to ensure that HF technology is compatible with the assumptions implicit in the Internet architecture. Beginning with the characteristics of HF systems, one of the key aspects of the HF medium that distinguishes it from more popular Internet media is that propagation is highly variable over a wide range of time scales:

- multipath effects on the scale of milliseconds
- fading on the scale of seconds to minutes
- diurnal variation on the scale of hours
- ionospheric disturbances and sunspot activity on the scale of days to years

The unique characteristics of HF technology are largely the results of addressing this challenging environment, including unique modem waveforms, interleavers, and coding for shorter-term variations, and adaptive frequency and antenna selection for the longer-term variations. The ability of automated HF node controllers to rapidly adapt to changing conditions is steadily improving the reliability of HF links (see next section). However, the data rates that can be reliably achieved over long-haul HF skywave channels are substantially lower than those expected over Internet backbones (or even dial-up modem links); this will impose some limits on the functions that can be efficiently performed over HF Internet links, as discussed below.

The architecture of the Internet emphasizes issues at a higher level[1] than those that make HF radio unique. The essence of the Internet is technology which links disparate subnetworks into a seamless network of networks. The key component of this technology is the Internet Protocol (IP) which provides "datagram" service to higher-layer end-to-end protocols. Because datagrams sent via a subnet are not guaranteed to emerge from that network in order, or without duplication (or even to emerge at all), the upper-layer protocols bear the burden of providing a user's expected quality of service. Thus, the existing Internet protocol architecture is already prepared to cope with the vagaries of HF propagation, although some of the assumptions implicit in those protocols do not hold over HF links. For example, the TCP congestion control mechanism

[1] Higher "layer" in terms of the ISO Open Systems Interconnection Reference Model [4].

assumes that packets are lost only as a result of congestion, so TCP will work best with a reliable link protocol.

A7-2.2 Performance limitations

Given that HF networks and the Internet are compatible on this most fundamental level of interoperability, we must examine issues of performance and congestion that arise in HF subnetworks due to the restricted bandwidth of HF links. Although HF modems with data rates of 9600 bps are currently in development, achievable throughput over HF links is currently closer to 1200 bps, an order of magnitude less than the rates achievable over wire-line modems. For example, a pair of 28.8 kbps modems operating within a metropolitan area and using v.42bis data compression may be expected to achieve a user data throughput on the order of 16 kbps for text transfer. HF data modems, operating over a mid-latitude skywave path (Boulder, CO to San Diego, CA, USA) were able to achieve about 1 kbps user data throughput [1].

The data rates required by Internet users vary over several orders of magnitude, depending on the application. Electronic mail (without attachments) typically requires only a few thousand bytes per day, while a World-Wide Web server must sustain data rates of a million bytes per second. Clearly, users of multimedia applications will be disappointed with the throughput of an HF connection to the Internet, while other users may be satisfied. The key to expanding the class of potential satisfied users of HF Internet links is improving the throughput of user data.

Three possible avenues for increasing the usable data bandwidth of HF links are as follows:

- Increase the allocation of HF spectrum per link.
- Improve the data efficiency of the modem (in bits/Hz).
- Increase the information content (reduce redundancy) in the modem bit stream.

The first is beyond the scope of this paper; the second is properly the domain of my esteemed colleague, Stephen Cook [2], which leaves for this paper an evaluation of compressing Internet traffic to improve the response time to users within the constraint of relatively low actual link data rates.

The lower data rates of HF links compared to wireline modems, local-area networks (LANs) and so on, allow more time per channel data bit for compression. Although this increased time will not result in proportional increases in compression, it does allow for somewhat better compression than the high-speed technique commonly used in wireline modems. The figures below illustrate the improvement in compression achievable when increasing computational effort is applied. All are variants of the Lempel-Ziv algorithm. Timings were collected on an IBM RS/6000 model 580 workstation running AIX 3.2.5.

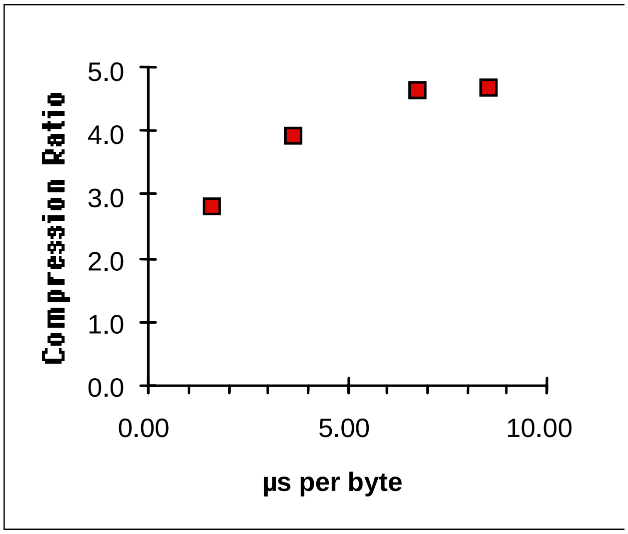


FIGURE A7-1 **Compression of PostScript®**

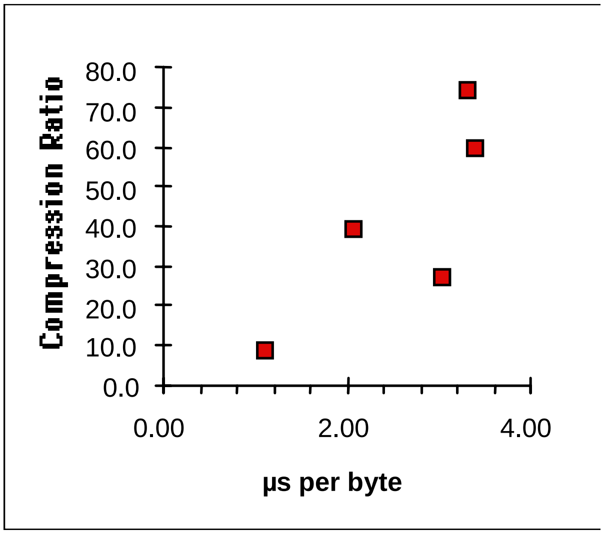


FIGURE A7-2 **Compression of audio (.WAV)**

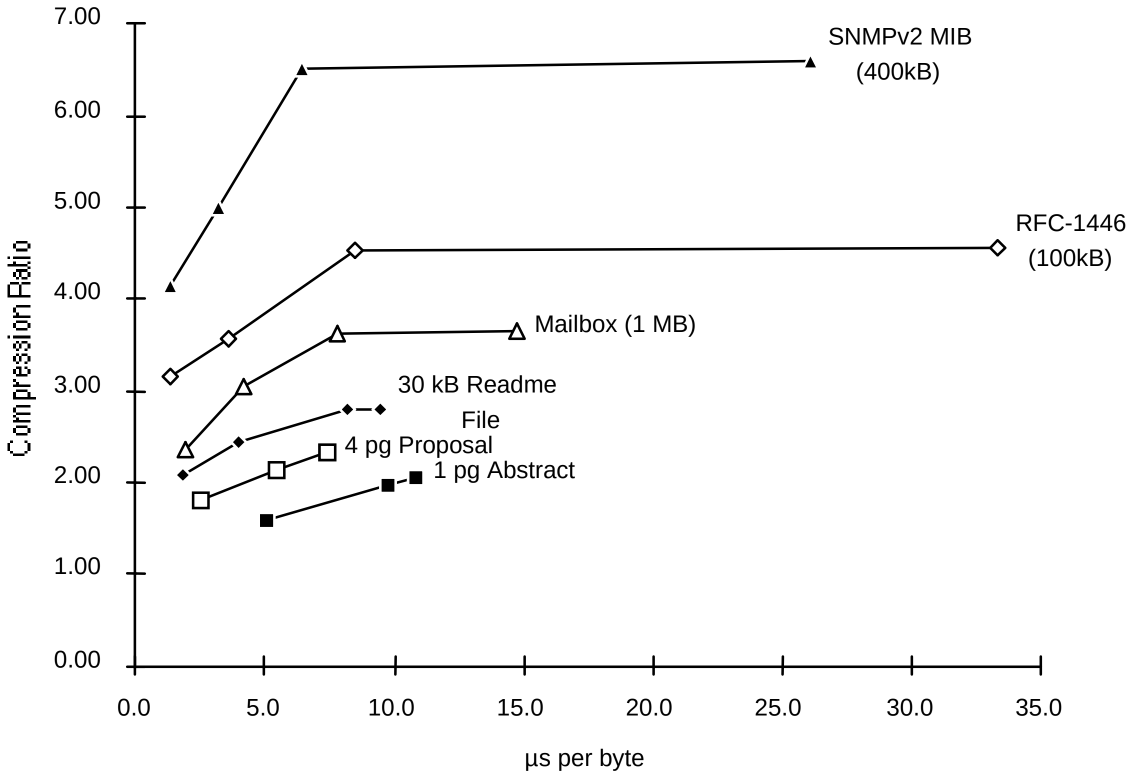


FIGURE A7-3

Compression of text files

The compression of text files (Figure A7-3) is much the same as for PostScript files (Figure A7-1). The lowest compression ratio in every case is achieved by the Lempel-Ziv-Welch (LZW) algorithm, which is widely used (*e.g.*, in GIF files and the Unix compress command) due to its high compression speed. For HF applications, we can achieve 50% better compression by instead using a more aggressive implementation of the Lempel-Ziv algorithm such as that in the gzip utility (which produced the third point in each case in Figure A7-3). Graphic images (GIF) and QuickTime movies (MOV) are stored in a compressed format by default, so no additional compression by networks is usually feasible.

From these compression results, it is apparent that Internet access via HF is most likely to prove satisfactory for applications that are text- or PostScript-based, because the additional compression achievable partially mitigates the lower data rates of HF versus wireline modems. Audio files can also be compressed remarkably well. However, applications that require the transfer of large photo or video files will probably not work well over HF links.

A7-2.3 HF interface to the Internet

One inexpensive technique for connecting an HF subnetwork to the Internet is shown in FigureA7- 4. Here, a desktop computer (labeled "gateway") executes off-the-shelf Internet Protocol software that routes packets among any connected data links. The figure shows both an Ethernet board and an HFNC present in this computer, so it serves as the gateway between all nodes reachable via the Ethernet (probably the entire Internet) and all nodes reachable from the local HF station.

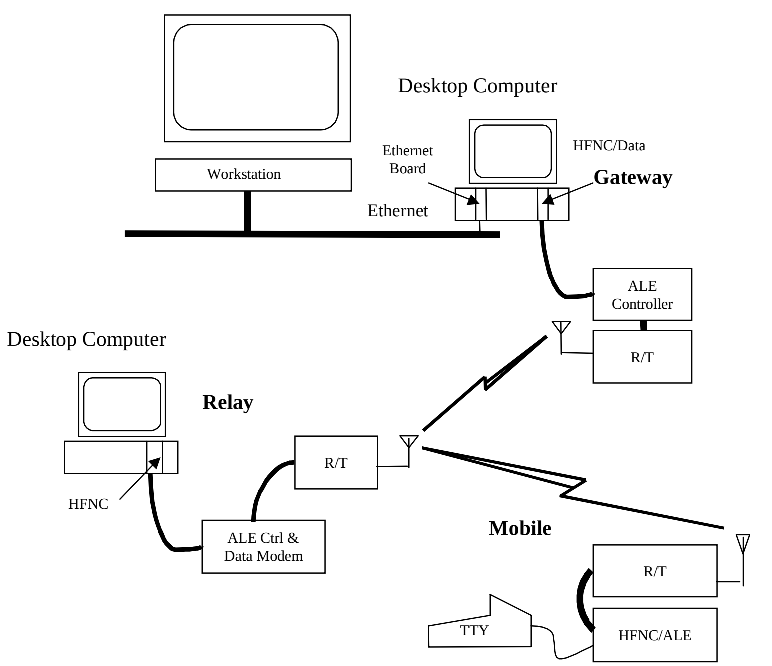


FIGURE A7-4

HF Internet gateway

Although communications with the Mobile station could be direct from the Gateway, a Relay station is shown as an intermediate node in the path to illustrate the capabilities of the new generation of automated HF technology, described in the next section.

A7-3 New standards for HF automation

The United States Department of Defense has recently completed work on a standard suite of technologies to automate the operation and management of HF radio networks, MIL-STD-188-141B[3]. This standard includes a third generation of HF link establishment and ARQ technology, network-layer functions to support routing and topology-monitoring functions, and application-layer functions such as electronic mail and network management.

A7.3.1 HF node controllers

For the purposes of discussion, the network layer [2] functionality of an automated HF station is considered to reside in HF Node Controllers. Figure 5 shows the conceptual organization of the HF automation physical, data link, and network layer functionality, followed by a block diagram of the HFNC in Figure A7-6.

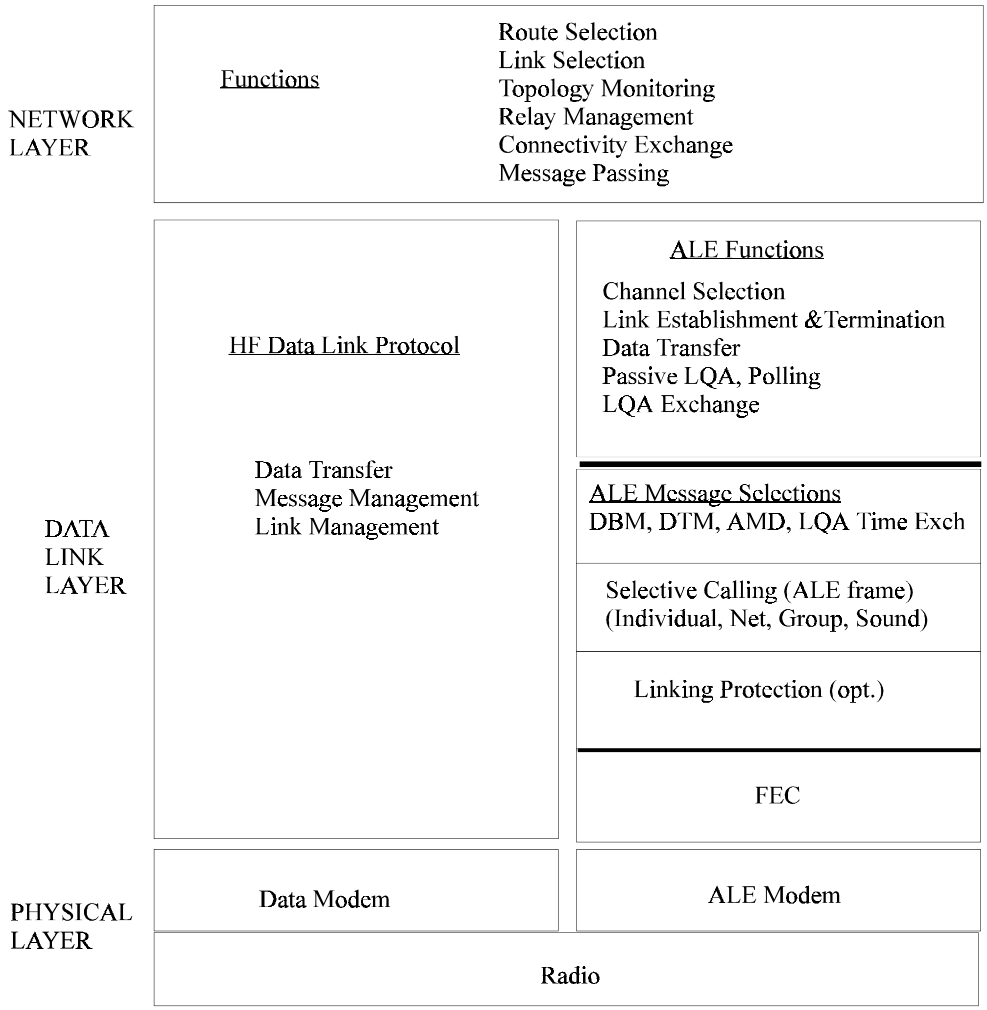


FIGURE A7-5

HF automation overview

In Figure A7-6, "S&F" refers to the Store and Forward function, which is responsible for finding a route through the subnetwork, using relays and other media as necessary. "AME" refers to the Automatic Message Exchange function, which is responsible for conveying messages over each data link in the path through a subnetwork.

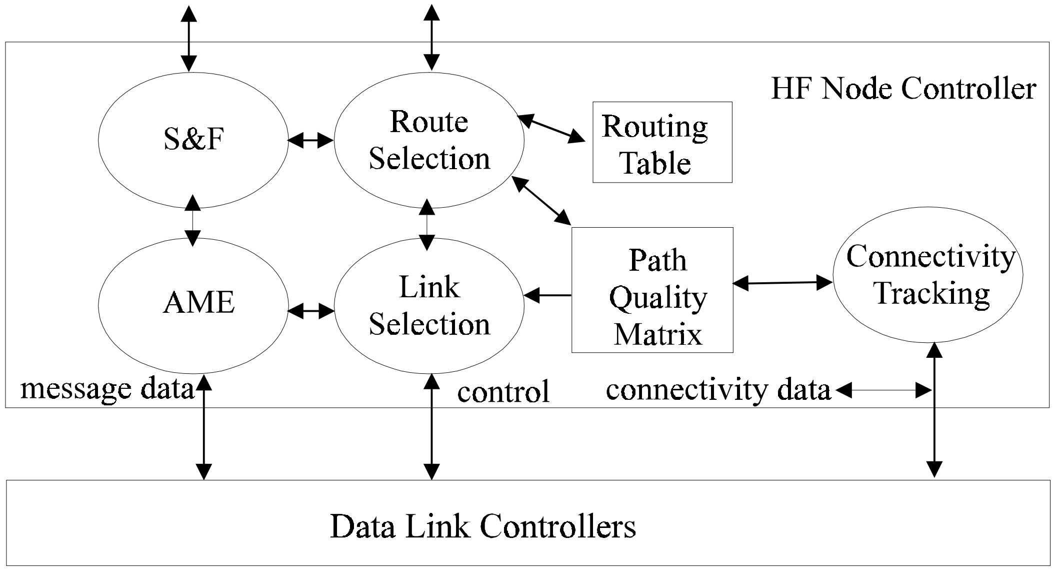


FIGURE A7-6

HF node controller functions

The Routing Table is a listing of previously computed Destination – Next Station pairs for use in routing incoming messages. For each message destination, the Routing Table contains the address of one or more recommended relay stations to use when direct transmission to that destination is not possible. The Path Quality Matrix is a dynamically updated table of aggregate (single- or multi-link) voice and data path qualities to various destinations via the best known paths to those destinations.

MIL-STD-188-141B defines four standard levels of HFNC functional capability [5]:

- A Level 1 HFNC has no Routing Table, Path Quality Matrix, nor Store-and-Forward functionality. It can route messages only to directly-reachable stations. Thus, indirect routing must be generated by an external router, which will explicitly name the next relay station when passing a message to the HFNC for delivery.
- A Level 2 HFNC includes a Routing Table and Store-and-Forward ability, but no Path Quality Matrix. Indirect routing is performed automatically, but the Routing Table will usually be generated externally. In a typical application, a level 2 HFNC would receive its Routing Table from a central network control site, with updates provided either manually by local operators, over the air from the network control station, or from its own connectivity tracking function.
- Store-and-Forward functionality in Level 2 (and higher) HFNCs is supported by connectivity monitoring and routing queries. When connectivity is lost to a station listed in the Routing Table, messages destined for that station are queued until a connection is reestablished. The HFNC can also actively seek new relay stations through the routing query protocol, and post the results to its Routing Table.
- A Level 3 HFNC adds the Path Quality Matrix and the Connectivity Exchange protocol to the Level 2 capabilities. Level 3 controllers discriminate among possible paths for messages using path quality formulas that consider link degradation due to congestion as

well as natural phenomena. Routing decisions thus adapt more quickly in Level 3 HFNCs than in Level 2, because the latter respond only to link loss, while the former can detect a deteriorating link and switch before the link becomes unusable.

- A Level 4 HFNC adds an Internet router to the capabilities of a Level 3 HFNC, and can therefore act as a gateway between HF and other subnetworks.

HF subnetworks in Internet applications will typically employ Level 4 HFNC gateways at interface points between HF and other media, with Level 2 or 3 HFNCs at other stations in the network. Unlike the mesh topologies commonly found in wired wide-area networks (WANs), HF networks will often be hierarchies of star topologies. One possibility is shown in Figure A7-7, in which Level 4 stations serve as hubs of stars of less-capable stations, and are themselves linked into a “backbone” star.

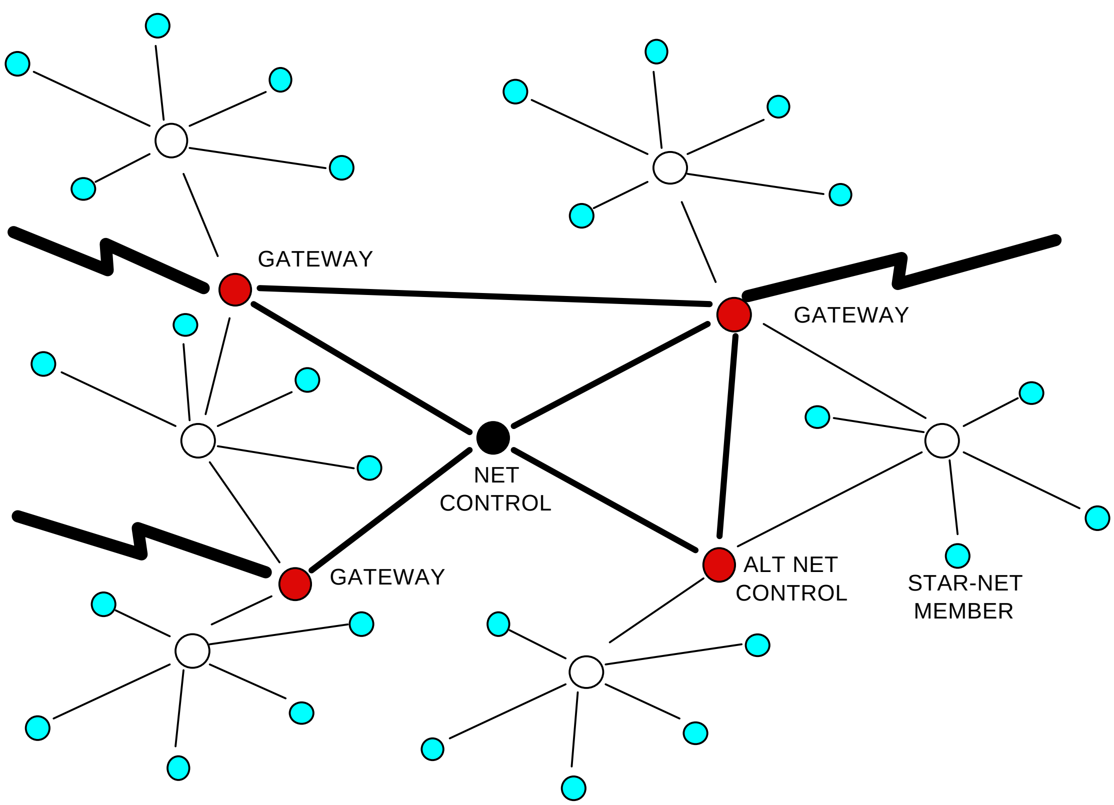


FIGURE A7-7

Example HF subnetwork topology

A7-3.2 Network layer protocols

The suite of protocols at the network layer supports automatic message exchange, connectivity exchange, relay management, and station status monitoring.

Automatic Message Exchange. The Automatic Message Exchange (AME) protocol [6] provides a simple, connectionless, datagram service. A port number is included in the AME header to support internal routing of AME datagrams to higher-layer entities such as the Internet Protocol, the HF Network Management Protocol, or the operator display (for orderwire messages).

The AME header also includes a flexible mechanism for appending source routing to messages: in addition to the source and destination station addresses, additional stations can be named as recommended or mandatory relay stations for the message. This supports, for example, a network consisting only of Level 1 HFNCs, with source routing performed by operators or by host computers that maintain routing tables.

Connectivity Exchange. The Connectivity Exchange protocol [7] is used by Level 3 and 4 HFNCs to share path quality data. For example, if station A receives a report from B about the path from B to C, A can combine its measurement of the link quality to B to compute the end-to-end quality of the path from A to C through B.

HF Relay Management Protocol. HRMP [8] is used to remotely control repeaters, and to query directly-reachable stations about connectivity to a locally unreachable station. Precedence and preemption are supported for optimum use of network resources.

HRMP also includes a connectivity monitoring mechanism that can be used to track indirect connectivity without the overhead of the full CONEX protocol (which can consume sizable fractions of HF channel bandwidth). For example, assume station A routes messages to C through B. Station A may request that B asynchronously report loss of connectivity to C so that A could then find (or activate) an alternate route to C.

HF Station Status Protocol. HSSP [9] may be used to support a notification based mechanism for tracking the status of network member stations with less overhead traffic than a polling-based approach. Status reports are sent when a station changes scan set, begins radio silence, goes out of service, assumes network management duties, returns to normal operation, and so on.

Although the level of network monitoring provided by these protocols may be sufficient within an HF subnetwork, management of interconnected subnetworks in the Internet usually requires the ability to examine detailed operating statistics at key stations, and to remotely manipulate their control states. This capability is extended to HF networks by the HF Network Management architecture, described in the following section.

A7-3.3 HF Network Management

Use of HF radio to extend Internet services to the users identified in the Introduction will result in increasingly complex HF networks, with equipment often placed at remote sites. This, along with programs to consolidate high-power HF assets among military services into unmanned “lights out” facilities, indicates the need for a standardized protocol for remotely controlling HF stations and for remotely diagnosing problems in HF networks. Similar needs in the existing Internet have led to the development of the Simple Network Management Protocol

(SNMP). However, the hostility of the HF medium presents clear challenges to the development of a mechanism for reliably monitoring and controlling distant radio stations.

MIL-STD-187-721C describes a protocol that addresses these challenges, while maintaining compatibility with the standard Internet SNMP network management architecture.

A7-3.3.1 Background

Automation of High Frequency (HF) radio networks to date has simplified the tasks related to establishing links using HF radios. However, Automatic Link Establishment (ALE) and other HF automation technology [3] have brought a new problem to managing radio networks: the automatic controllers use a number of intricate data structures that must be kept consistent throughout a network if operations are to proceed smoothly.

Another aspect of network management that has not been addressed by the ALE standards is the need to observe network connectivity and equipment status from network control sites (Figure 8) so that corrective action can be initiated promptly when malfunctions or other disruptions occur.

Managers of packet networks have been at work on these problems for some time. The most mature and widespread of the existing network management architectures is the Internet-standard Network Management Framework, which was developed in the late 1980's. This technology is more often referred to by the protocol that it employs for managing network nodes, the Simple Network Management Protocol, or SNMP [10].

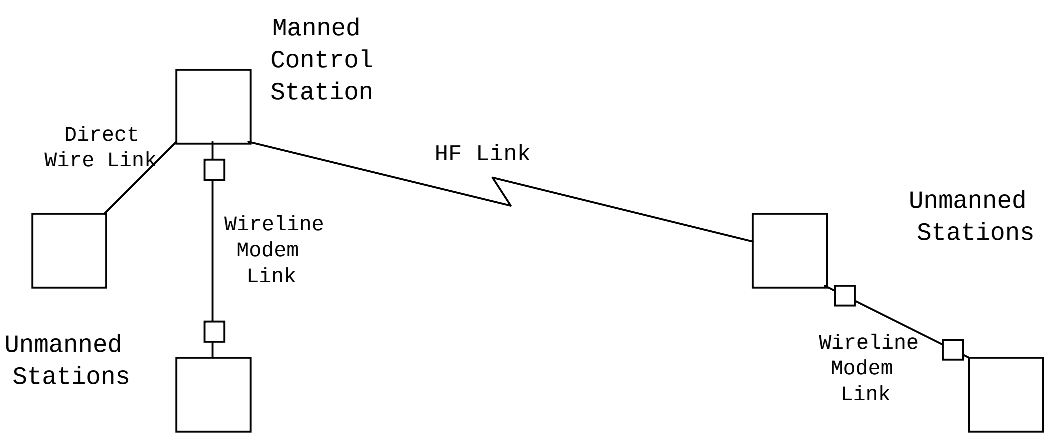


FIGURE A7-8

Network management example

SNMP was designed so that it "explicitly minimizes the number and complexity of management functions realized by the management agent itself" [10]. That is, the development costs of including SNMP in managed equipment are minimized, at the expense of (perhaps) increasing the complexity of the software that manages such nodes. Fortunately, the ratio of managed nodes to management stations is large, so the benefit of widespread implementation has greatly outweighed the cost of implementing the management software.

To briefly summarize the salient points of the SNMP approach:

- *Network management stations* monitor and control *network elements* by communicating with *agents* in those elements.
- This interaction uses SNMP [10] to *get* and *set* the values of defined data objects. Agents may also send *trap* messages to management stations to announce important events asynchronously.
- The defined data objects are described in the *Management Information Base* (MIB), which is currently strongly oriented to the TCP/IP protocol suite, but is easily extensible. Object definitions are expressed formally in *Abstract Syntax Notation 1* (ASN.1) [11].
- Object names and values are encoded for transmission in accordance with a set of ASN.1 *Basic Encoding Rules* [12].
- When elements do not implement SNMP, they may still be managed by using *proxy agents* that translate the standard SNMP messages into messages understood by these elements.
- Authentication is included in the standard, although current practice uses only trivial authentication. The mechanism is extensible using ideas similar to HF linking protection [13-17].
- SNMP requires only a connectionless datagram transport service (*e.g.*, the User Datagram Protocol UDP [18] in the Internet).

A7-3.3.2 HF Network Management Requirements

The assets to be managed in an automated HF network include media-specific equipment such as transceivers, modems, ALE controllers, and HF Node Controllers (HFNCs). Figure A7-9 depicts a network management station and a controlled HF network node. The management station as shown uses HF links to control this node, but it could just as well employ a wide area network (WAN), wireline modems, or other types of links.

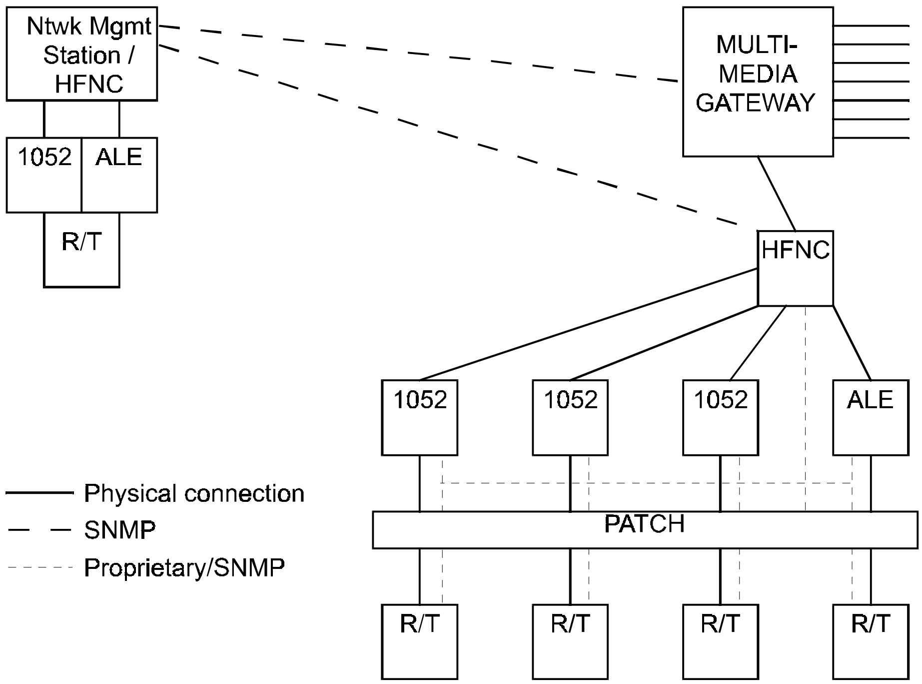


FIGURE A7-9

Management of HF network nodes

An automated network management system must support the efficient control of automated HF stations and networks, including the following functions:

- Monitoring and reporting network status (topology, capabilities, congestion, faults, etc.).
- Updating network routing tables.
- Manipulating the operating data of automated communications controllers.
- Identifying software versions, and updating the software, in ALE and other communications controllers.
- Re-keying linking protection scramblers.
- Remotely operating all communications equipment, including adjusting transmitter power of linked stations, reading "meters," rotating antennas, and so on.

Because of the mission-critical nature of the networks to be controlled, authentication must be integral to the network management protocol.

A7-3.3.3 Applicability of SNMP for HF network management

Several questions must be addressed in assessing SNMP for HF network management [13]: whether it can support all of the functions required (functionality), work over the HF medium (compatibility), and perform acceptably without imposing unacceptable overhead (performance). These issues are discussed below.

Functionality. Over-the-air data manipulation functions clearly depend upon the interrogation and revision of data at remote sites, which is precisely the model supported by SNMP. Over-the-air rekeying can also be cast as an authenticated transfer of new values to defined objects, in this case the storage locations of keys. Remote control is less clearly supported by the SNMP approach, but, as noted in the SNMP standard, all control actions may be implemented as “side effects” of writing to appropriate variables in an automated controller. For example, rotating an antenna occurs as a side-effect of updating a variable that specifies the azimuth of that antenna. Thus, all of the network management functions can be supported by SNMP.

Compatibility. Because SNMP was designed to help network managers find problems in networks under crisis conditions, it makes few assumptions about the reliability of the communications paths to the managed elements. It expects only unreliable connectionless service from the transport layer. This can be satisfied either by implementing UDP on top of IP, or through the use of no transport protocol at all, on top of the Store and Forward capability of the MIL-STD-187-721C network layer. Any available HF modem technology can be used to provide usable HF data links to the network layer.

Thus, SNMP will be isolated from direct interface to the HF medium, and has been designed specifically to work through the unreliable conditions that sometimes plague HF links.

Performance. Network management stations monitor and control network elements by communicating with agents in those elements. This communication is carried in SNMP messages, so both management stations and agents must execute the SNMP protocol. The protocol is deliberately lightweight; this is intended to keep the costs of implementing and executing SNMP sufficiently low that all elements in a network can be directly managed (i.e., that all equipment of interest will implement SNMP).

The result of minimizing the complexity of the software that implements SNMP is that most of the complexity of network management is transferred to the management station software. However, due to the relatively low rate of messages expected in managing typical HF radio networks, even an inexpensive notebook computer should posses adequate processing power to serve as a network management station.

A key requirement for any management protocol to be used over HF channels is that it minimize the number of bits communicated in performing its functions. The minimization of traffic was a goal of the SNMP developers, but the networks for which it was designed place far lower costs on each bit sent. Thus, while SNMP is generally regarded to be a lightweight protocol in the Ethernet environment (10 Mbps), it is not clear that it is sufficiently lightweight to be used over HF, where all overhead traffic is viewed much more suspiciously.

The basic message format for the current version of SNMP (version 2), includes privacy and authentication header fields, an SNMP command (e.g., a *get* to read an object, a *set* to update an object, or a *response* to return a value), a data field that holds a request ID, error status and index fields, and a list of variable bindings. Each variable binding contains an object identifier and (in *set* requests and *get* responses) a value. It is these variable bindings that carry the management information.

In the variable bindings, each *object identifier* specifies the name of a managed object by describing where it is defined in a tree of standards. This formal system of naming objects typically consumes ten or more octets for each object. *Values* of objects can be encoded in as few as three octets (for integers less than 128); however, strings of N characters will require N+2 octets for their encodings.

No provision is made in SNMP for getting or setting entire tables. Each entry must be individually named in requests and responses.

If the headers for UDP and IP are included, an SNMP message that responds to a request for a three-character address from an ALE controller address table will require on the order of 70 octets, plus the HF Automatic Message Exchange header and data link layer header. Eliminating UDP and IP would remove 28 octets from this total. Reduction of this overhead is one of the key goals of the HF variant of SNMP.

A7-3.3.4 HNMP: The HF variant of SNMP

Because the initial version of SNMP did not provide sufficient authentication capability for HF network management, MIL-STD-187-721C is based on version 2 of SNMP [19-30], usually denoted SNMPv2. This section describes this differences between SNMPv2 and the HF variant of SNMP (termed HNMP), and addresses questions of managing existing assets that do not implement SNMP, controlling access to managed assets, and integrating the management protocol with the existing HF protocol suite.

HNMP is identical with SNMPv2 [19-30], with the following variations:

a. Object identifiers for objects defined in the HF MIB are encoded for transmission using a truncated encoding scheme that reduces overhead.

b. A GetRows variant of the GetBulk message is introduced.

c. A PIN authentication scheme is mandatory, while the SNMPv2 MD5 authentication scheme is optional.

d. Retransmission timeouts in network management programs are adjusted to allow time for link establishment, and for the transmission of requests and responses over modems that may be able to achieve throughputs of 100 bps or less.

The relationship of the network management protocol to the other protocols in use within an HF station is shown in Figure 10. HNMP requires only a connectionless datagram transport service (e.g., the User Datagram Protocol (UDP)). Consequently, Figure 10 shows HNMP using UDP for a transport-layer protocol, IP for an Internet-layer protocol, and the HF Automatic Message Exchange (AME) protocol as the Network-layer protocol. Figure 10 also shows integration of IEEE 802 protocols as an illustration of the use of HNMP over an Ethernet local area network. Other LAN and WAN protocols may be integrated similarly. When interoperation with management stations outside the local HF sub-network is not required, UDP and IP may be eliminated to reduce the overhead of network management messages.

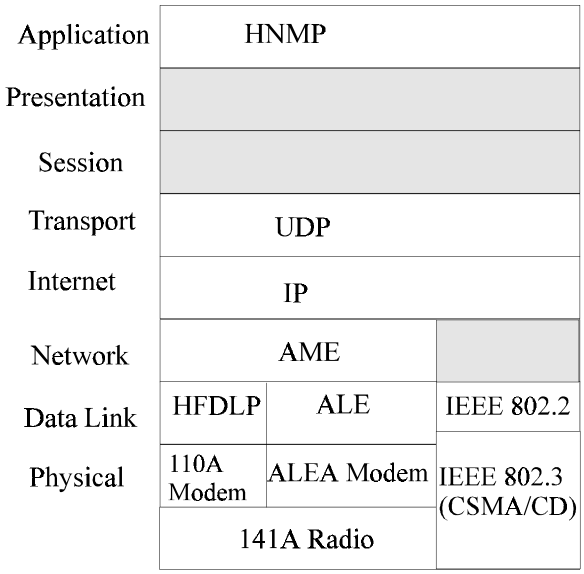


FIGURE A7-10
Interrelationship of protocols

A7-3.3.5 Objects used in network management

SNMP functions by reading and writing data *objects* defined for each functional element (e.g., HF node controller, ALE controller, modem, or radio). These data structures are defined using an abstract syntax so that the details of how the data are stored by individual network components are hidden.

- RFC-1450 defines the objects commonly used to manage TCP/IP internets.
- The standard objects for HF network management are defined in the HF Management Information Base (HF MIB). This MIB module contains groups of objects for radios (and related RF equipment), ALE controllers, linking protection, HF data modems (and associated data link controllers), and networking controllers.
- Objects specific to each manufacturer’s equipment are specified in a MIB provided by that manufacturer.

A management station integrates MIB modules from the elements it manages, resulting in access to a wide-ranging and dynamic set of management data. The structure of MIBs is defined in RFC-1442 [20].

When data is exchanged over the air (or some other medium), it is necessary that all parties to the exchange use the same encodings for the data. Object names and values sent in HNMP messages are encoded IAW the Basic Encoding Rules for ASN.1, found in [12], with a truncated encoding used for OBJECT IDENTIFIERS of objects from the HF MIB [31].

A7-3.3.6 GetRows mechanism

In addition to the SNMPv2 protocol data units (PDUs), HNMP includes GetRowsRequest and GetRows Response PDUs. The GetRows operation is similar to the SNMPv2 GetBulk operation, except that the response to a GetRows is a new compact PDU. A GetRows response includes the object ID only of the first object in each row, followed by the values of all objects requested in that row. This elimination of the largely redundant transmission of object IDs can dramatically reduce the number of bits sent when reading tables, which is an important consideration for managing ALE controllers and radios over the relatively low bandwidth of HF channels. A similar idea could be employed for efficiently setting rows of tables, but is not part of the standard.

A7-3.3.7 Access control

Access to the management information of network elements is controlled in HNMP at two levels. The first level is an administrative model that restricts the objects at each element that are accessible to other parties and the operations that may be performed by those parties.

The second level of access control is authentication of messages; that is, determination that a message actually comes from the party named in the message. The following three mechanisms are available to authenticate HNMP messages:

- *Trivial Authentication*. Check the transport-layer address of the originator of the message.
- *Personal Identification Number Authentication*. Require operator entry of a PIN, which is appended to every message and checked by agents.
- *Cryptographic Authentication*. Attach a *digest* of each authenticated message at the beginning of the message (authInfo in the SnmpAuthMsg). This digest is computed from the message contents and a secret initialization vector in such a way that it is considered computationally infeasible to “spoof” the authentication system [32]. A time-of-day mechanism is included as well, to limit the effects of replay attacks.

An extra level of access control is imposed on HF access to managed stations when linking protection is used to authenticate ALE calls. In this case, anonymous distant HF stations can be denied the ability to even establish links to the managed network.

A7-3.3.8 Proxy management

When elements do not implement HNMP, they may still be managed by using proxy agents that translate the standard HNMP messages into messages understood by the non-HNMP (“foreign”) elements. As HNMP management of HF radio networks is phased in, few network elements will initially implement HNMP. Proxy agents will be needed to extend the management capability to current-generation equipment. As a general rule, the proxy agent for any foreign network element should reside in the lowest-level controller that has a control path to that element, often an HFNC.

The provision for proxy agents in HNMP will greatly ease its use in HF networks. A phased approach to integrating HNMP into automated HF networks is to initially limit the penetration of HNMP to no level lower than HFNCs, with proxy agent software running within each HFNC to translate HNMP messages into the peculiar command sequences used by the other equipment at each site. This has the clear advantage of limiting the initial round of new software development to equipment that is software-based (HFNCs) rather than requiring upgrades to firmware-based equipment such as fielded ALE controllers.

A7-3.3.9 Performance

The performance of HNMP may be gauged by how many bits are transferred to perform common operations. A fairly complex station such as that shown schematically in Figure A7-11 may be used for computing some example bit counts.

A similar station containing 1 ALE controller, 7 radios, 10 antennas, 6 HF Data Link Protocol (HFDLP) controllers, 1 antenna matrix, and 1 automated BLACK patch panel was analyzed [33] with the following results: at 1200 bps, and assuming 50% overhead for ARQ, a complete download of the management information for this station would consume approximately 200 seconds. Of course, over a LAN, a WAN, or even a high-speed modem link, the time for this download would be on the order of one second, primarily determined by the overhead of the lower-level protocols rather than the HNMP overhead.

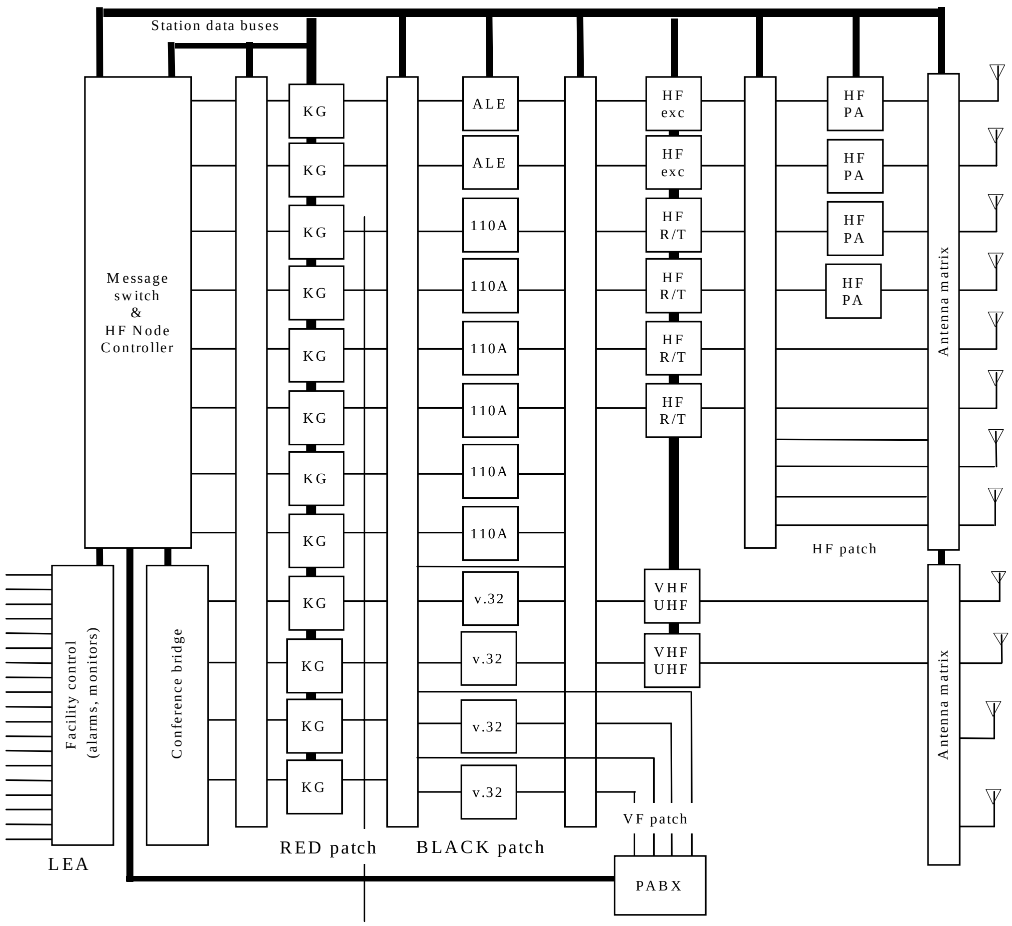


FIGURE A7-11

Large-Scale HF Internet Gateway

A7-4 Conclusion

HF radio appears well-suited to provide connectivity to and within the Internet for applications that can tolerate the relatively low bandwidth currently available from HF modems. These applications certainly include text-oriented applications, for which powerful compression algorithms mitigate the lower throughput of HF compared to wireline modems. Audio files can also be compressed substantially, but photo and video files will be more difficult to accommodate without incurring very long file transfer times and producing significant congestion of HF networks.

Due to the compatibility between the standards developed for HF automation and the Internet standards, the integration of HF into the international information infrastructure should be relatively painless. Much of the software required for the end-to-end protocols and internetwork routing is commercially available, with documented interfaces.

New development may be required only to implement the HF-specific protocols and algorithms for routing and station control. This software can be targeted to the inexpensive desktop and portable computers that currently run the higher-layer protocols and applications, and will benefit from the mature development environments available for these machines.

PC Cards are currently available that pack both an Ethernet interface and a fax/data modem into a credit card size form factor. The day may not be far distant when a PC Card implementation of the automated HF technology described here will connect a palmtop computer to a LAN and an HF transceiver to form a compact, fully functional HF Internet gateway.

ANNEX 8
TERMINOLOGY AND ACRONYMS

Below are definitions from FED-STD-1037C, *Glossary of Telecommunication Terms* and from *HF Communications—Science and Technology* by J. M. Goodman (1992, Van Nostrand), and from *Communications Standard Dictionary,* 2nd ed., by M. Weik (1989, Van Nostrand), reprinted (with permission) for handy reference here. The full text of the Federal Standard glossary—with its definitions from the international treaty documents of the *NTIA Manual of Regulations and Procedures for Federal Radio Frequency Management* and the ITU *Radio Regulations*—is available at the Web address of http://glossary.its.bldrdoc.gov/fs-1037

ACK: *Abbreviation for* **acknowledge character.**

acknowledge character (ACK): A transmission control character transmitted by the receiving station as an affirmative response to the sending station. *Note:* An acknowledge character may also be used as an accuracy control character.

acknowledgement: 1. A response sent by a receiver to indicate successful receipt of a transmission. An example of an acknowledgement is a protocol data unit, or element thereof, between peer entities, to indicate the status of data units that have been successfully received. **2.** A message from the addressee informing the originator that the originator's communication has been received and understood.

adaptive: The process associated with automatically altering operating parameters and/or system configuration in response to changes in time-varying channel propagation conditions and external noise.

adaptive routing: The process of routing calls based on network conditions. The routing decision may come from the sender, may be dynamic with each node making routing decisions, or may be based on instructions issued by a centralized point such as a network control station (NCS). The sender may not have up-to-date information, so this node may not be able to direct traffic for maximum efficiency. In some cases, a centralized scheme may be desirable, but the central node may not have the latest information. The individual node in the process of relaying will likely have the best information for at least one hop. However, unless information is distributed or relayed throughout the system, this node may not be able to see beyond a single hop with any degree of efficiency.

additive white gaussian noise (AWGN): *Synonym* **white noise.**

ALE: *Abbreviation for* **automatic link establishment. 1.** In high-frequency (HF) radio, the capability of a station to make contact, or initiate a circuit, between itself and another specified radio station, without human intervention and usually under processor control. ALE techniques include automatic signaling, selective calling, and automatic handshaking. Other automatic techniques that are related to ALE are channel scanning and selection, link quality analysis (LQA), polling, sounding, message store-and-forward, address protection, and anti-spoofing. **2.** In HF radio, a link control system that includes automatic scanning, selective calling, sounding, and transmit channel selection using link quality analysis data. Optional ALE functions include polling and the exchange of orderwire commands and messages.

allcall: In adaptive high-frequency (HF) radio automatic link establishment (ALE), a general broadcast that does not request responses and does not designate any specific addresses. This essential function is required for emergencies ("HELP"), sounding-type data exchanges, and propagation and connectivity tracking.

availability: **1.** The degree to which a system, subsystem, or equipment is operable and in a committable state at the start of a mission, when the mission is called for at an unknown, *i.e.*, a random, time. The conditions determining operability and committability must be specified. Expressed mathematically, availability is 1 minus the unavailability. **2.** The ratio of (a) the total time a functional unit is capable of being used during a given interval to (b) the length of the interval. An example of availability is 100/168 if the unit is capable of being used for 100 hours a week. Typical availability objectives are specified in decimal fractions, such a 0.9998.

backscattering: **1.** Radio wave propagation in which the direction of the incident and scattered waves, resolved along a reference direction (usually horizontal) are oppositely directed. A signal received by backscattering is often referred to as "backscatter." **2.** In optics, the scattering of light into a direction generally opposite to the original one.

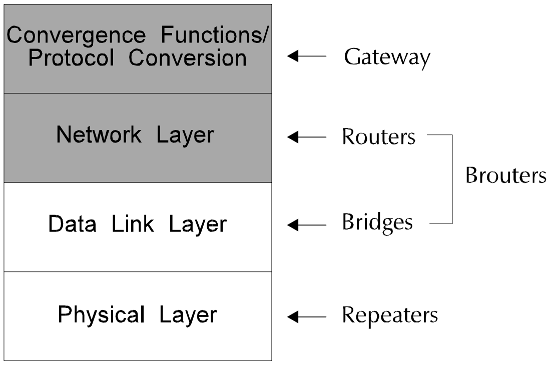
basic mode reliability: The mode reliability, denoted by the term R_m, is given by:

$$R_m = P_{SNR}$$

where Q is the mode availability, and PSNR is a conditional probability that the required signal-to-noise ratio (SNR) is exceeded, under the condition that the mode exists. The above equation presumes that mode presence is independent of signal strength.

BER: *Abbreviation for* **bit error ratio**. The number of erroneous bits divided by the total number of bits transmitted, received, or processed over some stipulated period. Examples of bit error ratio are (a) transmission BER, *i.e.*, the number of erroneous bits received divided by the total number of bits transmitted; and (b) information BER, *i.e.*, the number of erroneous decoded (corrected) bits divided by the total number of decoded (corrected) bits. The BER is usually expressed as a coefficient and a power of 10; for example, 2.5 erroneous bits out of 100,000 bits transmitted would be 2.5 out of 10^5 or 2.5 x 10^{-5}.

bridge: **1.** In communications networks, a device that (a) links or routes signals from one ring or bus to another or from one network to another, (b) may extend the distance span and capacity of a single LAN system, (c) performs no modification to packets or messages, (d) operates at the data-link layer of the OSI—Reference Model (Layer 2), (e) reads packets, and (f) passes only those with addresses on the same segment of the network as the originating user. **2.** A functional unit that interconnects two local area networks that use the same logical link control procedure, but may use different medium access control procedures. **3.** A balanced electrical network, *e.g.*, a Wheatstone bridge. A bridge may be used for electrical measurements, especially resistances or impedances. **4.** *See* **hybrid coil.**



Association of OSI Ref-Model layers with bridges, gateways, *etc.*

broadband: *Synonym* **wideband.**

broadcast operation: The transmission of signals that may be simultaneously received by stations that usually make no acknowledgement.

brouter: A combined bridge and router that operates without protocol restrictions, routes data using a protocol it supports, and bridges data it cannot route.

buffer: **1.** A routine or storage medium used to compensate for a difference in rate of flow of data, or time of occurrence of events, when transferring data from one device to another. Buffers are used for many purposes, such as (a) interconnecting two digital circuits operating at different rates, (b) holding data for use at a later time, (c) allowing timing corrections to be made on a data stream, (d) collecting binary data bits into groups that can then be operated on as a unit, (e) delaying the transit time of a signal in order to allow other operations to occur. **2.** To use a buffer or buffers. **3.** An isolating circuit, often an amplifier, used to minimize the influence of a driven circuit on the driving circuit. *Synonym* **buffer amplifier**. **4.** In a fiber optic communication cable, one type of component used to encapsulate one or more optical fibers for the purpose of providing such functions as mechanical isolation, protection from physical damage and fiber identification. *Note:* The buffer may take the form of a miniature conduit, contained within the cable and called a loose buffer, or loose buffer tube, in which one or more fibers may be enclosed, often with a lubricating gel. A tight buffer consists of a polymer coating in intimate contact with the primary coating applied to the fiber during manufacture.

busy hour: In a communications system, the sliding 60-minute period during which occurs the maximum total traffic load in a given 24-hour period. *Note 1:* The busy hour is determined by fitting a horizontal line segment equivalent to one hour under the traffic load curve about the peak load point. *Note 2:* If the service time interval is less than 60 minutes, the busy hour is the 60-minute interval that contains the service timer interval. *Note 3:* In cases where more than one busy hour occurs in a 24-hour period, *i.e.*, when saturation occurs, the busy hour or hours most applicable to the particular situation are used. *Synonym* **peak busy hour.**

call intensity: *Synonym* **traffic intensity.**

channel frequency scanning: *See* **scanning.**

channel occupancy: The fraction of measurement time in which the interference level exceeds a defined threshold. *[From Goodman, 1992, used with written permission.]*

chirpsounding: linear sweep sounding or linear FM modulation that consists of sendin a low-power 2-to-30-MHz linear FM/cw test signal over the communication path. This method can be used over eith a vertical or an oblique path. The data received from the chirpsounding equipment is similar to the pulse sounding equipment, but has the advantage of causing less interference to nearby equipment.

circuit reliability: **1.** The probability that for a given circuit and single frequency, a specified performance is achieved. **2.** The percentage of time a circuit was available for use in a specified period of scheduled availability. *Note 1:* Circuit reliability is given by

$$CiR = 100\,[1 - T_o/T_s] = 100\,(T_a/T_s)$$

where T_o is the circuit total outage time, T_s is the circuit total scheduled time, and T_a is the circuit total available time.
Note 2: $T_s = T_a + T_o$. *Synonym* **time availability.**

class of emission: The set of characteristics of an emission, designated by standard symbols, *e.g.* , type of modulation of the main carrier, modulating signal, type of information to be transmitted, and also, if appropriate, any additional signal characteristics. [NTIA] [RR]

class of service: 1. A designation assigned to describe the service treatment and privileges given to a particular terminal. **2.** A subgrouping of telephone users for the purpose of rate distinction. Note: Examples of class of service subgrouping include distinguishing between (a) individual and party lines, (b) Government and non-Government lines, (c) those permitted to make unrestricted international dialed calls and those not so permitted, (d) business, residence, and coin-operated, (e) flat rate and message rate, and (f) restricted and extended area service. **3.** A category of data transmission provided by a public data network in which the data signaling rate, the terminal operating mode, and the code structure, are standardized. *Note:* Class of service is defined in CCITT Recommendation X.1. *Synonym* **user service class.**

communications net: An organization of stations capable of direct communication on a common channel or frequency. *Synonym* **net**.

congestion: 1. In a communications switch, a state or condition that occurs when more subscribers attempt simultaneously to access the switch than it is able to handle, even if unsaturated. **2**. In a saturated communications system, the condition that occurs when an additional demand for service occurs. [from 1037C] **4.** The probability of randomly finding within each 50-kHz spectrum a 100-Hz frequency interval in which the average interference level exceeds a defined threshold. *[from Goodman, 1992, used with permission]*

cutover: The physical changing of circuits or lines from one configuration to another.

data rate: *See* **data signaling rate.**

data signaling rate (DSR): The aggregate rate at which data pass a point in the transmission path of a data transmission system. *Note 1:* The DSR is usually expressed in bits per second. *Note 2:* The data signaling rate is given by

$$\sum_{i=1}^{m} \frac{\log_2 n_i}{T_i},$$

where m is the number of parallel channels, ni is the number of significant conditions of the modulation in the I-th channel, and Ti is the unit interval, expressed in seconds, for the I-th channel. *Note 3*: For serial transmission in a single channel, the DSR reduces to (1/T)$\log_2$n ; with a two-condition modulation, *i.e.* , n =2, the DSR is 1/T . *Note 4:* For parallel transmission with equal unit intervals and equal numbers of significant conditions on each channel, the DSR is (m /T)$\log_2$ n ; in the case of a two-condition modulation, this reduces to m /T . *Note 5:* The DSR may be expressed in bauds, in which case, the factor $\log_2$ni in the above summation formula should be deleted when calculating bauds. *Note 6:* In synchronous binary signaling, the DSR in bits per second may be numerically the same as the modulation rate expressed in bauds. Signal processors, such as four-phase modems, cannot change the DSR, but the modulation rate depends on the line modulation scheme, in accordance with Note 4. For example, in a 2400 b/s 4-phase sending modem, the signaling rate is 2400 b/s on the serial input side, but the modulation rate is only 1200 bauds on the 4-phase output side.

delay: **1.** The amount of time by which an event is retarded. **2.** The time between the instant at which a given event occurs and the instant at which a related aspect of that event occurs. *Note 1:* The events, relationships, and aspects of the entity being delayed must be precisely specified. *Note 2:* Total delay may be demonstrated by the impulse response of a device or system. *Note 3:* In analog systems, total delay is described in terms of the transfer functions in the frequency domain. *Synonym* **delay time.** **3** . In radar, the electronic delay of the start of the time base used to select a particular segment of the total.

delay time: *Synonym* **delay** (def. #1).

demand assignment: An operation in which several users share access to a communications channel on a real-time basis, i.e. , a user needing to communicate with another user on the same network requests the required circuit, uses it, and when the call is finished, the circuit is released, making the circuit available to other users. *Note*: Demand assignment is similar to conventional telephone switching, in which common trunks are provided for many users, on a demand basis, through a limited-size trunk group.

disengagement attempt: An attempt to terminate a telecommunications system access. *Note*: Disengagement attempts may be initiated by a user or the telecommunications system.

disengagement denial: After a disengagement attempt, a failure to terminate the telecommunications system access. *Note*: Disengagement denial is usually caused by excessive delay in the telecommunications system.

disengagement failure: Failure of a disengagement attempt to return a communication system to the idle state, for a given user, within a specified maximum disengagement time.

e-mail (electronic mail): An electronic means for communication in which (a) usually text is transmitted, (b) operations include sending, storing, processing, and receiving information, (c) users are allowed to communicate under specified conditions, and (d) messages are held in storage until called for by the addressee.

e-mail reflector: *Synonym* **reflector.**

equalization: The maintenance of system transfer function characteristics within specified limits by modifying circuit parameters. Equalization includes modification of circuit parameters, such as resistance, inductance, or capacitance.

erlang: A dimensionless unit of the average traffic intensity (occupancy) of a facility during a period of time, usually a busy hour. *Note 1:* Erlangs, a number between 0 and 1, inclusive, is expressed as the ratio of (a) the time during which a facility is continuously or cumulatively occupied to (b) the time that the facility is available for occupancy. *Note 2:* Communications traffic, measured in erlangs for a period of time, and offered to a group of shared facilities, such as a trunk group, is equal to the average of the traffic intensity, in erlangs for the same period of time, of all individual sources, such as telephones, that share and are served exclusively by this group of facilities. *Synonym* **traffic unit.**

exempted addressee: An organization, activity, or person included in the collective address group of a message and deemed by the message originator as having no need for the information in the message. *Note*: Exempted addressees may be explicitly excluded from the collective address group for the particular message to which the exemption applies.

exploder: *Synonyms* **e-mail mailing list; reflector, server.**

flood search routing: In a telephone network, nondeterministic routing in which a dialed number received at a switch is transmitted to all switches, *i.e.*, flooded, in the area code directly connected to that switch; if the dialed number is not an affiliated subscriber at that switch, the number is then retransmitted to all directly connected switches, and then routed through the switch that has the dialed number corresponding to the particular user end instrument affiliated with it. *Note 1:* All digits of the numbering plan are used to identify a particular subscriber. *Note 2:* Flood search routing allows subscribers to have telephone numbers independent of switch codes. *Note 3:* Flood search routing provides the highest probability that a call will go through even though a number of switches and links fail.

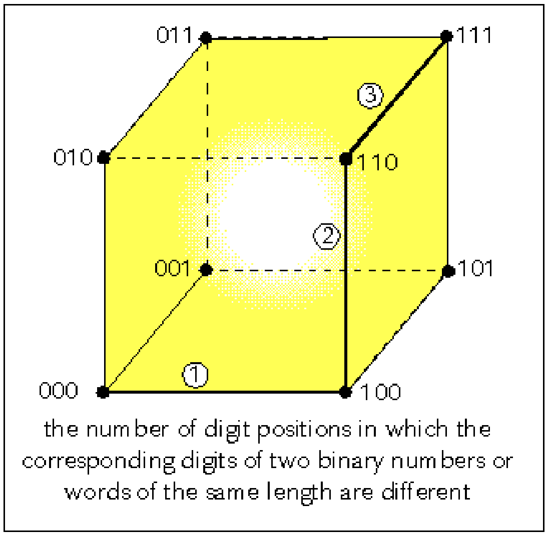
flow control: *See* **transmit flow control.**

FOT: *Abbreviation for* **frequency of optimum travail.** In transmission of radio waves via ionospheric reflection, the highest effective, *i.e.*, working frequency that is predicted to be usable for a specified path and time for 90% of the days of the month. The FOT is normally just below the value of the maximum usable frequency 9MUF). In the prediction of usable frequencies, the FOT is commonly taken as 15% below the monthly median value of the MUF for the specified time and path. The FOT is usually the most effective frequency for ionospheric reflection of radio waves between two specified points on Earth. *Synonyms* frequency of optimum traffic, optimum traffic frequency, optimum transmission frequency, optimum working frequency.

Fourier analysis: The definition of a periodic waveform of arbitrary shape as a summation of sine waves having specific amplitudes and phases, and having frequencies corresponding to the harmonics of the waveform being defined. A Fourier analysis is particularly well suited for communications equipment design and for predicting the performance of a given design.

gateway: 1. In a communications network, a network node equipped for interfacing with another network that uses different protocols. *Note 1:* A gateway may contain devices such as protocol translators, impedance matching devices, rate converters, fault isolators, or signal translators as necessary to provide system interoperability. It also requires that mutually acceptable administrative procedures be established between the two networks. *Note 2:* A protocol translation/mapping gateway interconnects networks with different network protocol technologies by performing the required protocol conversions. **2.** *Loosely*, a computer configured to perform the tasks of a gateway.

Hamming distance: The number of digit positions in which the corresponding digits of two binary words of the same length are different. The Hamming distance between 1011101 and 1001001 is two. The concept can be extended to other notation systems. For example, the Hamming distance between 2143896 and 2233796 is three, and between "toned" and "roses" it is also three. *Synonym* **signal distance**.

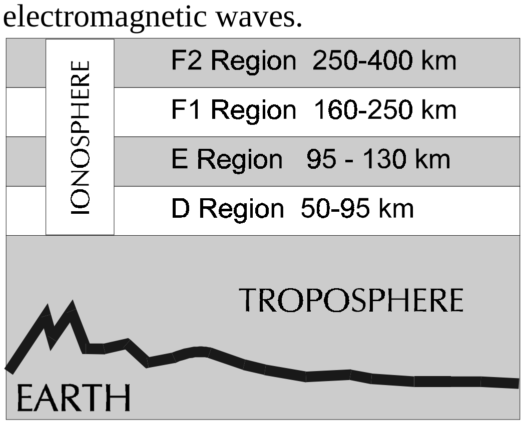


Hamming distance

HF: *Abbreviation for* **high frequency.** Frequencies from 3 MHz to 30 MHz.

hierarchical routing: Routing that is based on hierarchical addressing. *Note:* Most Transmission Control Protocol/Internet Protocol (TCP/IP) routing is based on a two-level hierarchical routing in which an IP address is divided into a network portion and a host portion. Gateways use only the network portion until an IP datagram reaches a gateway that can deliver it directly. Additional levels of hierarchical routing are introduced by the addition of subnetworks.

ionosphere: That part of the atmosphere, extending from about 70 to 500 km, in which ions and free electrons exist in sufficient quantities to reflect and/or refract electromagnetic waves.



ionosphere sounder: A device that transmits signals for the purpose of determining ionospheric conditions. [NTIA] [Radio Regulations—RR]

ionospheric pulse sounding: *See* **ionospheric sounding, sounding.**

ionospheric reflection: Of electromagnetic waves propagating in the ionosphere, a redirection, *i.e.*, bending—by a complex processing involving reflection and refraction—of the waves back toward the Earth. The amount of bending depends on the extent of penetration (which is a function of frequency), the angle of incidence, polarization of the wave, and ionospheric conditions, such as the ionization density.

ionospheric scatter: The propagation of radio waves by scattering as a result of irregularities or discontinuities in the ionization of the ionosphere. [NTIA] [RR]

ionospheric sounding: A technique that provides real-time data on high-frequency ionospheric-dependent radio propagation, using a basic system consisting of a synchronized transmitter and receiver. The time delay between transmission and reception is translated into effective ionospheric layer altitude. Vertical incident sounding uses a collocated transmitter and receiver and involves directing a range of frequencies vertically to the ionosphere and measuring the values of the reflected returned signals to determine the effective ionosphere layer altitude. This technique is also used to determine the critical frequency. Oblique sounders use a transmitter at one end of a given propagation path, and a synchronized receiver, usually with an oscilloscope-type display (ionogram), at the other end. The transmitter emits a stepped- or swept-frequency signal, which is displayed or measured at the receiver. The measurement converts time delay to effective altitude of the ionospheric layer.

The ionogram display shows the effective altitude of the ionospheric layer as a function of frequency.

ionospheric turbulence: Ongoing disturbances of the ionosphere that scatter incident electromagnetic waves. Ionospheric turbulence results in irregularities in the composition of the ionosphere that change with time. This causes changes in reflection properties. These, in turn, cause changes in skip distance, fading, local intensification, and distortion of the incident waves.

intersymbol interference: **1.** In a digital transmission system, distortion of the received signal, which distortion is manifested in the temporal spreading and consequent overlap of individual pulses to the degree that the receiver cannot reliably distinguish between changes of state, *i.e.* , between individual signal elements. At a certain threshold, intersymbol interference will compromise the integrity of the received data. Intersymbol interference attributable to the statistical nature of quantum mechanisms sets the fundamental limit to receiver sensitivity. Intersymbol interference may be measured by eye patterns. **2.** Extraneous energy from the signal in one or more keying intervals that interferes with the reception of the signal in another keying interval. **3.** The disturbance caused by extraneous energy from the signal in one or more keying intervals that interferes with the reception of the signal in another keying interval.

linear sweep sounding: *See* **chirpsounding.**

link: **1.** The communications facilities between adjacent nodes of a network. **2.** A portion of a circuit connected in tandem with, *i.e.*, in series with, other portions. **3.** A radio path between two points, called a radio link. **4.** In communications, a general term used to indicate the existence of communications facilities between two points. [Joint Pub. 1-02] **5.** A conceptual circuit, *i.e.*, logical circuit, between two users of a network, that enables the users to communicate, even when different physical paths are used. In all cases, the type of link, such as data link, downlink, duplex link, fiber optic link, line-of-sight link, point-to-point link, radio link and satellite link, should be identified. A link may be simplex, half-duplex, or duplex. **6.** In a computer program. . . . **7.** In hypertext, . . .

link orderwire: A voice or data communications circuit that (a) serves as a transmission link between adjacent communications facilities that are interconnected by a transmission link and (b) is used only for coordination and control of link activities, such as traffic monitoring and traffic control.

link protocol: A set of rules relating to data communications over a data link. Link protocols define data link parameters, such as transmission code, transmission mode, control procedures, and recovery procedures.

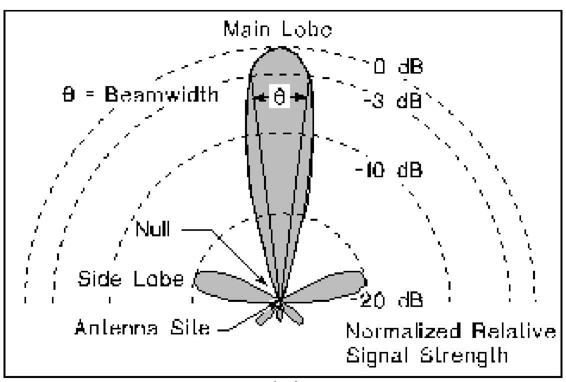
link quality analysis (LQA): In adaptive high-frequency (HF) radio, the overall process by which measurements of signal quality are made, assessed, and analyzed. In LQA, signal quality is determined by measuring, assessing, and analyzing link parameters, such as bit error ratio (BER), and the levels of the ratio of signal-plus-noise-plus-distortion to noise-plus-distortion (SINAD). Measurements are stored at—and exchanged between—stations, for use in making decisions about link establishment. For adaptive HF radio, LQA is automatically performed and is usually based on analyses of pseudo-BERs and SINAD readings.

lowest usable high frequency (LUF): The lowest frequency in the HF band at which the received field intensity is sufficient to provide the required signal-to-noise ratio for a specified time period, *e.g.*, 0100 to 0200 UTC, on 90% of the undisturbed days of the month.

LUF: *Abbreviation for* **lowest usable high frequency.**

main beam: *Synonym* **main lobe.**

main lobe: Of an antenna radiation pattern, the lobe containing the maximum power (exhibiting the greatest field strength). *Note:* The horizontal radiation pattern, *i.e.*, that which is plotted as a function of azimuth about the antenna, is usually specified. The width of the main lobe is usually specified as the angle encompassed between the points where the power has fallen 3 dB below the maximum value. The vertical radiation pattern, *i.e.* , that which is plotted as a function of elevation from a specified azimuth, is also of interest and may be similarly specified. *Synonym* **main beam.**



main lobe

maximum usable frequency: In radio transmission using reflection from the regular ionized layers of the ionosphere, the upper frequency limit that can be used for transmission between two points at a specified time. MUF is a median frequency applicable to 50% of the days of a month, as opposed to 90% cited for the lowest usable high frequency (LUF) and the optimum traffic frequency (FOT).

modem: *Acronym for* **modulator/demodulator. 1.** In general, a device that both modulates and demodulates signals. **2.** In computer communications, a device used for converting digital signals into, and recovering them from, quasi-analog signals suitable for transmission over analog communications channels. Many additional functions may be added to a modem to provide for customer service and control features. *Synonym* **signal conversion equipment. 3.** In FDM carrier systems, a device that converts the voice band to and recovers it from, the first level of frequency translation.

mode availability: The probability that for a single circuit and a single frequency a single mode can propagate by ionospheric refraction alone.

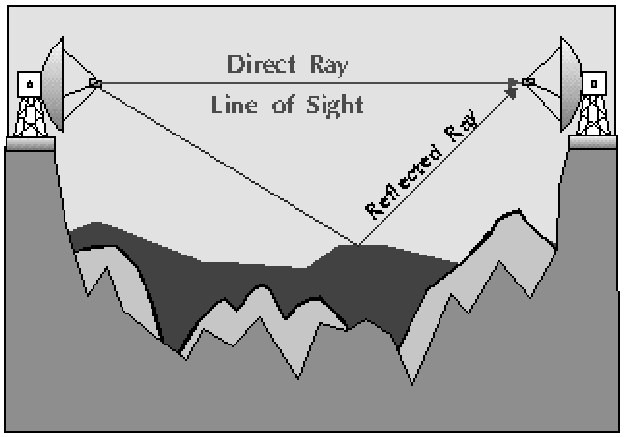
mode performance achievement: The probability that for a single circuit, single frequency, and a single mode (which propagates by ionospheric refraction along) a given performance is achieved.

mode reliability: the probability that for a single circuit and a single frequency a specified performance will be achieved by a single mode.

MUF: *Abbreviation for* **maximum usable frequency**.

multiaddress calling: A service feature that permits a user to designate more than one addressee for the same data. *Note*: Multiaddress calling may be performed sequentially or simultaneously.

multipath: The propagation phenomenon that results in radio signals' reaching the receiving antenna by two or more paths. Causes of multipath include atmospheric ducting, ionospheric reflection and refraction, and reflection from terrestrial objects, such as mountains and buildings. The effects of multipath include constructive and destructive interference, and phase shifting of the signal. In facsimile and television transmission, multipath causes jitter and ghosting.



multipath

multiplex (MUX): *See* **multiplexing.**

multiplexing (MUXing): The combining of two or more information channels onto a common transmission medium. *Note*: In electrical communications, the two basic forms of multiplexing are time-division multiplexing (TDM) and frequency-division multiplexing (FDM). In optical communications, the analog of FDM is referred to as wavelength-division multiplexing (WDM).

NAK: *Acronym for* **negative-acknowledge character.**

NAK attack: In communications security systems, a security penetration technique that makes use of the negative-acknowledge transmission-control character and capitalizes on a potential weakness in a system that handles asynchronous transmission interruption in such a manner that the system is in an unprotected state against unauthorized access during certain periods. [From Weik '89]

narrowband modem: A modem whose modulated output signal has an essential frequency spectrum that is limited to that which can be wholly contained within, and faithfully transmitted through, a voice channel with a nominal 4-kHz bandwidth. High frequency (HF) modems are limited to operation over a voice channel with a nominal 3-kHz bandwidth.

narrowband radio voice frequency (NBRVF): In narrowband radio, the nominal 3-kHz bandwidth allocated for single channel radio that provides a transmission path for analog and quasi-analog signals.

narrowband signal: Any analog signal or analog representation of a digital signal whose essential spectral content is limited to that which can be contained within a voice channel of nominal 4-kHz bandwidth. Narrowband radio uses a voice channel with nominal 3-kHz bandwidth.

negative-acknowledge character (NAK): A transmission control character sent by a station as a negative response to the station with which the connection has been set up. *Note 1:* In binary synchronous communication protocol, the NAK is used to indicate that an error was detected in the previously received block and that the receiver is ready to accept retransmission of that block. *Note 2:* In multipoint systems, the NAK is used as the not-ready reply to a poll.

net: *Synonym* **communications net.**

net control station (NCS): 1. A radio station that performs net control functions, such as controlling traffic and enforcing operational discipline. [From Weik '89] **2.** [A] terminal in a secure telecommunications net responsible for distributing key in electronic form to the members of the net. [NIS]

net operation: The operation of an organization of stations capable of direct communication on a common channel or frequency. *Note*: Net operations (a) allow participants to conduct ordered conferences among participants who usually have common information needs or related functions to perform, (b) are characterized by adherence to standard formats and procedures, and (c) are responsive to a common supervisory station, called the "net control station," which permits access to the net and maintains net operational discipline.

network: 1. An interconnection of three or more communicating entities. **2.** An interconnection of usually passive electronic components that performs a specific function (which is usually limited in scope), *e.g.*, to simulate a transmission line or to perform a mathematical function such as integration or differentiation. *Note*: A network may be part of a larger circuit.

network administration: A group of network management functions that (a) provide support services, (b) ensure that the network is used efficiently, and (c) ensure prescribed service-quality objectives are met. *Note:* Network administration may include activities such as network address assignment, assignment of routing protocols and routing table configuration, and directory service configuration.

network architecture: 1. The design principles, physical configuration, functional organization, operational procedures, and data formats used as the bases for the design, construction, modification, and operation of a communications network. **2.** The structure of an existing communications network, including the physical configuration, facilities, operational structure, operational procedures, and the data formats in use.

network busy hour (NBH): *See* **busy hour.**

network connectivity: The topological description of a network that specifies, in terms of circuit termination locations and quantities, the interconnection of the transmission nodes.

network engineering: 1. In telephony, the discipline concerned with (a) determining internetworking service requirements for switched networks, and (b) developing and implementing hardware and software to meet them. **2.** In computer science, the discipline of hardware and software engineering to accomplish the design goals of a computer network. **3.** In radio communications, the discipline concerned with developing network topologies.

network interface: 1. The point of interconnection between a user terminal and a private or public network. **2.** The point of interconnection between the public switched network and a privately owned terminal. *Note: Code of Federal Regulations, Title 47, Part 68*, stipulates the interface parameters. **3.** The point of interconnection between one network and another network.

network management: The execution of the set of functions required for controlling, planning, allocating, deploying, coordinating, and monitoring the resources of a telecommunications network, including performing functions such as initial network planning, frequency allocation, predetermined traffic routing to support load balancing, cryptographic key distribution authorization, configuration management, fault management, security management, performance management, and accounting management. *Note:* Network management does not include user terminal equipment.

network manager: In network management, the entity that initiates requests for management information from managed systems or receives spontaneous management-related notifications from managed systems.

network topology: The specific physical, *i.e.,* real, or logical, *i.e.,* virtual, arrangement of the elements of a network. *Note 1*: Two networks have the same topology if the connection configuration is the same, although the networks may differ in physical interconnections, distances between nodes, transmission rates, and/or signal types. *Note 2:* The common types of network topology are illustrated [refer to the figure below] and defined in alphabetical order below:

bus topology: A network topology in which all nodes, *i.e.*, stations, are connected together by a single bus.

fully connected topology: A network topology in which there is a direct path (branch) between any two nodes. *Note:* In a fully connected network with n nodes, there are n(n-1)/2 direct paths, *i.e.,* branches. Synonym fully connected mesh network.

hybrid topology: A combination of any two or more network topologies. *Note 1:* Instances can occur where two basic network topologies, when connected together, can still retain the basic network character, and therefore not be a hybrid network. For example, a tree network connected to a tree network is still a tree network. Therefore, a hybrid network accrues only when two basic networks are connected and the resulting network topology fails to meet one of the basic topology definitions. For example, two star networks connected together exhibit hybrid network topologies. *Note 2:* A hybrid topology always accrues when two different basic network topologies are connected.

linear topology: *See* **bus topology.**

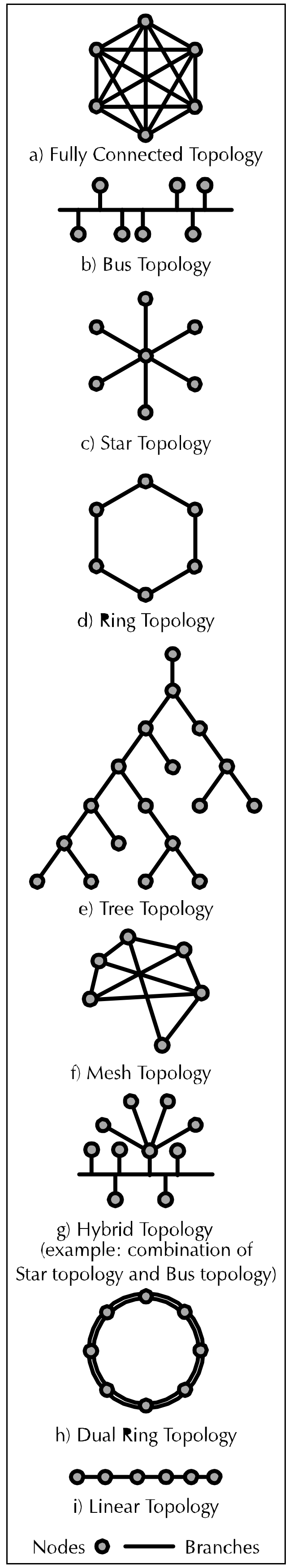
mesh topology: A network topology in which there are at least two nodes with two or more paths between them.

ring topology: A network topology in which every node has exactly two branches connected to it.

star topology: A network topology in which peripheral nodes are connected to a central node, which rebroadcasts all transmissions received from any peripheral node to all peripheral nodes on the network, including the originating node. *Note 1:* All peripheral nodes may thus communicate with all others by transmitting to, and receiving from, the central node only. *Note 2:* The failure of a transmission line, *i.e.*, channel, linking any peripheral node to the central node will result in the isolation of that peripheral node from all others. *Note 3:* If the star central node is passive, the originating node must be able to tolerate the reception of an echo of its own transmission, delayed by the two-way transmission time, *i.e.*, to and from the central node, plus any delay generated in the central node. An active star network has an active central node that usually has the means to prevent echo-related problems.

tree topology: A network topology that, from a purely topologic viewpoint, resembles an interconnection of star networks in that individual peripheral nodes are required to transmit to and receive from one other node only, toward a central node, and are not required to act as repeaters or regenerators. *Note 1:* The function of the central node may be distributed. *Note 2:* As in the conventional star network, individual nodes may thus still be isolated from the network by a single-point failure of a transmission path to the node. *Note 3:* A single-point failure of a transmission path within a distributed node will result in partitioning two or more stations from the rest of the network.

null: 1. In an antenna radiation pattern, a zone in which the effective radiated power is at a minimum relative to the maximum effective radiated power of the main beam. *Note 1:* A null often has a narrow directivity angle compared to that of the main beam. Thus, the null is useful for several purposes, such as radio navigation and suppression of interfering signals in a given direction. *Note 2:* Because there is reciprocity between the transmitting and receiving characteristics of an antenna, there will be corresponding nulls for both the transmitting and receiving functions**. 2.** A dummy letter, letter symbol, or code group inserted in an encrypted message to delay or prevent its solution, or to complete encrypted groups for transmission or transmission security purposes. [NIS] **3**. In database management systems, a special value assigned to a row or a column indicating either unknown values or inapplicable usage. **4.** *Synonym* **node** (def. #4).



network topologies

Nyquist interval: The maximum time interval between equally spaced samples of a signal that will enable the signal waveform to be completely determined. The Nyquist interval is equal to the reciprocal of twice the highest frequency component of the sampled signal. In practice, when analog signals are sampled for the purpose of digital transmission or other processing, the sampling rate must be more frequent than that defined by Nyquist's theorem, because of quantization error introduced by the digitizing process. The required sampling rate is determined by the accuracy of the digitizing process.

Nyquist rate: The reciprocal of the Nyquist interval, *i.e.*, the minimum theoretical sampling rate that fully describes a given signal, i.e., enables its faithful reconstruction from the samples. *Note*: The actual sampling rate required to reconstruct the original signal will be somewhat higher than the Nyquist rate, because of quantization errors introduced by the sampling process.

Nyquist's theorem: A theorem, developed by H. Nyquist, which states that an analog signal waveform may be uniquely reconstructed, without error, from samples taken at equal time intervals. The sampling rate must be equal to, or greater than, twice the highest frequency component in the analog signal. *Synonym* **sampling theorem.**

orderwire: *See* **orderwire circuit.**

orderwire circuit: A voice or data circuit used by technical control and maintenance personnel for coordination and control actions relative to activation, deactivation, change, rerouting, reporting, and maintenance of communications systems and services. *Synonyms* **engineering channel, engineering orderwire, orderwire, service channel.**

packet: In data communication, a sequence of binary digits (arranged in a specific format), including data and control signals, that is transmitted and switched as a composite whole.

packet transfer mode: A method of information transfer, by means of packet transmission and packet switching, that permits dynamic sharing of network resources among many connections.

path: 1. In communications systems and network topologies, a route between any two points. **2.** In radio communications, the route that (a) lies between a transmitter and a receiver and (b) may consist of two or more concatenated links. *Note:* Examples of paths are line-of-sight paths and ionospheric paths. **3.** In a computer program, the logical sequence of instructions executed by a computer. **4.** In database management systems, a series of physical or logical connections between records or segments, usually requiring the use of pointers.

point-to-point link: A dedicated data link that connects only two stations.

point-to-point transmission: Communications between two designated stations only.

polar cap absorption: An intense radiowave absorption phenomenon in magnetic polar regions, and one of the most catastrophic events in connection with HF radio propagation in the high-latitude zone.

polling: 1. Network control in which the control station invites tributary stations to transmit in the sequence specified by the control station. **2.** In point-to-point or multipoint communication, the process whereby stations are invited one at a time to transmit. **3.** Sequential interrogation of devices for various purposes, such as avoiding contention, determining operational status, or determining readiness to send or receive data. **4.** In automated HF radio systems, a technique for measuring and reporting channel quality.

pulse sounding: *See* **sounding.**

push-to-talk (PTT) operation: In telephone or two-way radio systems, that method of communication over a speech circuit in which the talker is required to keep a switch operated while talking. *Note*: In two-way radio, push-to-talk operation must be used when the same frequency is employed by both transmitters. For use in noisy environments, or for privacy, some telephone handsets have push-to-talk switches that allow the speaker to be heard only when the switch is activated. *Synonym* **press-to-talk operation.**

query call: In adaptive high-frequency (HF) radio, an automatic-link-establishment call that requests responses from stations having connectivity to the destination specified in the call.

queue: A set of items, such as telephone calls or packets, arranged in sequence. *Note*: Queues are used to store events occurring at random times and to service them according to a prescribed discipline that may be fixed or adaptive.

queue traffic: 1. A series of outgoing or incoming calls waiting for service. **2.** In a store-and-forward switching center, the outgoing messages awaiting transmission at the outgoing line position.

queuing: The process of entering elements into or removing elements from a queue.

queuing delay: 1. In a switched network, the time between the completion of signaling by the call originator and the arrival of a ringing signal at the call receiver. *Note*: Queues may be caused by delays at the originating switch, intermediate switches, or the call receiver servicing switch. **2.** In a data network, the sum of the delays between the request for service and the establishment of a circuit to the called data terminal equipment (DTE). **3.** In a packet-switched network, the sum of the delays encountered by a packet between the time of insertion into the network and the time of delivery to the addressee.

queuing theory: The theoretical study of waiting lines, expressed in mathematical terms--including components such as number of waiting lines, number of servers, average wait time, number of queues or lines, and probabilities of queue times' either increasing or decreasing. *Note:* Queuing theory is directly applicable to network telecommunications, server queuing, mainframe computer queuing of telecommunications terminals, and advanced telecommunications systems.

rake: A processing technique designed to compensate for multipath fading effects by “raking” together all multipath components that are encountered over a signal path. Raking belongs to a class of matched-filter techniques that may be used to dispose of selective fading. Appropriate modification of the concept (with adaptive equalization) permits elimination of intersymbol interference.

Rayleigh distribution: A mathematical statement, usually applied to frequency distributions of random variables, for the case in which two orthogonal variables are independent and normally distributed with unit variance.

Rayleigh fading: In electromagnetic wave propagation, phase-interference fading caused by multipath, and which may be approximated by the Rayleigh distribution.

real-time channel evaluation (RTCE): The process of measuring appropriate parameters from a set of communication channels in real time and using the data thus obtained to describe quantitatively the states of those channels and hence the capabilities for passing a given class, or classes, of communication traffic.

reception reliability: the probability that for a given circuit and for all transmitted frequencies a specified performance is achieved.

reflector: **1.** In Yagi antenna systems, the element (behind the driven element) that is used to produce a unidirectional radiation pattern. **2.** A select e-mail mailing list that consists of e-mail addresses for a specific interest group. *Synonyms:* **e-mail exploder, mailing list, server.**

relay: **1.** To retransmit a received message from one station to another station. **2.** An electromechanical or semiconductor switch (*i.e.,* solid-state relay) in which a current or voltage applied across one port or terminal controls electrical currents or voltages that appear across another terminal or terminals.

reliability: **1.** The probability that a specified performance is achieved. **2.** The ability of an item to perform a required function under stated conditions for a specified period of time. **3.** The continuous availability of communication services to the general public, and emergency response activities in particular, during normal operating conditions and under emergency circumstances with minimal disruption. *See also*

- **basic mode reliability**
- **circuit reliability**
- **mode reliability**
- **reception reliability**
- **service reliability**

ROTHR: relocatable over-the-horizon radar.

route: **1.** In communications systems operations, the geographical path that is followed by a call or message over the circuits that are used in establishing a chain of connections. **2.** To determine the path that a message or call is to take in a communications network. *Note*: In a Transmission Control Protocol/Internet Protocol (TCP/IP) internet, each IP datagram is routed separately. The route a datagram follows may include many gateways and many physical networks. **3.** To construct the path that a call or message is to take in a communications network in going from one station to another or from a source user end instrument to a destination user end instrument.

route diversity: The allocation of circuits between two points over more than one geographic or physical route with no geographic points in common.

route matrix: In communications network operations, a record that indicates the interconnections between pairs of nodes in the network, and is used to produce direct routes, alternate routes, and available route tables from point to point.

router: In data communications, a functional unit used to interconnect two or more networks. *Note 1:* Routers operate at the network layer (layer 3) of the ISO Open Systems Interconnection—Reference Model. *Note 2:* The router reads the network layer address of all packets transmitted by a network, and forwards only those addressed to another network.

RTCE: **real-time channel evaluation.**

RTTY: **radio teletype.**

scanning: **1.** In telecommunications systems, examination of traffic activity to determine whether further processing is required. *Note:* Scanning is usually performed periodically. **2.** In television, facsimile, and picture transmission, the process of successively analyzing the colors and densities of the object according to a predetermined pattern. **3.** The process of tuning a device through a predetermined range of frequencies in prescribed increments and at prescribed times. *Note:* Scanning may be performed at regular or random increments and intervals. **4.** In radar and radio direction-finding, the slewing of an antenna or radiation pattern for the purpose of probing in a different direction. *Note 1:* In radar, scanning may be mechanical, using a rotary microwave joint to feed the antenna, or electronic, using a phased array of radiators, the radiated pattern (beam) of which depends on the relative phases of the signals fed to the individual radiators. *Note 2:* In civilian air traffic control radar, scanning usually implies continuous rotation of the antenna or beam about a vertical axis. In military radars, scanning may occur about other than a vertical axis, and may not encompass a full 360°.

service reliability: the probability that for a specified percentage of the service area and for all transmitted frequencies a specified performance will be achieved.

SID: sudden ionospheric disturbance.

signal-to-noise ratio (SNR): The ratio of the amplitude of the desired signal to the amplitude of noise signals at a given point in time. [Joint Pub. 1-02] SNR is expressed as 20 times the logarithm of the amplitude ratio, or 10 times the logarithm of the pour ratio. SNR is usually expressed in dB and in terms of peak values for impulse noise and root-mean-square values for random noise. In defining or specifying the SNR, both the signal and noise should be characterized, *e.g.,* peak-signal-to-peak noise ratio, in order to avoid ambiguity.

selcall: *Acronym for* **selective calling.** Calling from one station in which call identification is sent to signal automatically one or more remote stations and to establish links among them. *Note 1:* Selective calling may be used to un-mute the speakers at designated stations or to initiate a handshake for link establishment. *Note 2:* Selective calling is specified in CCIR Recommendations for HF and VHF/UHF radio, generally for ship-to-shore, ship-to-ship, aircraft-to-aircraft, and aircraft-to-ground communications.

selective calling: *See* **selcall**.

skywave: A radio wave that travels upward from the antenna. *Note:* A skywave may be reflected to Earth by the ionosphere.

SHF: 3 to 30 GHz, radio propagation frequencies used principally in troposcatter and LOS situations.

space diversity: A method of transmission or reception, or both, in which the effects of fading are minimized by the simultaneous use of two or more physically separated antennas, ideally separated by one or more wavelengths.

SNR: *Abbreviation for* **signal-to-noise ratio.**

sounding: **1.** In automated HF radio systems, the broadcasting of a very brief signal, containing the station address, station identifier, or call sign, to permit receiving stations to measure link quality. **2** The ability to empirically test selected channels (and propagation paths) by providing a very brief, beacon-like, identifying broadcast which may be utilized by other stations to evaluate connectivity, propagation, and availability; and to select known channels for possible later use for communications. The sounding signal is a unilateral, one-way transmission which is performed at periodic intervals on unoccupied channels. If used, the following sounding parameters must be consistently applied in an agreed-upon manner: frequency of use, length of time it can be used, and length of time to wait after a faulty attempt.

source quench: A congestion-control technique in which a computer experiencing data traffic congestion sends a message back to the source of the messages or packets causing the congestion, requesting that the source stop transmitting.

store-and-forward (S-F): Pertaining to communications systems in which messages are received at intermediate routing points and recorded *i.e.,* stored, and then transmitted, *i.e.,* forwarded, to the next routing point or to the ultimate recipient.

sudden frequency deviation: A quasi-global disturbance phenomenon that may influence long-haul HF systems and that occurs within minutes of the appearance of an X-ray flare on the Sun's surface.

SWF: short wave faces A quasi-global disturbance phenomenon that may influence long-haul HF systems and that usually occurs within minutes of the appearance of an X-ray flare on the solar surface.

synchronism: 1. The state of being synchronous. **2.** For repetitive events with the same, multiple, or submultiple repetition rates, a relationship among the events such that a significant instant of one event bears a fixed time relationship to a corresponding instant in another event. Synchronism is maintained when there is a fixed, *i.e.,* constant, phase relationship among the group of repetitive events. **3.** The simultaneous occurrence of two or more events at the same instant on the same coordinated time scale.

synchronization: 1. The attaining of synchronism. **2.** The obtaining of a desired fixed relationship among corresponding significant instants of two or more signals. **3.** A state of simultaneous occurrences of significant instants among two or more signals.

throughput: 1. The number of bits, characters, or blocks passing through a data communication system, or portion of that system. Throughput may vary greatly from its theoretical maximum. Throughput is expressed in data units per period of time; *e.g.,* in the DDN, as blocks per second. **2.** The maximum capacity of a communications channel or system. **3.** A measure of the amount of work performed by a system over a period of time, *e.g.,* the number of jobs per day.

traffic: 1. The information moved over a communication channel. **2.** A quantitative measurement of the total messages and their length, expressed in CCS or other units, during a specified period of time.

traffic analysis: 1. In a communications system, the analysis of traffic rates, volumes, densities, capacities, and patterns specifically for system performance improvement. [From Weik '89] **2.** [The] study of communications characteristics external to the text. [NIS] **3.** The analysis of the communications-electronic environment for use in the design, development, and operation of new communications systems. [From Weik '89]

traffic capacity: The maximum traffic per unit of time that a given telecommunications system, subsystem, or device can carry under specified conditions.

traffic engineering: The determination of the numbers and kinds of circuits and quantities of related terminating and switching equipment required to meet anticipated traffic loads throughout a communications system.

traffic-flow security: 1. The protection resulting from features, inherent in some cryptoequipment, that conceal the presence of valid messages on a communications circuit; normally achieved by causing the circuit to appear busy at all times. [After JP1] **2.** Measures used to conceal the presence of valid messages in an on-line cryptosystem or secure communications system. *Note:* Encryption of sending and receiving addresses and causing the circuit to appear busy at all times by sending dummy traffic are two methods of traffic-flow security. A more common method is to send a continuous encrypted signal, whether or not traffic is being transmitted.

traffic intensity: A measure of the average occupancy of a facility during a specified period of time, normally a busy hour, measured in traffic units (erlangs) and defined as the ratio of the time during which a facility is occupied (continuously or cumulatively) to the time this facility is available for occupancy. Note: A traffic intensity of one traffic unit (one erlang) means continuous occupancy of a facility during the time period under consideration, regardless of whether or not information is transmitted. *Synonym* **call intensity.**

traffic load: The total traffic carried by a trunk or trunk group during a specified time interval.

traffic monitor: In a communications network, a service feature that provides basic data on the amount and type of traffic handled by the network.

traffic overflow: 1. That condition wherein the traffic offered to a portion of a communication system exceeds its capacity and the excess may be blocked or may be provided with alternate routing. **2.** The excess traffic itself.

traffic unit: *Synonym* **erlang**.

transmit flow control: In data communications systems, control of the rate at which data are transmitted from a terminal so that the data can be received by another terminal. *Note 1:* Transmit flow control may occur between data terminal equipment (DTE) and a switching center, via data circuit-terminating equipment (DCE), or between two DTEs. The transmission rate may be controlled because of network or DTE requirements. *Note 2:* Transmit flow control can occur independently in the two directions of data transfer, thus permitting the transfer rates in one direction to be different from the transfer rates in the other.

UHF: ultra-high frequency (300-3000 MHz) used for line-of-sight propagation (SATCOM, broadcast, radar, navigation, and TV).

VHF: very high frequency (30-300 MHz), used for line-of-sight and Es scatter propagation. [Television and FM broadcast.]

VLF: very low frequency (3-30 kHz), used for waveguides and for groundwave propagation. [Navigation, standard frequency transmission, transmission of standard time signals.]

voiceband: *Synonym* **voice frequency.**

voice channel availability: The probability of finding a 2.5-kHz spectral window where the interference level, measured within contiguous 100-Hz intervals throughout the 2.5-kHz window, is always below a defined threshold level. (This condition is not as highly correlated with congestion as might be supposed.) *[From Goodman, 1992, used with written permission.]*

voice frequency (VF): Pertaining to those frequencies within that part of the audio range that is used for the transmission of speech. In telephony, the usable voice-frequency band ranges from approximately 300 Hz to 3400 Hz. In telephony the bandwidth allocated for a single voice-frequency transmission channel is usually 4 kHz, including guard bands. *Synonym* **voiceband.**

white noise: Noise having a frequency spectrum that is continuous and uniform over a specified frequency band. White noise has equal power per hertz over the specified frequency band. *Synonym* **additive white gaussian noise.**

wideband: **1.** The property of any communications facility, equipment, channel, or system in which the range of frequencies used for transmission is greater than 0.1% of the midband frequency. "Wideband" has many meanings depending upon application. "Wideband" is often used to distinguish it from "narrowband," where both terms are subjectively defined relative to the implied context. **2.** In communications security systems, a bandwidth exceeding that of a nominal 4-kHz telephone channel. **3.** The property of a circuit that has a bandwidth wider than normal for the type of circuit, frequency of operation, or type of modulation. **4.** In telephony, the property of a circuit that has a bandwidth greater than 4 kHz. **5.** Pertaining to a signal that occupies a broad frequency spectrum. *Synonym* **broadband.**

ANNEX 9
REFERENCES AND BIBLIOGRAPHY

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