NRL Report 8637

Preliminary System Concept for an HF Intra-Task Force Communication Network

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August 9, 1983

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NAVAL RESEARCH LABORATORY
Washington, D.C.

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER
NRL Report 8637

2. GOVT ACCESSION NO.

3. RECIPIENT'S CATALOG NUMBER

4. TITLE (and Subtitle)
PRELIMINARY SYSTEM CONCEPT FOR AN HF INTRA-TASK FORCE COMMUNICATION NETWORK

5. TYPE OF REPORT & PERIOD COVERED
Interim report on a continuing NRL problem.

6. PERFORMING ORG. REPORT NUMBER

7. AUTHOR(s)
J. E. Wieselthier, D. J. Baker, A. Ephremides, and D. N. McGregor

8. CONTRACT OR GRANT NUMBER(s)

9. PERFORMING ORGANIZATION NAME AND ADDRESS
Naval Research Laboratory
Washington, DC 20735

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS
61153N; RR0210542; 75-0142-0-2
62721N; RF21222805; 75-0139-A-2

11. CONTROLLING OFFICE NAME AND ADDRESS
Office of Naval Research
Arlington, VA 22217

12. REPORT DATE
August 9, 1983

13. NUMBER OF PAGES
120

14. MONITORING AGENCY NAME & ADDRESS(if different from Controlling Office)

15. SECURITY CLASS. (of this report)
UNCLASSIFIED

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE

16. DISTRIBUTION STATEMENT (of this Report)

Distribution limited to U.S. Government agencies only; test and evaluation; August 1983. Other requests for this document must be referred to the Commanding Officer, Naval Research Laboratory, Washington, DC 20375.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)

18. SUPPLEMENTARY NOTES

19. KEY WORDS (Continue on reverse side if necessary and identify by block number)

Communications network	Military communications	Antijam communication
High frequency (HF)	Packet switching	Frequency hopping
Multiple access	Distributed Network Control	Spread spectrum
Task force	Frequency Shift Keying (FSK)	Error Correction Coding

20. ABSTRACT (Continue on reverse side if necessary and identify by block number)

A High Frequency (HF) Intra-Task Force (ITF) Network is being designed as a robust, survivable, antijam (AJ) communication network for the interconnection of mobile task force elements. The HF ITF Network must exhibit graceful degradation under severe stress. It must be designed for Extended Line of Sight (ELOS) communication among a variable number of platforms (ships, aircraft, and submarines), be capable of handling voice and data, and satisfy specific precedence, timeliness, and error-rate requirements. It must also provide point-to-point

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DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE
S/N 0102-014-6601

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

20. ABSTRACT (Continued)

and broadcast communication modes, and must interface with other networks to implement functional nets and/or serve as backup for long-haul traffic.

In this report we review the work accomplished to date in the design of the HF ITF Network. This work has produced a baseline design concept for the network and a detailed plan for the remaining steps for its completion.

We begin by discussing the requirements and constraints under which our efforts have proceeded. The major HF ITF Network design issues are then discussed in the context of the Open Systems Interconnection layered protocol structure, and network evaluation criteria are considered.

Next we discuss the Linked Cluster Architecture, which is central to the HF ITF Network concept. We describe the algorithms that have been developed to implement this architecture. The channel allocation problem is also addressed, and a preliminary concept of network operation is presented.

We then consider the signaling issues related to the design of the HF ITF Network. After discussing the complex nature of the HF channel, we study the issues that arise in point-to-point and network communication for the cases of both narrowband and wideband signaling. Results on the AJ capability provided by M-ary FSK signaling with convolutional coding and optimum diversity are presented. We also study the effects of other-user interference on error probability and channel throughput.

Finally, we review the main categories of multiple access methods with emphasis on the criteria to be employed for their evaluation as to suitability for use in the HF ITF Network. The relationship between multiple access protocols and the Linked Cluster Architecture is also discussed.

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EXECUTIVE SUMMARY

Scope

The High Frequency (HF) Intra-Task Force (ITF) Network is being designed as a robust, survivable, antijam (AJ) communication network for the interconnection of mobile task force elements. The HF ITF Network must exhibit graceful degradation under severe stress. It must be designed for Extended Line of Sight (ELOS) communication among a variable number of platforms (ships, aircraft, and submarines), be capable of handling voice and data, and satisfy specific precedence, timeliness, and error-rate requirements. It must also provide point-to-point and broadcast communication modes, and must interface with other networks in order to implement functional nets and/or serve as backup for long-haul traffic. The development of such a network is essential because fleet communication requirements have increased to the point where they far exceed the capabilities of existing communication systems.

In this report we review the work accomplished to date in the design of the HF ITF Network. This work has produced a baseline design concept for the Network and a detailed plan for the remaining steps for its completion. Both in-house and contracted efforts have contributed to the progress made thus far.

In a preliminary report [1] the problems in the design of an HF ITF Network were identified and reviewed. The progress accomplished since then is primarily in the areas of architectural organization, multiple access protocols, and signaling (a term which we use here to refer to waveform design and coding considerations). The results of these efforts are reviewed in this report. More detailed discussions of these studies can be found in two separate companion reports [2,3]. Also, a number of journal articles [4-7] and conference presentations [8-14] by the authors of this report have covered in detail various specialized aspects of the HF ITF Networking effort.

The ITF Network will consist of various platforms with markedly different characteristics, and is expected to support the traffic requirements of many diverse scenarios. The use of the HF (2 to 30 MHz) groundwave medium is dictated by its natural survivability properties in post nuclear detonation environments and by its ELOS communication range. At the same time HF suffers from time-variable and unpredictable fading and self-interference, and as a result it is extremely difficult to obtain an accurate model for the HF channel. Consequently, the ITF Network must exhibit a high degree of robustness with respect to channel behavior uncertainties both in terms of its organization and in terms of the signaling used. Furthermore, equipment limitations place additional important constraints on the network.

In the design of such a network many choices must be made for highly interdependent variables. It is not prudent to make arbitrary choices for any of these variables to facilitate the determination of the remaining ones, nor is it possible to determine simultaneously optimum or even simply "good"

choices for all of them. We have thus proceeded in a hierarchical fashion by choosing first those variables that either placed minimal constraints on others or allowed maximum flexibility in the subsequent choices. We quickly identified three areas of design issues that, although interdependent, could be pursued in a parallel fashion. These areas are:

1. the architectural organization of the network;

2. the signaling issues (i.e., waveform and coding considerations); and

3. the multiple access protocols for the sharing of communication resources.

We deferred for subsequent study other areas such as network link management, flow control, and routing as well as detailed waveform design.

In each of the areas in which progress was made we have obtained definite or "hard" conclusions for some of the issues and preliminary or "soft" conclusions for others pending additional investigations.

Design Choices

What are the design choices in the HF ITF Network? They can be summarized best in the context of the Open Systems Interconnection (OSI) layering structure that has been proposed by the International Standards Organization (ISO) as a means of describing networking protocols. Under this structure there are seven layers, each referring to the communication process between similar entities in the network, starting with layer 1 that describes the physical process of producing "local connections" and ending with layer 7 that describes the conceptual link between the end-users of the network. Layers 1 through 4 are of primary importance to the design of the HF ITF Network.

At the first (Physical) layer of our network, the function that must be performed at the transmitting node is the conversion of streams of digital symbols to HF waveforms, and at the receiving node the reverse operation must be performed. An important issue in the physical layer is the HF signal waveform design for broadband channels. Waveforms are needed that provide rapid bit synchronization, efficient bandwidth usage, low mutual interference levels among users, and protection from jamming. The second or Link layer is concerned with transforming a raw transmission facility into a virtually error free communication link. The highly variable quality of the HF channel implies the need for sophisticated error handling techniques, coding, encryption, and interference rejection. Another important issue at this layer is the selection of protocols for controlling access to the communication link. At the third or Network layer, paths must be established between nodes that are not within communication range of each other. The establishment of paths requires the specification of the methods of switching and link management that include routing. Fundamental decisions include whether to use circuit or packet switching, and whether to use centralized or distributed control. The fourth or Transport layer represents the interface between the Command and Control system and the communication system as well as the interface between different networks. The problems at this layer reflect back to problems in the lower layers as they concern operational "end-to-end" requirements such as response times and priorities, and they present new problem areas such as user-to-user error and flow control.

The higher layers, namely the Session (fifth), Presentation (sixth), and Application (seventh) layers, are not of direct concern to the network design at this time. They are user-oriented and do not concern the transportation of information, but rather the users' terminal software for the establishment of handshake with the intended destination, the transformation of data formats, and the ultimate user application.

The evaluation of a complex system such as the HF ITF Network is based on a hierarchy of performance measures which are, in order of relative importance:

- measures of survivability,
- measures of effectiveness, and
- measures of efficiency.

Measures of effectiveness refer to system performance primarily from a commander's viewpoint, while measures of efficiency deal mainly with system performance from an engineering viewpoint. These measures cannot be evaluated fully by analytical methods alone because of the complexity of the network. Thus, overall evaluation must also rely on simulation.

Network Architecture

The first major decision concerning the HF ITF Network is the Linked Cluster organizational architecture (Fig. 1). Many other design issues can easily be imbedded and studied in the framework of this architecture. Indeed, the desire to provide a framework in which other networking issues could be evaluated motivated our early consideration of a network architecture. To assure survivability, the proposed architecture is based on the use of distributed algorithms that enable the Task Force platforms to self-organize into a reliable network structure and to continually monitor the changing connectivities for the maintenance of such a structure. This structure consists of clusters of platforms within communication range of local controllers known as cluster heads. The architectural profile of the network at any given moment consists of clusters that either overlap or are linked to each other via gateways. The set of links that interconnect the cluster heads and gateways is known as the backbone network. The Linked Cluster Architecture is robust with respect to node and link losses. It also strikes a compromise between efficiency in the use of the network's resources and redundancy to ensure reliability. Thus, it provides alternate paths for relaying and routing purposes, but keeps the number of these paths under control. It is a flexible architecture that allows for many optional uses of the links once they are established. Such flexibility is essential because a number of constraints that could affect other design choices are not known precisely at this time; these include equipment constraints, threats to network operation (including jamming and node destruction), and possible changes in communication policy.

Under this architecture and its implementation algorithms the network is highly survivable, self-organizing, and automatically adaptive to link or node losses. It permits the use of a variety of multiple-access switching and routing protocols with either narrowband or wideband signaling. Finally, and perhaps most importantly, the architecture takes full advantage of the apparent shortcoming of wide variation of the communication range over the HF band. This has been accomplished by partitioning the HF band into a number of subbands, each with a bandwidth of a few MHz over which the communication range for groundwaves is approximately constant. The organization algorithm is run consecutively for each subband, thus producing a set of overlaid connectivity maps that give rise to a set of simultaneously operating networks. The HF ITF Network consists of this set of individual networks that are defined in separate subbands. Network management schemes will be developed to coordinate the operation of each of the individual networks into an effective overall ITF Network structure.

The length of time needed for the organization to be achieved in one subband is called an epoch, as is illustrated in Fig. 2, and has been estimated to be of the order of a few seconds. If we consider M, say ten, such subbands, then the total time for the completion of one cycle of reorganization across the entire HF band is approximately one minute. This reorganization process can be executed continuously. Thus once every minute and for a duration of about five or six seconds there would be an

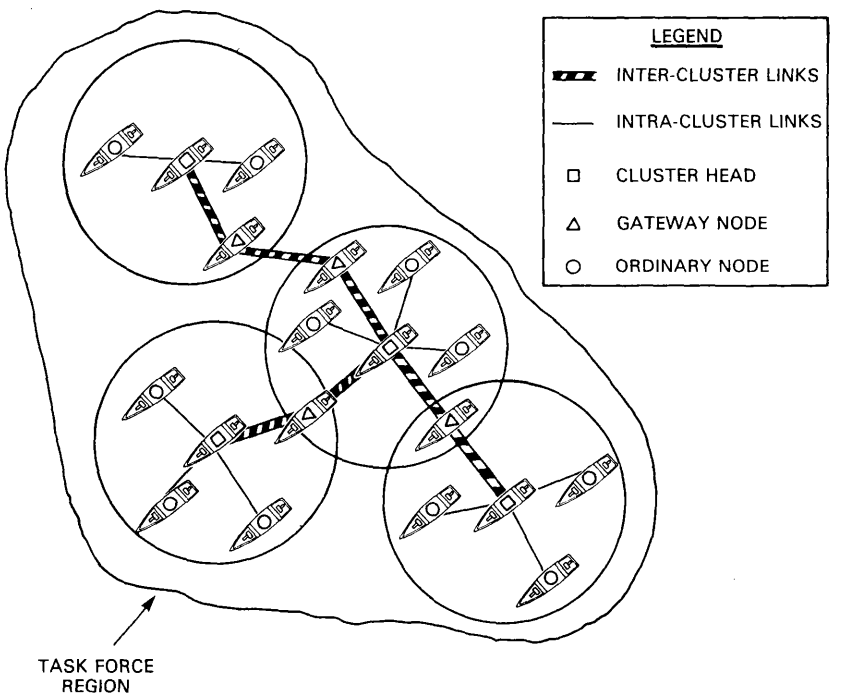


Fig.1 — Network organizational structure—Linked Cluster Architecture

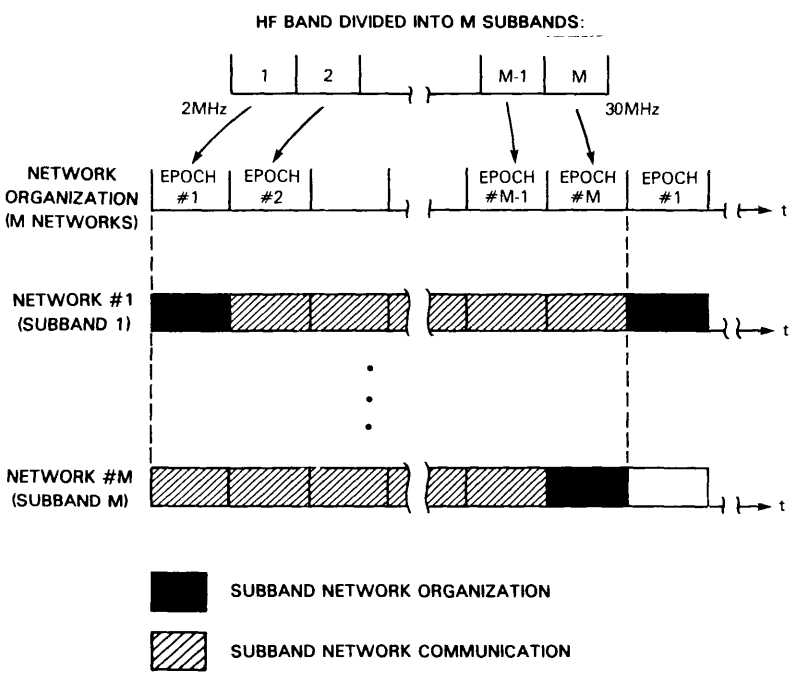


Fig. 2 — Timing structure for organization and communication under the Linked Cluster Architecture

update of the connectivity map at one particular frequency subband (with a bandwidth of about two to five MHz). The rest of the time during each cycle the links corresponding to the previous connectivity map are open for normal communication as indicated in Fig. 2.

Link Signaling Issues

The overriding factor in determining many of the ITF Network's features that distinguishes this network from other radio networks is in fact the special nature of the HF medium. The HF radio channel is both fading and dispersive with propagation occurring via both groundwaves and skywaves. The ITF Network will rely primarily on the use of groundwaves to connect nodes, because although groundwave attenuation varies with frequency and sea state conditions, it is much more predictable and less dispersive than skywave propagation, which is supported at any time only over a portion of the HF band. Skywave signals must be considered as a source of multipath interference. The use of skywaves to supplement groundwave paths within the ITF Network and to link the ITF Network with other networks will be considered in the future.

In addition to multipath, sources of interference in the HF channel include atmospheric noise, local platform noise, and other-user interference. In the networking environment other-user interference may be divided into two classes, i.e., interference resulting from platforms external to the network, and interference caused by other network members (or other platforms with which the network is communicating). Interference caused by other task force platforms is characteristic of a networking environment, and it is clear that network management schemes are needed to minimize the effects of such interference. A major part of the HF ITF Networking study has in fact been directed toward this problem. Interference arising from platforms external to the network and interference due to jamming cannot be controlled by the network. Since jamming represents the most significant limitation and threat to HF communication, it has been given special attention in the design of the ITF Network.

We have considered the signaling aspects of point-to-point communication and of multi-user communication for both narrowband and wideband environments. The following point-to-point discussion brings forth clearly many of the issues. The subsequent multi-user discussion complements this understanding by identifying additional issues that are unique to networking. Study of both narrowband and wideband networking considerations is necessary since present day narrowband signaling will be replaced by wideband signaling as new equipment is developed, necessitating a hybrid form of operation in the interim.

Point-to-Point Communication

Narrowband signaling is not capable of providing satisfactory protection from anticipated jamming threats, even with the use of adaptive antenna arrays and selective band use. The use of wideband (spread spectrum) signaling, however, can provide considerable protection from jamming. In addition, spread spectrum signaling provides selective addressing capability, code division multiple access (CDMA) capability, inherent privacy and security, low interceptibility, and high resolution ranging. It has been concluded that among the candidate schemes for spreading in the HF channel a pure Frequency Hopping (FH) system is the most practical choice for use in the ITF Network, because FH systems are more robust than Direct Sequence (DS) or Hybrid FH-DS systems. Specifically, FH systems are virtually immune to problems caused by differences in relative signal strength, are less sensitive to dispersion, and do not require a contiguous bandwidth. Also, the spreading factor can be considerably greater, and the pseudo-noise (PN) code acquisition is easier to achieve and more difficult to disrupt for such systems.

Another issue in any form of signaling is the selection of the modulation method. Noncoherent M-ary frequency shift keying (MFSK) is a practical scheme for the HF ITF Network because of its feasibility of implementation, its robustness with respect to fading and interference, and its compatibility with a wide range of hopping rates.

Bit error rate (BER) performance under worst case partial band (WCPB) noise jamming has been evaluated as a function of the equivalent signal-to-noise ratio for FH-MFSK signaling. Performance tradeoffs were developed for several alphabet sizes, many values of diversity, several coding schemes, both hard and soft decision receivers, known or unknown jammer state, and for nonfading as well as Rayleigh fading channels. From these results it is concluded that coding and/or diversity are essential for jamming resistance in the HF ITF Network employing FH-MFSK. In fact, when operating under a high quality data reception criterion (BER = 10^{-5}), AJ coding/diversity gains of the order of 35 to 37 dB are obtainable via the use of convolutional coding, with considerably reduced need for diversity. If the data reception criterion is relaxed to a medium quality level (BER = 10^{-3}), the AJ coding/diversity gain is of the order of 16 to 18 dB.

We have analyzed in detail the tradeoffs necessary to achieve acceptable levels of AJ performance. The detailed analyses and comparisons are presented in [3], and in more compact form in this report. For example, under some reasonable assumptions it is possible to operate links at a jammer to signal power ratio between 25 dB (at a data rate of 2400 bps) and 40 dB (at 75 bps) for a nominal case of 8-ary FSK signaling, a nonfading channel, 5 MHz spread bandwidth, 10^{-5} BER, soft decision receiver, worst case partial band noise jamming, and known jammer state. Results for 4-ary FSK are within 0.7 dB of those for 8-ary FSK. When the BER requirement is relaxed to 10^{-3}, and all other conditions are unchanged, the tolerable J/S ratio is increased by about 1.7 dB. Our estimates of jammer to signal levels at which satisfactory communication can be maintained may have to be reduced somewhat after some issues related to practical implementation are examined.

Multipoint (Network) Communication

When one considers multipoint or network communication, the signaling issues become considerably more complex because of the potential interference among the users. In a narrowband architecture, there are a number of frequency slots to be managed ("switched") and distributed to the users. The new issue then is the development of link management schemes that permit the efficient apportionment of these frequency slots to the users via either dedicated or shared links. In a wideband architecture, such as that envisioned for the HF ITF Network, the use of spread spectrum signaling provides an inherent natural means of multiplexing the different users with acceptable levels of interference. This is achieved via code division multiple access (CDMA) techniques, in which, for the proposed choice of frequency hopping, each FH pattern corresponds to a distinct code. CDMA operation is usually asynchronous, and therefore it is possible for two or more users (using different hopping patterns) to transmit simultaneously at the same frequency, resulting in loss of data. The loss of data caused by such frequency "hits" can be handled via the use of coding and/or diversity.

The number of local users that can simultaneously use the same wideband channel is approximately one tenth of the number of frequency slots into which the channel is divided and over which the users are hopping. The exact number depends on factors such as signal-to-noise ratio, modulation scheme, coding, diversity, and acceptable BER criterion. Frequency re-use at distant parts of the network is of course possible. Nevertheless, the limitation in interference rejection capability that can be provided by a pure FH-CDMA system requires the development of additional control and channel-sharing ideas. Important issues specifically related to the use of FH-CDMA include synchronization requirements, hopping rates, the generation and distribution of FH patterns, and contention among signals that use either the same or different FH codes. Ideas for control and channel sharing come from the field of multiple access protocols.

Multiple Access Protocols

While the Linked Cluster Architecture provides a highly survivable organizational structure for the ITF Network, it does not specify how the HF band is to be shared by the task force platforms. What is needed is a set of multiple access protocols, imbedded within the Linked Cluster structure, that will permit the efficient allocation of bandwidth and equipment resources.

The choice of multiple access protocols for the ITF Network has been an important one since the initial stages of the network effort. The work on the architecture and on signaling has constantly focused attention on the access protocols that may be used in the network. The whole area of multiple access has received considerable attention in the last decade with the advent of packet switching in radio nets as well as the development of local ring networks. The traditional and straightforward schemes of distributing channel capacity by frequency or time division methods have been augmented by a variety of alternative strategies, each of which has its advantages as well as its limitations, making selection extremely difficult.

First of all, the nontraditional methods include the so called code division approach that accomplishes essentially what the frequency and time division approaches do, with improved AJ capability resulting from the use of spread spectrum signaling. However, there are methods with radically different approaches such as random access or contention-based techniques as well as reservation schemes. These schemes have originally been proposed and studied in the time domain. Currently under study are code domain versions of these schemes. Any of these methods may be used in a static (nonswitched) fashion or in a responsive, dynamic way that takes into account the status of traffic load and distribution in the network. Especially important is the compatibility of the multiple access protocol with the Linked Cluster Architecture and with the selected signaling structures.

We propose the use of dedicated links (actually fractions of links apportioned on a contention-free time-division basis) for much of the intercluster communication over the backbone network. Distributed channel allocation algorithms for this purpose are presently under development. Intracluster communication consists of communication between a cluster head and its members. Communication from a cluster head to its members could be implemented either on a broadcast or a point-to-point basis, depending on the type of traffic. The multiple access protocol used by cluster members to gain access to their heads will very likely combine elements of fixed assignment, reservation, and conflict resolution. A firm commitment to the details of multiple access protocol choices is not necessary until other design issues such as routing are also addressed. An important early decision, however, is the implementation of the access and switching methods partially in the code domain via the use of FH-CDMA. In all cases, owing to equipment limitations as well as limits on the number of spread spectrum signals that can simultaneously be present in a local area, channel resources will also have to be shared in the time domain.

Baseline HF ITF Network System Concept

To summarize, the work accomplished thus far in the design of the HF ITF Network has resulted in a baseline concept for the architecture of the network, for the signaling methods, and for the multiple access protocols. This provides a comfortable framework for the study of the remaining design issues. The following listing indicates our recommendations for a survivable HF ITF Network design.

NETWORKING: Robust Network Design

- Number and Types of Nodes: 2 to 100; ships, aircraft and submarines.
- Task Force Dispersion: approximately 500-km diameter (ELOS communication ranges).
- Network Structure: Overlay of several (expected to be between five and ten) networks in different portions of HF band.
- Network Architecture: Overlapping clusters of nodes within each of these several frequency subbands.

- Network Control: Hybrid (centralized local control within clusters, and distributed operation among clusters).

- Intracluster Operation: Protocols will include features of broadcasting, contention, and reservation. They must be compatible with frequency hopping spread spectrum signaling.

- Intercluster Operation: Dedicated links over Backbone Network and Auxiliary Links; a distributed algorithm for link activation is presently under development.

- Topological Changes: Adaptive and robust network control (continual updating of connectivities).

SIGNALING: Robust Waveform Design

- Frequency Band: HF (2 to 30 MHz).

- Propagation Medium: HF groundwave.

- AJ Scheme: Frequency hopping spread spectrum.

- Modulation: M-ary FSK ($M = 4$ or 8 are possible choices).

- Receiver Detection: Noncoherent.

- Coding and/or Diversity: Required to combat jamming, fading, and other-user interference. Both convolutional and block coding are being considered.

- Signaling-Related Parameters:

  — Data Rates: 75 b/s to 2400 b/s

  — Acceptable BER for data: 10^{-3} to 10^{-5}.

  — Typical Hopping Bandwidth (Bandwidth of one of the subbands): 2 to 5 MHz.

- Tolerable Received Jammer to Signal Power Ratios (Convolutional Coding and Optimum Diversity; 8-ary FSK; 5MHz spread BW; BER = 10^{-5}; soft decision receiver; known jammer state*):

	2400 b/s	75 b/s
Worst Case Partial Band Noise Jammed Nonfading Channel:	24.9 dB $\leqslant$ J/S $\leqslant$ 39.9 dB	
Rayleigh Fading Channel With Broadband** Jamming:	22.7 dB $\leqslant$ J/S $\leqslant$ 37.7 dB	

Future Efforts

Our future efforts will proceed within the framework provided by the baseline concept presented above. Several of the remaining design issues have been noted, e.g., the specification of multiple

*i.e., receiver can detect which symbols are jammed.

**Broadband noise jamming is worst case partial band noise jamming for the Rayleigh fading channel.

access protocols for intracluster communication and the continued development of link activation algorithms for distributed control. In addition, a number of network parameters still to be determined were noted, including the number of simultaneously operating networks (and related to it the bandwidth of each of these networks and therefore the frequency hopping bandwidth), and the alphabet size M for M-ary FSK signaling. A major signaling issue will be the acquisition and maintenance of synchronization of the frequency hopped signals. The tolerable J/S ratios presented above are based on an ideal receiver that uses soft decision decoding and is aware of which of the received chips have been jammed. These results can be easily extended to the case of a hard decision receiver, either with or without such jammer state information. Further work is needed to assess the impact of the nonideal nature of both the HF channel and the limitations imposed by practical equipment considerations.

A study plan that summarizes past, current, and future efforts is presented in Appendix A. Some of the major items to be addressed in the future include:

- the specification of multiple access protocols;
- practical considerations relating to tolerable J/S ratios;
- the development of routing methods;
- AJ networking techniques (as opposed to the AJ link techniques discussed in this report);
- the development of detailed test scenarios;
- the development of a simulation test bed;
- voice/data integration;
- specification of the role of aircraft and submarines;
- internetting issues;
- acquisition and maintenance of synchronization;
- security issues (including their impact on synchronization);
- priority structures; and
- the design of network protocols up through the transport layer.

Outline of the Report

In Sec. 1 an overview of the HF ITF Network is presented. We begin by discussing the requirements and constraints under which our efforts have proceeded. The major HF ITF Network design issues are then discussed in the context of the OSI layered protocol structure. Network evaluation criteria are discussed. A study outline that summarizes our past, current, and future efforts is presented in Appendix A.

Central to the HF ITF Network concept is the Linked Cluster Architecture and the algorithms that have been developed to implement it. These topics are discussed in Sec. 2. In this section the channel allocation problem is also addressed, and a preliminary concept of network operation is presented.

In Sec. 3 the signaling issues related to the design of the HF ITF Network are addressed. After discussing the complex nature of the HF channel, we discuss the issues that arise in point-to-point and network communication. Both narrowband and wideband signaling are considered. Results on the AJ performance provided by frequency hopped M-ary FSK signaling with convolutional coding and diversity are presented. We also discuss the effects of other-user interference on error probability and channel throughput.

Section 3 is supplemented by four appendixes. In Appendix B we discuss spread spectrum signaling considerations for the HF ITF Network. In Appendix C we discuss the basis for the choice of noncoherent frequency shift keying (MFSK) as the modulation method. Appendixes D and E consider the AJ performance of uncoded and coded signaling schemes, respectively.

In Sec. 4 the main categories of multiple access methods are reviewed. Emphasis is placed on the criteria to be employed for their evaluation as to their suitability for use in the HF ITF Network. The relationship between multiple access protocols and the Linked Cluster architecture is discussed.

In Sec. 5 we present our major conclusions from this research, and outline our future plans.

PRELIMINARY SYSTEM CONCEPT FOR AN HF INTRA-TASK FORCE COMMUNICATION NETWORK

1.0 HF ITF SYSTEM DEVELOPMENT OVERVIEW

Fleet communication requirements have increased to the point where they far exceed the capabilities of existing communication systems. This is particularly evident in the area of antiair warfare (AAW) where ever increasing missile speeds and ranges keep shortening the allowed response time to such attacks. In addition, the number of air tracks that must be maintained during AAW operations can result in extremely high communication traffic loads. The situation is greatly exacerbated by enemy jamming, the destruction of communication satellites, and the loss of airborne UHF relays.

In the absence of satellites and airborne relays, one is left with HF as a medium for Extended Line of Sight (ELOS) communication. High frequency is important for intra-task force ELOS communication for two reasons: i. HF groundwave propagation is relatively immune to nuclear effects, and ii. over the horizon communication is possible without the use of relays. Because of these two features, HF is likely to be especially relied upon when the task force is under attack. Unfortunately, Navy HF nets do not currently have a level of survivability close to that which HF radio wave propagation permits. The HF nets are not survivable because they are narrowband, and thus highly susceptible to jamming. Fleet data nets, such as Link 11, are not survivable because they rely on a central controller. In addition, most task force HF nets are inefficient.

Most HF nets that are used for intra-task force communication are "free" nets. That is, access to the communication channel by a net member is not controlled. The push-to-talk (PTT) voice nets are examples of free nets. The problem with free nets is that throughput becomes very low if the communication load becomes very high. This is because the users tend to interfere with each other so often that virtually nothing gets through. In Sec. 4 we shall see that this form of channel access is an example of inefficient use of valuable communication resources. Such inefficiences reduce network traffic throughput and increase communication delays, thus reducing the effectiveness of these networks in highly stressed environments such as can occur in antiair warfare.

In an effort to overcome many of the deficiencies of the existing systems, the HF Intra-Task Force (ITF) Communication Network is being designed. This new network will rely on modern networking techniques including: distributed control, adaptive routing, integrated (voice/data) switching, channel sharing, and packetized transmissions.

1.1 HF ITF Network Requirements and Constraints

A previous report [1] describes the requirements and constraints imposed upon the HF ITF Network and previews the significant networking issues that arise in its design. An organizational architecture for this network is described in [2]. In the present report we examine in greater detail the operation of the network and the overall system design. We begin by reviewing the requirements and constraints imposed upon the network.

Manuscript approved July 20, 1982.

1.1.1 Summary of Requirements and Constraints

The requirements and constraints that apply to the ITF Network were extracted from several naval references including [15,16]. A summary of the major requirements appears in Table 1.1. Short discussions of each requirement follow this table.

Table 1.1 — Summary of the Major Requirements Imposed upon the HF ITF Network

Item	Requirement
1. Number and types of nodes	2 to 100; ships, aircraft, and submarines
2. Traffic types	voice and data
3. Timeliness	5 s to several h
4. Acceptable bit error rates:	
Voice	10^{-3}
Data (including message and imagery)	10^{-3} to 10^{-5}
5. Traffic precedence levels	4
6. Traffic classification levels	4
7. Communication medium	HF radio (2 to 30 MHz)
8. Communication modes	Point-to-point and broadcast
9. Emission control modes	LPI/LRI

Number and Types of Nodes — Nodes can be ships, aircraft, or submarines. The number of nodes in the task force may range from 2 to 100; however, it is unlikely that a task force will include more than about 40 ships [17]. A task force may include, but is not limited to, the platform types listed in Table 1.2. Other task force nodes include amphibious platforms and noncombat ships. Important for network design considerations is the fact that the nodes are mobile.

Traffic — Past emphasis on the use of voice in naval communications indicates that a significant portion of the ITF traffic will be voice. Indeed, one estimate [18] projects that 70% of the 1985 task force traffic will be voice. Recent advances in digital processing techniques may result in greater emphasis on data communication than is suggested by the above estimate; however, voice undoubtedly will remain an important means of communication within the task force for the foreseeable future. Consequently, detailed specifications of traffic load requirements for voice as well as data are needed. Voice messages, however, need not be in analog form.

The Tri-Lab report [19] provides the necessary data base for obtaining traffic load requirements. This report analyzes the communication requirements for 22 representative naval operational situations (OPSITS). OPSITS differ from scenarios in that they treat warfare areas singly and they do not indicate force levels. For each OPSIT the command, control, and communication needs were identified and the communication requirements were characterized according to the format of Fig. 1.1. We examine the

Table 1.2 — Partial Listing of Task Force Platform Types

Subsurface and Surface Platform Types	
CV/CVN	Multipurpose aircraft carrier/(nuclear-powered)
CG/CGN	Guided missile cruiser/(nuclear-powered)
D	Destroyer
DDG	Guided missile destroyer
FF	Frigate
FFG	Guided missile frigate
SSN	Submarine (nuclear-powered)
Airborne Plateform Types	
VAW(AEW)	Airborne early warning (E-2 aircraft)
VA	Attack aircraft
VF	Fighter (carrier based)
VS(S-3A)	ASW fixed wing (carrier based)
VP,MPA	Patrol aircraft
HS	ASW helicopter
LAMPS	Light Airborne Multipurpose System
VQ	Reconnaissance aircraft

implications of these communication needs in Sec. 1.1.2. Unfortunately, the Tri-Lab data base does not distinguish between LOS and ELOS communications; such a traffic breakdown is needed to determine traffic loading on the HF ITF net, which is basically an ELOS system.

The Tri-Lab data base was used in the Sea Based Air study [20] to determine traffic loading for a combined antiair and antisubmarine warfare scenario. This study is particularly important because antiair warfare is expected to generate the greatest traffic loads that the HF ITF will be required to handle. Fortunately, the Sea Based Air study does classify communication traffic loading as either LOS or ELOS. Thus the ELOS traffic levels obtained for the Sea Based Air scenario are directly applicable to the HF ITF Network. The latter results are examined in Sec. 1.1.2.

Timeliness — This is the tolerable delay for information transfer between users while the information is still useful. The most demanding requirements in this area are associated with air track updates which occur every 5 s.

Quality of Service — Reference [16] gives a maximum bit error rate (BER) for message traffic of 10^{-3}. This figure does not include user-associated error control. Error control procedures should assure that header information for store and forward traffic is transmitted at a BER of better than 10^{-5}.

The allowed BER for imagery is given by [16] as 10^{-5}. This assumes that the imagery is transmitted as compressed data.

The BER requirements given above and in Table 1.1 should not be regarded as absolute, fixed requirements. Specifically, we do not rule out the possibility that new systems may come along that will require greater accuracies than we have indicated.

LINE NUMBER	
COMMAND DECISION LEVEL	
FUNCTION	
INFORMATION NEED	
Originator	CHARACTERISTICS
Receiver	
Information Length	
User Form	
Acknowledgment	
Volume	
Maximum Range	
Interoperability	
Intercept Resistance	
Security	
Jam Resistance	
Communications Essential Level	
Timeliness	
Comments	

Fig. 1.1 — Tri-Lab data base format for characterizing information transfer requirements

Traffic Precedence Levels — Each naval message is assigned a precedence and a classification. The precedence determines the relative importance of the message, and thus the order in which it will be transmitted. The precedences are, in ascending order, ROUTINE, PRIORITY, IMMEDIATE, and FLASH; additional precedence levels may be added in the future.

Traffic Classification Levels — Messages are classified according to their content, and are transmitted and distributed according to that classification. In order of ascending level of sensitivity, the message classifications are UNCLASSIFIED, CONFIDENTIAL, SECRET, and TOP SECRET. Classification and precedence are not related, i.e., a message may have any combination of classification and precedence levels.

Communication Medium — The choice of HF as the primary communication medium for ITF ELOS communications is based on the relative immunity to nuclear effects of HF groundwave propagation and on the ability of these waves to propagate beyond the horizon. However, some of the other characteristics of the HF medium constrain the ITF network design. Those properties of the HF medium that are of particular importance for the ITF network design study are described next.

HF waves propagate as both groundwaves and skywaves. The theory of groundwave propagation is given in [21]. Important for the ITF network design are the following characteristics of HF groundwave propagation: i. Attenuation increases with increasing sea state ii. Attenuation decreases with increasing altitude, and, most important, iii. higher frequency HF groundwaves attenuate much more rapidly than lower frequency HF groundwaves. Propagation questions are considered in greater detail in Sec. 3.1.

Another factor of considerable importance is the noise in the HF band. Noise sources that must be considered include atmospheric and galactic noise, other-user (nonlocal) interference, mutual (local) interference from other ITF network users, and jamming. Again, interference issues are addressed in greater detail in Sec. 3. Noise resulting from jamming is likely to be the most severe of all noise sources. The threat to the ITF net of jamming is treated in Sec. 3.2.5. The likelihood that raw error rates on the HF channel will be relatively high (compared with error rates typical for wire-line networks) places a significant constraint on the design of the HF ITF Network. For example, in many cases coding may be needed to achieve acceptable error rate levels.

Emission Control — The network must be able to operate in low probability of intercept (LPI), limited range of intercept (LRI), and low probability of exploitation (LPE) modes.

Equipment Limitations — Equipment limitations place additional important constraints on the HF ITF Network. The numbers of channels that can be used simultaneously will profoundly affect the ITF architecture. Typical expected numbers of narrowband transmitters and receivers available for use on naval combatant platforms are shown in Table 1.3. A new, wideband HF system, which is being developed for ITF AJ communications, is expected to have from one to four transmitters and receivers per platform; each transmitter may be able to transmit up to eight signals simultaneously. However, because these numbers are only estimates, the ITF network design must be flexible enough to accommodate a wide variation in the numbers of transmitters and receivers available on each platform.

The speed at which transmitters and receivers can acquire synchronization will have an impact on the design of the ITF net. Functions to be performed include bit, code, and crypto synchronizations. The synchronization speed of the equipment to be used by the ITF net is still unknown.

The relatively small (with respect to wavelengths in the HF band) space available for antennas on naval platforms makes large, highly directive arrays nonfeasible. In addition, ship superstructures can significantly affect antenna patterns [22]. Thus, although some control over directionality is possible, it is not likely that HF antenna patterns will be dynamically controlled to any great extent. In some cases, highly directional antennas can lead to signal fading caused by platform motion; such fading is especially pronounced for aircraft.

Table 1.3 — Representative Numbers of Narrowband Transmitters and Receivers Available on Nonamphibious Task Force Platforms [23(1)]

Subsurface and Surface Platforms								
	SSN	SSBN	CG	CV	DD	DDG	FF	FFG
XMTRS	2	1	5	11	3	5	3	5
XCVRS	0	0	2	2	2	2	2	1
RCVRS	2	2	12	22	9	10	8	9

Airborne Platforms						
	VAW (AEW)	VA, VF	VS (S-3A)	VP, MPA	HS, LAMPS	VQ
XMTRS	0	0	0	0	0	0
XCVRS	2	0	1	2	1	3
RCVRS	0	0	0	0	0	0

1.1.2 Task Force Scenarios and Network Load Estimation

(The material for this section will appear in a classified addendum.)

1.2 HF ITF Network Design Issues and the OSI Reference Model

The International Standards Organization (ISO) has proposed a layered approach to network design. The seven layer structure, called the Open Systems Interconnection (OSI) Reference Model [24], is shown in Fig. 1.2. Each layer corresponds to a different level of communication. The purpose of layering is to divide a system logically into more manageable subsystems. The basic idea is to define services to be provided by each layer to its next higher layer, without specifying how these services are to be performed. This permits changes to be made in the way a layer or set of layers operate, provided they still offer the same service to the next higher layer. The ISO model provides a convenient framework for describing the issues that arise in the design of the HF ITF Network; however, there is no requirement that the HF ITF net conform to the OSI model in all respects. In the next few subsections we outline the major design issues of the network by grouping them according to the layer they are likely to reside in or affect the most.

7 APPLICATION
6 PRESENTATION
5 SESSION
4 TRANSPORT
3 NETWORK
2 DATA LINK
1 PHYSICAL

Fig. 1.2 — Seven layers of the OSI reference model

The Physical Layer

At the transmitting node, the function of the Physical layer is to take the 1's and 0's received from the data link layer, usually received as DC voltages, and transform them into modulated HF radio waves. The Physical layer at the receiving node has the function of taking the analog HF radio signals and demodulating them to form a stream of 1's and 0's that are input to the Data Link layer.

The Physical layer of the ITF Network will comprise many HF channels. Some of these will be narrowband (about 3 kHz bandwidth) and others will be broadband (e.g., frequency hopping bandwidths of a few megahertz). The decision as to which channel to use for a particular transmission is made at higher layers in the protocol hierarchy. To assist in the channel selection process, the Physical layer can provide some channel evaluation information to the higher layers.

Besides controlling the selection of channels, the higher layers may also control transmitter power levels. The transmitter power might be varied for several reasons including: to decrease the bit error rate, to combat jamming, to reduce the probability of signal intercept, or to reduce mutual interference among net members.

An important issue in the Physical layer is the HF signal waveform design for broadband channels. Waveforms are needed that provide rapid synchronization, efficient bandwidth usage, low mutual interference among net users, and AJ protection. The last two considerations imply the need for a robust waveform design. Considerable attention to these issues is given in Sec. 3.

The Data Link Layer

The Data Link Layer has the task of transforming a raw transmission channel into a virtually error free communication link. The existence of this layer also makes it possible for the Network layer to activate, maintain, and deactivate links.

An important issue for the HF ITF Network design study is the selection of a protocol for controlling access to the communication link (i.e., the multiple access problem). The multiaccess protocol may differ depending on whether voice or data traffic is being sent. Issues related to channel sharing and allocation are addressed in Sec. 4.

The highly variable quality of the HF channel implies the need for sophisticated error handling techniques. The raw error rate can change by several orders of magnitude in a period of minutes or even seconds; on the other hand, error rates can be quite low for long periods of time with only occassional bursts of errors occurring.

The Data Link layer also encompasses link crypto functions for transmission security (TRANSEC) such as the selection of crypto keys for frequency-hop coded, spread spectrum signals; protection from jamming is achieved in this layer by coding.

The Network Layer

The Network layer provides the means to establish, maintain, and terminate network connections (paths) and to control subsequent communications over these paths.

A path may consist of a single link or it may be the concatenation of several links. Because many links in the HF ITF Network are potential links (requiring transmitter/receiver coordination before they can be used), an important function to be performed by the Network layer is to coordinate the activation of these links.

A fundamental decision is whether to use centralized or distributed network control. Centralized control has the disadvantage that the network is disabled if the central controller is lost. On the other hand, distributed control techniques are much more difficult to implement. Since survivability is of major concern in the design of the ITF net, we have proposed an architecture for the ITF net that is based on a fully distributed algorithm for organizing the network into a Linked Cluster Architecture. Although this architecture has a hierarchical structure that in the end mixes distributed and centralized control, the structure is derived and maintained with a fully distributed algorithm. Each node runs the very same algorithm, exchanges control messages with its neighbors, and uses these messages to establish an efficient control structure for the network.

Other issues specific to the Network layer include: routing, flow control, recovery from Network errors, and end-to-end encryption.

The Transport Layer

For military networks, the Transport layer represents the interface between the Command and Control system and the communication system. This is the highest layer of the OSI model that is concerned with the transportation of data. Since presently our main concern is the design of the ITF communication system, we omit a discussion of the functions performed in OSI layers five, six, and seven, which concern the formatting and presentation of the data.

The Transport layer performs the end-to-end data control functions that are not performed by intermediate nodes. Since the Transport layer relieves the higher layer entities from any concern with the transport of data, this layer must contain the rules and procedures for acting upon user communication requirements including: acceptable BER, desired network response time, throughput rate, and mode of communication.

Typically, distinct networks are formed to provide transport services requested in the Transport layer. For the task force, the distinct OSI layer 3 networks include UHF satellite, UHF LOS, and HF ELOS nets.

1.3 System Evaluation Criteria

The design of the ITF Network requires many trade-offs. To justify particular design choices we need to specify our evaluation criteria. Additionally, we need to specify how our system performance indices are to be measured.

1.3.1 Defining of Measures

Military command, control, and communication systems can be evaluated in terms of three classes of measures [25] which are, in order of relative importance:

- measures of survivability
- measures of effectiveness
- measures of efficiency.

Measures of survivability indicate how well a system can withstand threats. Survivability relates to continuity of service. Survivability is the most important consideration because without it the other measures are meaningless. Measures of effectiveness refer to system performance primarily from a commander's viewpoint while measures of efficiency deal mainly with system performance from an engineering viewpoint.

Survivability of a radio-communication network or system includes the ability to withstand physical and electromagnetic attacks. Mobile military networks such as the ITF network are especially susceptible to physical attack. In addition, units of the task force are vulnerable to enemy jamming. Spoofing, that is the ability of the enemy to inject bogus messages into the network, is another concern that relates to network survivability. To combat spoofing a network must be able to authenticate transmissions. These three network characteristics, namely, physical survivability, data integrity, and message authentication are the most important requirements of performance.

Measures of effectiveness relate to the military impact of various system trade-offs. The platforms that constitute a task force must be capable of performing a variety of military missions. Table 1.4 lists the mission areas for naval platforms. Most platforms can perform several missions simultaneously. Measures of effectiveness tell how well the task force accomplishes the missions assigned to it. Measures of effectiveness are more important than measures of efficiency because unless a system is effective it does not matter how efficient it is.

Measures of efficiency relate to the use of time and resources. In commercial networks, where survivability is not of major concern and where effectiveness is often measured in terms of cost per bit, efficiency considerations are quite important. In military networks too, there is often an interdependence among efficiency, effectiveness, and survivability. For example, when communication capacity is at a premium, the ability of a task force to withstand a missile attack may be closely linked to the efficiency of the communication network.

Table 1.4 — Naval Mission Areas

(AAW)	Antiair Warfare
(ASW)	Antisubmarine Warfare
(ASU)	Antisurface Ship Warfare
(STW)	Strike Warfare
(AMW)	Amphibious Warfare
(MIW)	Mine Warfare
(SPW)	Special Warfare
(MOB)	Mobility
(CCC)	Command and Control and Communications
(INT)	Intelligence
(ELW)	Electronic Warfare
(LOG)	Logistics
(FSO)	Fleet Support Operations
(CON)	Construction
(NCO)	Noncombat Operations

1.3.2 Quantifying of Measures

There are many criteria that can be used to quantify survivability; for the HF ITF net, we are especially concerned with the connectivity of the net. That is, we need to know if there exists a communication path (or paths) between pairs of nodes. Since the ITF net will use store and forward techniques, not all the links of a path need to exist at the same time. Sometimes it will be important to consider if there exists a path between every pair of nodes, and sometimes only a specific pair of nodes will need to be considered. Under severe jamming, some nodes might not be able to hear any other nodes, although other nodes might be able to hear them. In such cases, the criteria for survivability might only address the existence of certain one-way paths; for example, whether there exists a path from, say, an early warning aircraft to an AEGIS cruiser. In summary then, the following criteria will be used for quantifying the survivability of the HF ITF net:

1. the existence, within some period of time, of communication paths between every pair of nodes;

2. the existence, within some period of time, of a two-way communication path between specified pairs of nodes; and

3. the existence, within some period of time, of a one-way communication path from a specific source node to a specific destination node.

Other survivability criteria are also being considered and will be used when appropriate.

Quantifying the effectiveness of the ITF net is a two-step process. First, traffic requirements are generated for a given operational situation and scenario. An example of this is the antiair warfare scenario analyzed in the Sea Based Air Study [20]. The second step is to compute the fraction of this traffic that reaches its destination within the required delivery time. A computer simulation of the ITF net can be used to make the latter determination although the assistance of analytical techniques is not ruled out.

Definitions of specific measures of efficiency, which also quantify these measures, are given in Sec. 4.4. These include definitions of network throughput and average delay per message.

1.3.3 Measuring of Measures

The HF ITF Network design will provide for the routine collection of system performance statistics and for the maintenance of a comprehensive set of network status indicators.

1.3.4 ITF Network Test Bed

The complexity of the ITF Network precludes a design evaluation and validation based solely on analysis. Therefore we plan to rely heavily on the use of a simulation facility to serve as an HF ITF Network test bed. The purpose of the test bed is threefold:

1. to assist in concept development,

2. to provide a method for concept evaluation, and

3. to serve as a tool for system design and validation.

A computer simulation model has been generated, which is used to develop and evaluate HF ITF Network concepts. The simulator is coded in the language SIMULA and runs on a DEC-10 computer. Computer memory constraints limit the current network model to 25 nodes or less.

Currently, each node in the ITF Network simulation model is represented entirely by SIMULA-coded software. We plan to enhance the simulator to permit some "real" nodes in the network simulations. The latter nodes will be "smart" terminals that attach to the computer running the simulation. These real nodes will participate in the simulation in much the same way as their software counterparts. Thus, for example, a message sent from one real node to another will experience a delay similar to that which would occur in an actual task force. Benefits of incorporating real nodes into the HF ITF net simulation model include:

1. various distributed control techniques could be tested and evaluated using real, distributed nodes;

2. the communication processors of the actual system could, to some extent, be emulated by the simulator's "real" nodes;

3. capabilities of the network could be readily demonstrated; and

4. a network/user interface could be developed.

2.0 HF ITF NETWORK CONCEPT

In this section, the ITF Network is examined from the point of view of its layer 3 (network) functions. We describe a preliminary concept of organization and operation for the network, and we indicate the considerations that led to this concept. Detailed descriptions of parts of the organization of the network appear in [7,12,2].

2.1 Preliminary Concept of Network Organization and Operation

The HF ITF Network is being designed as a survivable, antijam communication network for interconnecting mobile, relatively unsurvivable task force platforms. Of paramount importance is the survivability of the network, a context in which we must consider the merits of various network control techniques.

Network control techniques are usually classified as centralized, distributed, or hybrid. In a centrally controlled network, the network assets are controlled by the single control node; hence, the survivability of the network can only be as great as the survivability of that node. Centrally controlled military networks rely heavily on node "hardening" to prevent the physical destruction of the central controller. Because of the vulnerability of naval platforms, a centrally controlled ITF Network lacks survivability. A common approach used to increase the survivability of centrally controlled nets is to provide automatic backup capability. Thus, if the central controller is disabled, a backup controller takes over. Provisions can be made for several backups. However, it is unlikely that the delay between the loss of a central controller and its replacement by a backup can be made short enough to make this approach usable for the ITF Network, nor is it possible to ensure survivability with one or a small number of backup controllers.

At the other extreme, in a distributed network control scheme, each node contributes to the control of the network assets and must cooperate with its neighbors to allocate network resources. No individual node is strictly necessary, and the network can sustain the loss of several nodes. Because of its inherent survivability, distributed control appears to be well suited for use in the ITF net. A drawback of some distributed control schemes is that they entail considerable communication overhead and significant intelligence at each node. This is of some concern since HF channels have relatively low capacity and since new equipment may be necessary to implement sophisticated, distributed control schemes.

An intermediate case is that of hybrid or hierarchical control. In this case, a set of several local central controllers cooperates in the use of global resources while maintaining full control over the distribution of local network resources. In the ITF net we use a distributed control scheme to set up such a hierarchical (hybrid) network structure and then let the network operate under the achieved hybrid structure.

The variable connectivity of the HF ITF Network is an important consideration that affects the network's design. The connectivity map for the network can change with time or frequency. At a given frequency, the connectivity map of the network can change owing, for example, to node motion, node destruction, changing noise levels, or changing propagation conditions. In the ITF network, connectivities will be periodically tested and the network organized using only those links that have been verified to be usable.

Because the propagation range also varies with frequency, there may be several different connectivity maps for the HF band at any given time. Consequently, we have considered a network architecture that consists of several, distinct, overlaid network structures, each structure similar to the others but based on a different connectivity map. As before, these connectivity maps are periodically reformed in order to adapt to the time variation of the HF ITF Network connectivities. The HF band is partitioned for this reason into M subbands, over each of which the propagation range is nearly constant; in each subband a separate structuring of the network is performed. These separate runs take place consecutively during M epochs. During epoch "i" the net is structured based on the network connectivity map corresponding to the ith subband of the HF channel. When the M runs are completed, the epochs repeat in a cyclic fashion providing a continual updating process. Note that during any epoch only one distinct structure is being reorganized—the remaining $M - 1$ structures are unaffected. To prevent disruptions in communication traffic flow, the network should route traffic so as to avoid the subband in which the network is being reorganized. Appropriate message framing provisions must be made, of course, in order to avoid interruption of message transmissions at the beginning of the corresponding reorganization epochs. The timing diagram for the organization and operation of the ITF network is shown in Fig. 2.1. (Note although we sometimes refer to "networks" corresponding to the different subbands, these "networks" are not actually autonomous but rather they constitute a single HF ITF Network.)

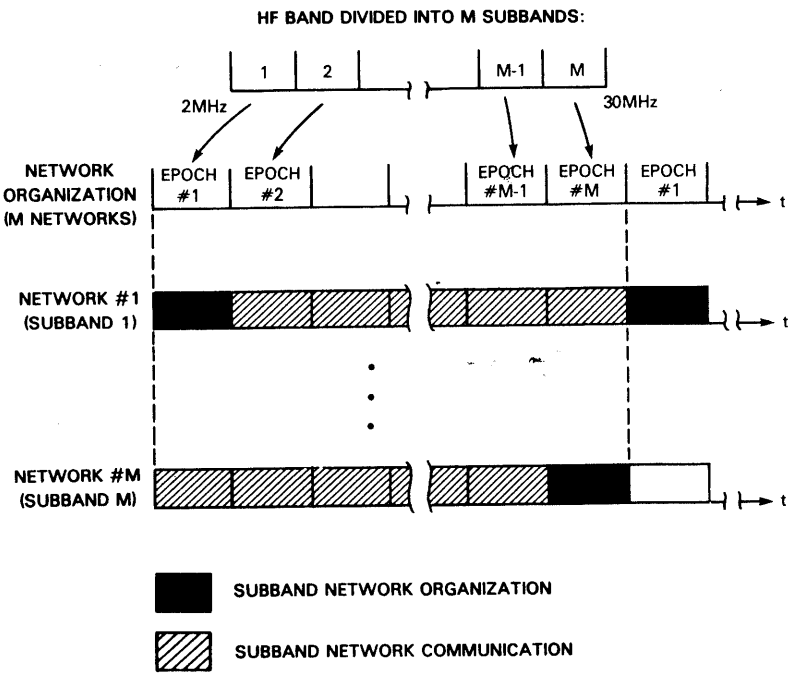


Fig. 2.1 — Timing structure for organization and communication under the Linked Cluster Architecture

An example of the structure that we propose for the HF ITF Network is shown in Fig. 2.2. The network is organized into a set of linked node-clusters. Each node belongs to at least one cluster. Every cluster has its own cluster head which acts as a local controller for the nodes in that cluster. The cluster heads are linked via gateways (as needed) to provide paths for intercluster communication and global network connectivity. The cluster heads, gateway nodes, and the two-way links joining these nodes form the "backbone network."

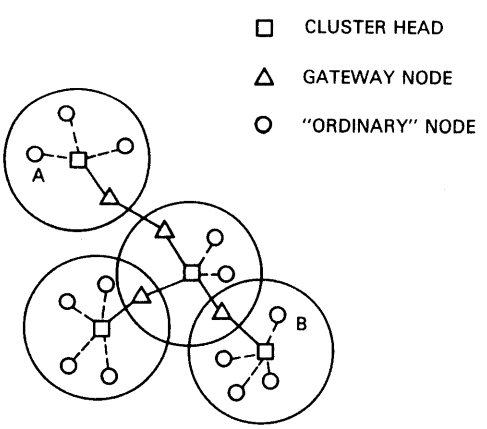


Fig. 2.2 — Example of Linked Cluster Architecture

The linked cluster structure facilitates the relaying (routing) of communication packets. For example, if Node A (see Fig. 2.2) wishes to send a packet to Node B, Node A simply sends the packet to a neighboring cluster head, which forwards the packet to Node B's cluster head for subsequent delivery to Node B. The advantage of this approach over that of a fully distributed routing scheme is that only cluster head and gateway nodes need to maintain routing tables. In addition, the linked cluster structure has the advantage of providing a connected net using only a relatively small number of links. Also, cluster heads can serve as broadcast nodes, thereby rapidly and efficiently disseminating messages intended for all network nodes. Furthermore, each cluster head can act as a channel access controller for the nodes in its cluster. Having a channel access controller is particularly advantageous in the case of random access protocols when all nodes are not within range of each other but are within range of a cluster head. In this case the cluster head can broadcast a "busy tone" to indicate when the channel is being used.

To avoid the vulnerabilities associated with a fixed-structure network, the ITF net adaptively and automatically restructures itself as needed. This structure, which we call the Linked Cluster Architecture, can be achieved via distributed algorithms that are described in Sec. 2.2. In Sec. 2.3 we describe a distributed algorithm for coordinating the activation of links in the ITF net.

The HF ITF net, as we have described it, provides the basis for handling network coordination, control, and signaling traffic in addition to some user traffic. We will call this the "primary" net and the links of this net will be called the "primary" links. The primary net consists of the backbone network plus each node and its two-way link to its own cluster head. It is important to realize that we do not intend all ITF traffic to flow over the primary net. Additional, "auxiliary" nets and "auxiliary" links will be established, as needed, to handle traffic not suited to the capabilities of the primary net. The primary net will, however, play an important role in establishing and terminating these auxiliary nets and links. Examples of traffic that calls for the creation of auxiliary nets and links are voice traffic, long data file transfers, and certain broadcast nets in which all net members transmit and receive on a common channel. The development of protocols for these auxiliary nets is an important, continuing effort.

2.2 Linked Cluster Architecture

We consider the problem of developing the linked cluster structure, as shown in Fig. 2.2, without the aid of a central controller. To solve the problem, two network structuring algorithms have been developed, which are very similar to each other. These are called Network Structuring Algorithms (NSA). The main function of these algorithms is to allow each node to make the determination of whether it should become a cluster head, gateway, or ordinary node. The two algorithms are described below.

2.2.1 Network Structuring Algorithms (NSA)

The schedule of events in the NSA is shown in Fig. 2.3. Each epoch of the control channel is divided into two frames of N time slots each, where N is the number of nodes. Each node transmits a control message during its assigned time slot in each frame of an epoch. During the first frame, a node broadcasts the identities of the nodes it has heard from during previous slots in the frame. Thus, by the time it is ready to transmit in Frame 2, each node knows all its neighbors.

Just prior to its Frame 2 transmission, each node determines whether it should become a cluster head; two different criteria have been proposed for making this determination. To distinguish which cluster head selection rule is being used, we identify our network structuring algorithms as either the Linked Cluster Algorithm (LCA) or the Alternative Linked Cluster Algorithm (ALCA). After the LCA was developed, we found a simpler rule for selecting cluster heads than that which we had used in the LCA. The newer selection rule also results in more uniform geographical distributions of cluster

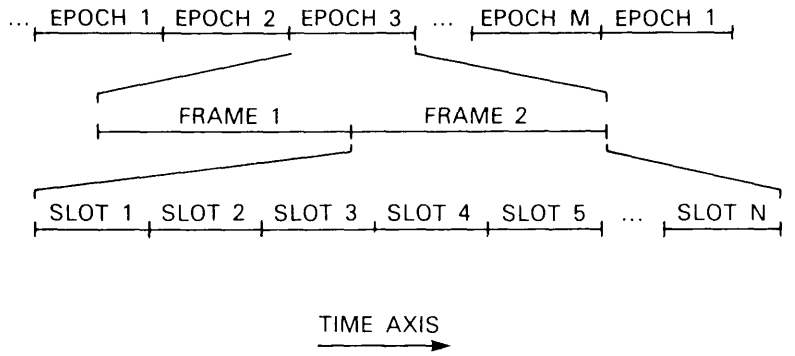


Fig. 2.3 — Schedule for network reorganization

heads. The newer cluster head selection rule is used in the ALCA; in other respects the LCA and ALCA are nearly identical. In the LCA version, the cluster head for node i is the highest numbered node connected to node i, including node i itself. The procedure for selecting cluster heads in the ALCA version is the following. First, node 1 always becomes a cluster head and announces, in slot 1 of Frame 2 that it is a head. Other nodes determine, just prior to their own Frame 2 transmissions, whether they should become cluster heads. The rule is that a node becomes a cluster head if it has no lower numbered head as a neighbor.

After determining whether it should become a cluster head, each node then broadcasts this determination in its assigned Frame 2 slot along with its list of neighbors. Thus, by the end of Frame 2, each node knows: its neighbors' neighbors, one hop away heads, and some of the two hops away heads. This information is needed to determine which nodes must become gateways for linking the clusters. Details relating to the formation of gateways, as well as other details about the network structuring algorithms, are given in [2,7,9]. After the M epochs have occurred, the network has been organized into a distinct structure for each of the M subbands. The algorithm is then repeated, recognizing that the connectivity is time varying.

LCA/ALCA Message Length Requirements—Both of our network structuring algorithms require that each node broadcast two control messages. The first transmission is for the purpose of announcing each node's NODESHEARD list. The NODESHEARD list contains the identification numbers of the nodes heard from during Frame 1 of the NSA. If there are N nodes in the network, then this list could be represented as an array of N binary symbols (bits). The second transmission consists of the connectivity vector information along with either the node's cluster head status (LCA) or OWNHEAD (ALCA) information. Cluster head status can be represented by a 1 or a 0 depending upon whether the node is a cluster head or not. OWNHEAD is the identification number of the cluster head of the transmitting node and can be represented by $\log_2 N$ bits (rounded upwards to the nearest integer). The connectivity vector, like the NODESHEARD list, can be represented as an array of N bits. Therefore the number of information bits in a control message (i.e., the number of information bits per slot), is less than or equal to $N + \log_2 N$. Additional bits for synchronization preambles (including crypto sync), message headers, error control coding, and other overhead functions are also needed, of course.

As an example, for the case of a 50-node network, approximately 5600 bits need to be sent in each epoch. If the information transfer rate is 2400 bits per second, then the duration of the epoch would be 2.3 s. To complete the rough estimation of an epoch's duration we may assume a one-half rate error correcting code plus an additional 20% overhead rate to conclude that approximately 6 s may be required for the completion of an epoch. Assuming further a partition of the HF band into six sub-

bands, the reorganization period would be close to 36 s, i.e., the network will have a chance to reform each of its six connectivity maps almost every 0.5 minute.

2.2.2 Simulation Results

A simulation model was constructed to provide examples of network structures obtained with both algorithms. In our simulation model the determination of whether two nodes are within communication range is based on the HF groundwave range model shown in Fig. 2.4. The actual communication range will differ, of course, from that given by the range model. However, the model is representative of the variation of the groundwave communication with frequency over the HF band. The range model assumes that communication is limited by worst-case atmospheric noise; further details concerning the range model are given in [16].

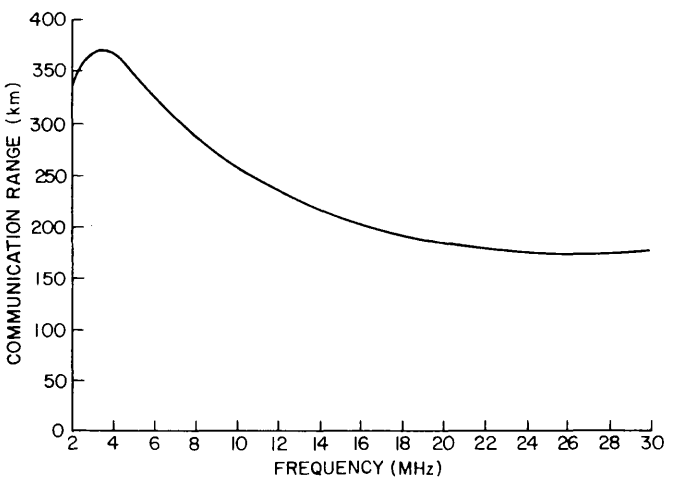


Fig. 2.4 — Communication range model

Frequency Dependence—Since the communication range varies significantly across the HF band, we envision the network as consisting of the overlay of several sets of linked clusters, each set derived from a connectivity map formed using a different frequency. The frames of Fig. 2.5 show the resultant network structures for six epoch frequencies. These particular frequencies were chosen because they provide examples corresponding to a wide variation in the communication range. In this example, connected nets are formed at all but the highest frequency.

The technique of overlaying several sets of linked clusters provides alternative communication paths. If a backbone network link is lost at one frequency due to jamming, other backbone networks at other frequencies can be used. When the net is reorganized in the subband in which the jamming occurs, a new backbone network will be set up that will not contain the jammed link.

Unfortunately, because the same nodes (e.g., the higher numbered ones in the case of the LCA) are more likely to become cluster heads and gateways for each epoch in our example, these nodes will be overburdened with network management and traffic direction responsibilities. Moreover, the appearance of the same nodes in several different backbone networks makes the network too dependent on these nodes. For example, in Fig. 2.5, the loss of node 9 would sever the backbone network at all frequencies. Although, the network would begin to compensate for the loss of this node by restructuring

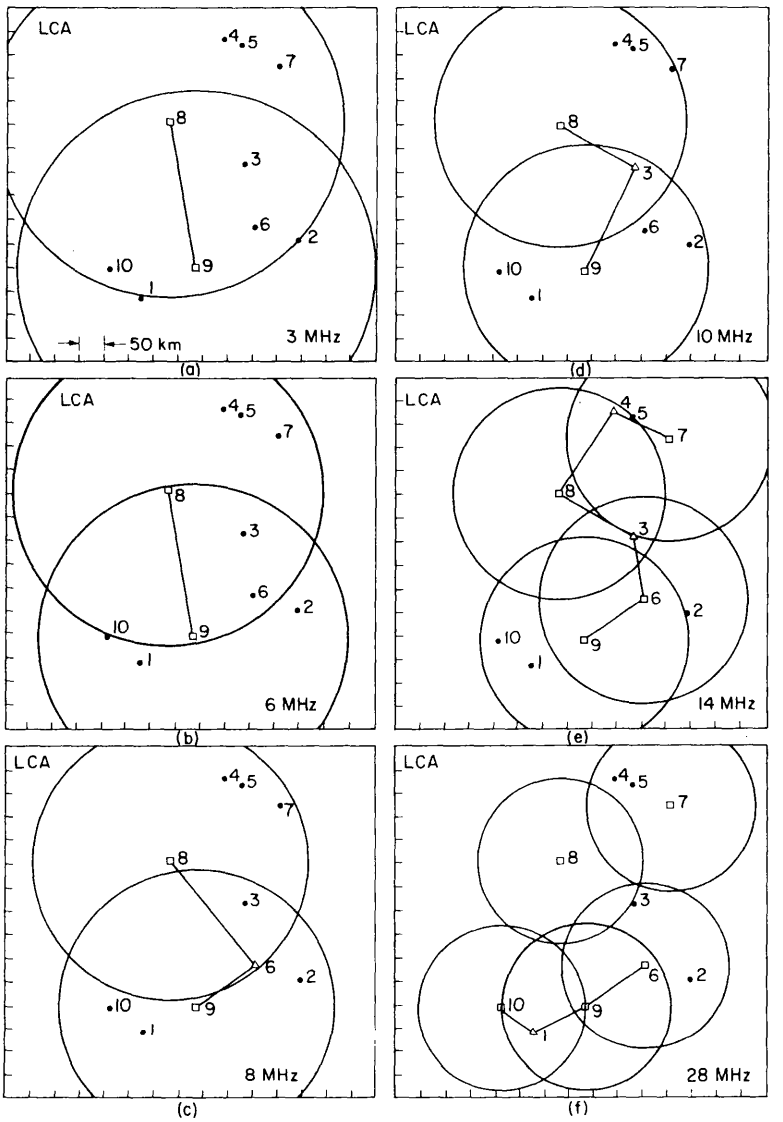


Fig. 2.5 — Network structures for different frequencies

the backbone network, epoch by epoch, parts of the network might remain disconnected until a full cycle of epochs occurred. This problem can be avoided by introducing a dynamic node numbering strategy.

Node Numbering—Given the simple strategy used in deciding the identity of a cluster head or a gateway node among a group of candidates, it is clear that number assignment to the nodes is a very important part of the proposed organization. For example, in the ALCA the lower numbered nodes simply have a greater tendency to become heads or acquire gateway status than higher numbered nodes while in the LCA the converse is true. One possible way to alleviate problems associated with having the same nodes become heads and gateways is to assign to each node a different number for each epoch. A simple strategy that tends to produce "orthogonal" backbone networks is to invert the numbering on successive epochs. That is, nodes 1, 2, 3, etc. in one epoch become nodes N, $N - 1$, $N - 2$, in the next, and so forth. An example of such a strategy is shown in Fig. 2.6 for both the LCA and ALCA. The results show some separation of the backbone networks; however, the nodes numbered 3 and 9 in Figs. 2.6a and 2.6d and 2 and 8 in Figs. 2.6b and 2.6c still appear in each of the backbone networks. However, this is unavoidable as can be seen by considering the complete connectivity map for this set of nodes, which is shown in Fig. 2.7. Since the loss of either node 2 or 8 would disconnect the network, they must necessarily be part of the backbone network. In general, a strategy of node number inversion followed by number randomizing on alternate epochs should produce well separated backbone networks. On the other hand, if a node still tends to become a head or gateway in several networks, then this node is likely to be a "critical" node in the sense that its loss may split the network. Alternatively, node numbering strategies could be based upon the communication capabilities of the nodes, with the more capable nodes being favored for the roles of cluster head or gateway. Other strategies are possible, of course.

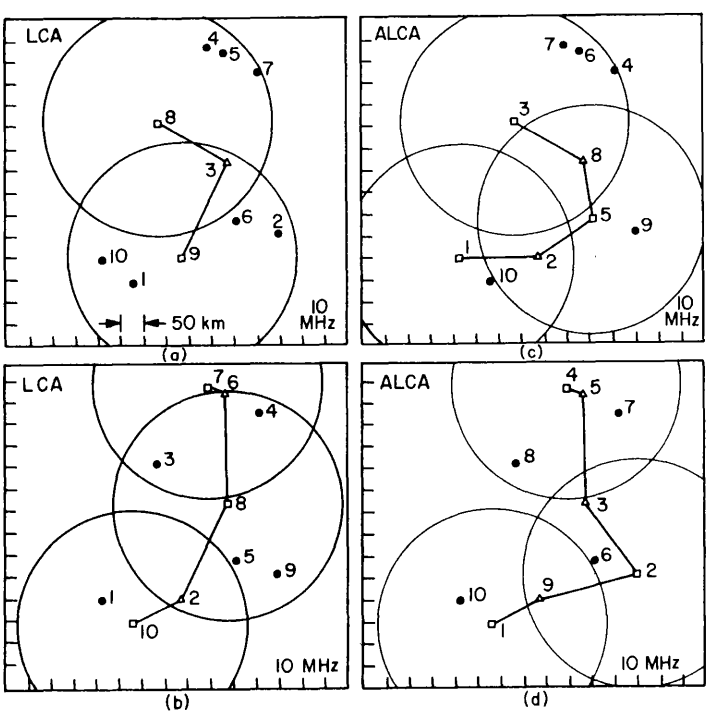


Fig. 2.6 — Examples of the effects of node renumbering

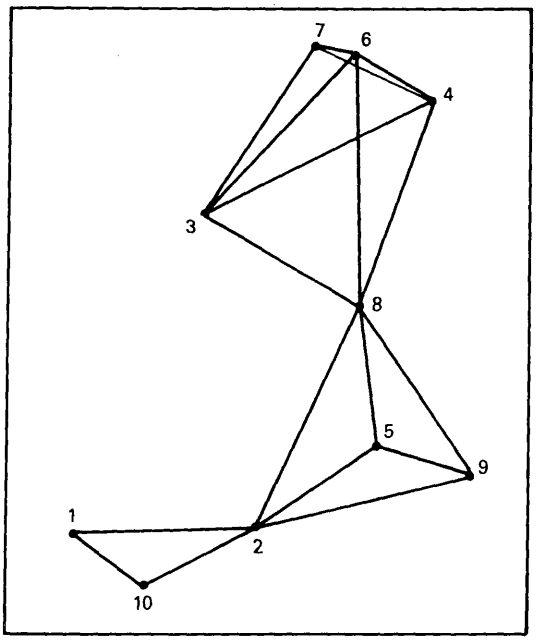


Fig. 2.7 — Connectivity map for the examples shown in Fig. 2.6

Loss of Nodes—Since the ITF Network is a military network, its nodes may be disabled or destroyed by physical attack. Consequently, both of our network structuring algorithms provide for sensing node losses and for reconfiguring the network, if necessary. An example of this feature using the ALCA is shown in Fig. 2.8. Figure 2.8a shows the resultant backbone network for an initial network of 20 nodes. Each subsequent frame of this figure corresponds to a network obtained by deleting five nodes from the network shown in the preceding frame. The nodes that are "lost" are chosen from among the nodes that are most likely to become cluster heads or gateways. Since the ALCA favors the selection of the lower numbered nodes as heads and gateways, the five lowest numbered nodes were deleted in successive frames.

The network adapts to the loss of nodes 1 through 5 as follows. The roles of heads 1 and 4 are taken over by nodes 10 and 7. The role of gateway node 2, which links clusters 1 to 8, 6 to 8, and 1 to 6, is assumed by node 15, which links clusters 8 to 10 and 6 to 10. The loss of node 2 also results in the creation of the new gateway at 9, which links clusters 6 and 8. The loss of nodes 3 and 5 has no immediate effect.

The additional loss of nodes 6 through 10 has the effect of disconnecting the backbone network. This is unavoidable since, for example, the loss of node 7 results in the isolation of node 20. Likewise, nodes 12, 13, and 19 are also isolated from the rest of the network once nodes 7 and 8 are lost. The cluster head roles of nodes 8 and 10 (Fig. 2.8b) are taken over by nodes 15 and 11 (Fig. 2.8c). The effects of the loss of head 6 are borne by new heads 11 and 15. That is, all the nodes within cluster 6 (Fig. 2.8b) are now contained within the combination of new clusters 11 and 15 (Fig. 2.8c). Also, the disappearance of 6 negates the need for a gateway node at 9. Thus the gateway role of 9 does not have to be taken over by any other node.

The additional loss of nodes 11 through 15 causes no further partitioning of the network; it still comprises three isolated parts. However, the roles of heads 11 and 15 and gateway 16 (Fig. 2.8c) are now taken over by the single head at node 16 (Fig. 2.8d). Again, we emphasize that, at other frequencies, the network may still be connected.

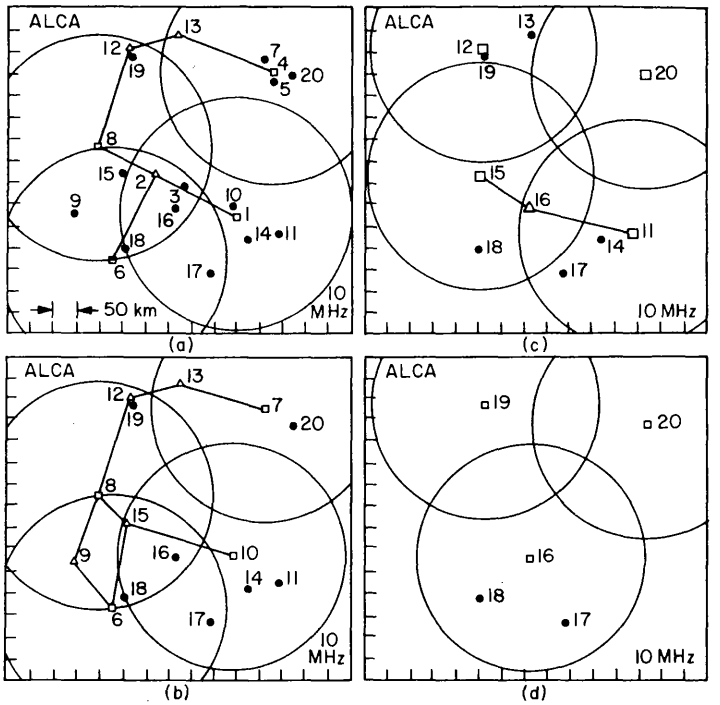


Fig. 2.8 — The effects of a loss of nodes

2.3 Activation of Links

Our network structuring algorithms provide for the selection of cluster heads and gateways. However, these algorithms do not address the problem of setting up the links of the backbone network. Furthermore, the establishment of the backbone network links is complicated by the fact that nodes do not always know which of their neighbors are gateways. Consequently, we have developed an algorithm, called the Link Activation Algorithm (LAA), that provides the communication coordination needed to facilitate the establishment of these links [14].

The basic idea of a Link Activation Algorithm is as follows. Each node constructs, for each subband, its own TDMA schedule for establishing communication with its neighbors. The formation of the link activation schedule for a particular subband occurs simultaneously with the network's reorganization in that subband, and the schedule applies to communication during the period following the reorganization and until the next reorganization occurs for this subband. The main purpose of the link activation schedule is to coordinate communications until the links of the backbone network are established. Once the backbone network is set up, it is not essential that communications continue to be governed by the TDMA format of the link activation schedules although this is an option being considered.

The link activation schedules have the following features.

1. The number of slots in a schedule may vary from node-to-node but is to be an integer power of 2.

2. A node has an assigned slot for communicating with each neighbor.

3. A slot is assigned for both receiving broadcasts from one's own cluster head and for transmitting to any neighboring cluster head.

If full duplex communication is not possible, then each slot is considered to be split into two parts with half duplex transmissions occurring during each half slot. Furthermore, we assume that many nodes can transmit simultaneously without destroying each others transmissions. This could be done, for example, using spread spectrum signaling with each transmitter using a different code. That is we are envisioning a mixed TDMA, CDMA structure. The dispersion of nodes will offer additional help in reducing mutual interference among network nodes.

Like the LCA and ALCA, the LAA is a distributed algorithm that requires the exchange of messages between neighboring nodes. The current version of the LAA is such that these messages can be appended to the transmissions of the LCA or ALCA.

The LAA can be considered as consisting of two activities, namely, allocating slots and resolving scheduling conflicts. Slot allocation occurs during Frame 1 and conflict resolution occurs in Frame 2 (see Fig. 2.3). During Frame 1 each node continually adjusts the size of its link activation schedule to accommodate neighboring nodes as they are heard from. Slots are allocated in such a manner as to avoid known scheduling conflicts. This can result in some slots not being allocated and thus in a reduction of efficiency.

At the time of its Frame 1 transmission, each node broadcasts information that describes the current status of its link activation schedule. This information is used by the other nodes to avoid known scheduling conflicts.

Some conflicts can arise during Frame 1 despite efforts to prevent them. Conflicts arising during Frame 1 are resolved during Frame 2. The details regarding how this is accomplished are left to a future report as this algorithm represents continuing work on the ITF network. For this report we describe only our concept of the link activation process.

Using the LAA, the nodes of our example network of Fig. 2.7 form the link activation schedules as shown in Fig. 2.9. Each schedule is repeated continuously until a new schedule is formed at the next reorganization of the network. Appropriate message framing and epoch timing coordination is needed, of course, to prevent the loss of messages at the onset of network reorganization. The first slot of each schedule is arbitrarily selected as a broadcast slot. During this slot each node monitors the transmissions from its own cluster head. It is during this slot that a node may communicate with any neighboring cluster head.

Node	Slot Number							
	1	2	3	4	5	6	7	8
1	B	2	10	—	B	2	10	—
2	B	1	5	8	9	1	5	10
3	B	4	6	7	8	—	—	7
4	B	3	7	6	—	—	8	—
5	B	8	2	9	B	—	2	9
6	B	7	3	4	—	8	—	—
7	B	6	4	3	B	—	—	3
8	B	5	9	2	3	6	4	—
9	B	—	8	5	2	—	—	5
10	B	—	1	—	—	—	1	2

Fig. 2.9 — Link activation schedules for the network example of Fig. 2.7

3.0 SIGNALING IN THE HF ITF NETWORK

In this section we address the signaling issues that arise in the design of the HF ITF Network. Note that we are using the term signaling to refer to waveform design and performance considerations, whereas the same term is often used to refer to communication link setup procedures. Specifically, we first discuss the properties of the HF medium that will have the greatest impact on intra-task force communication. The HF channel is difficult to characterize because of noise that is highly variable and highly non-Gaussian, fading, multipath interference, other-user interference, and jamming.

We address signaling, first from the standpoint of link (point-to-point) communication, and then in the context of network, or multiuser communication. The basic waveform design and coding issues are related to the lowest two layers of the OSI model, i.e., the Physical Layer and the Data Link Layer. It is demonstrated that signaling in the network environment raises many issues that are not encountered in the point-to-point case, and methods for solving these problems are discussed. Both narrowband and wideband (i.e., spread spectrum) signaling are addressed. While present day HF systems use narrowband signaling, the use of spread spectrum signaling is proposed for the HF ITF network in order to provide some degree of protection from jamming. The principles of spread spectrum communication are presented, with emphasis on specific issues that relate to the HF ITF environment, and in particular to the proposed Linked Cluster Architecture. Of fundamental importance are the choice of spectrum spreading mechanism (e.g., frequency hopping *vs* direct sequence), the networking implications of the use of Code Division Multiple Access (CDMA), and the choice of a modulation technique (e.g., frequency shift keying (FSK) *vs* differential phase shift keying (DPSK)).

It is demonstrated that frequency hopping with noncoherent M-ary (binary, 4-ary or 8-ary) FSK is a good choice for the HF ITF Network, and the antijamming (AJ) performance (including coding and diversity considerations) of this class of schemes is discussed. An exact determination of jamming protection measures is not possible because of the complex nature of the HF channel as well as scenario-dependent conditions. However, it appears that some modest to good AJ capability is possible for most links in the network because of the robustness of the signaling/coding schemes we have considered, as well as the robustness of the network architecture.

The purpose of this section is to demonstrate the relationships between channel characteristics, waveform design, and networking schemes. We do not present a detailed waveform design study. The signaling problem is, in fact, of such depth and importance that we have written a separate report devoted to this subject alone [3] that addresses these issues in considerably greater detail than is presented in this section.

3.1 HF Channel Characterization

The design of the HF ITF Network has been greatly influenced by the properties of the HF band (2 to 30 MHz). The HF radio channel is both fading and dispersive with propagation occurring via both groundwaves and skywaves. The HF ITF Network will rely primarily on the use of groundwaves to connect nodes. Groundwave attenuation varies with frequency and sea state conditions but is generally more predictable than skywave propagation, which is supported at any time only over a portion of the HF band. Typically skywave signals will be considered as a source of multipath interference, although the use of skywaves to advantage as a form of diversity reception may be considered in the future. In the following subsections we discuss the most important features of both groundwave and skywave propagation as they relate to the ITF environment. The reader is referred to [26] for an overview of the HF medium and to [27], which presents procedures and accompanying data for the evaluation of HF link performance measures.

3.1.1 HF Groundwave Propagation

The HF medium has been designated as the primary medium for Extended Line of Sight (ELOS) intratask force communication largely because of the ELOS propagation ranges (up to several hundred kilometers) of HF groundwaves. Another advantage of HF groundwave propagation is that it is expected to be only minimally affected by nuclear detonations. In addition to its being more predictable than skywave propagation, groundwave propagation has the advantage of having little dispersion; the use of groundwaves thus permits considerably greater signal bandwidths, and therefore data rates, than the use of skywaves. Furthermore, the use of HF groundwaves avoids the need to use relays external to the task force, such as geostationary satellites (operating at SHF and EHF), that are potentially vulnerable to physical attack.

Figure 3.1, taken from [21], illustrates typical groundwave path loss over a smooth sea as a function of range as frequency is varied between 3 and 50 MHz. It is clear from this figure that groundwave attenuation increases as frequency increases. The lower end of the HF band (2 to 6 MHz) is therefore especially attractive for ELOS ITF communication; however, it would be undesirable to limit HF ITF communication to any small part of the HF band. It is also important to note that propagation loss increases as sea state increases, and that this effect becomes more pronounced as frequency increases [21].

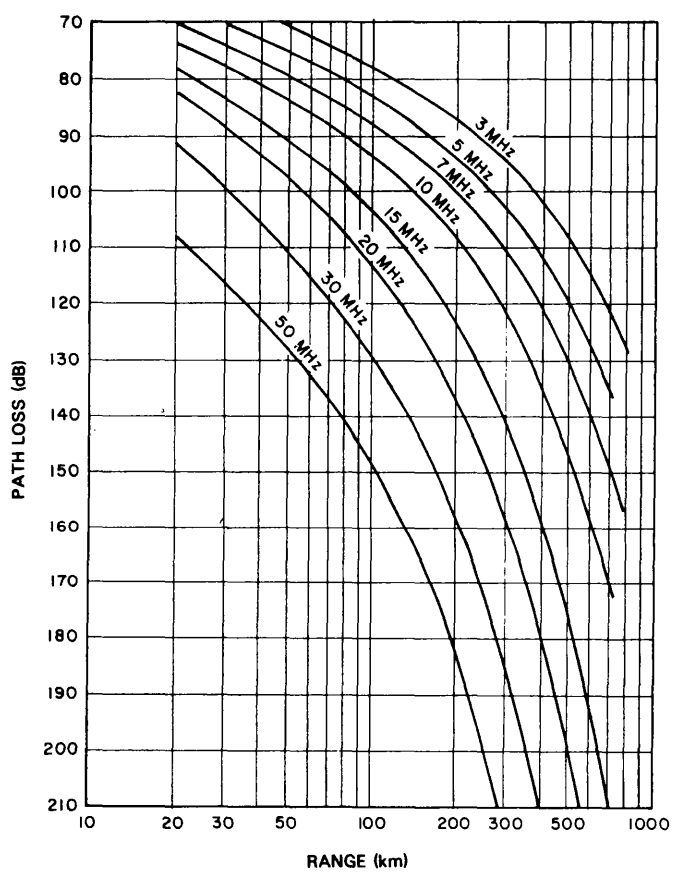


Fig. 3.1 — HF groundwave path loss over a smooth sea (from [21])

Despite the fact that we are relying only on groundwave connectivities to link the platforms in the network, we must also consider the effects of skywave propagation. Skywave signals are often generated along with the desired groundwave signals, and in such cases they will appear at the receiver as interference in the form of multipath signals. Other potential sources of skywave interference include hostile jamming as well as other-user interference. The effects of skywave propagation are therefore extremely important, and must be given serious consideration. The next subsection presents a discussion of HF skywave propagation, with emphasis on considerations relating to the ITF environment.

3.1.2 HF Skywave Propagation

High-frequency skywave propagation, which relies on the refraction of radio waves by the ionosphere, is normally used for Beyond Line of Sight (BLOS) communication at ranges of up to thousands of kilometers. Skywave propagation must be considered in the design of the HF ITF Network not only because it is a source of interference, but also because the Network will have to interface with other networks via long haul skywave links, and because it may be necessary to include skywave links within the HF ITF Network itself. An overview of HF skywave propagation is given in [26], and more exhaustive treatments are found in [28] and Chapter 9 of [29].

The ionosphere is a region in the upper atmosphere in which free electrons are produced by the ionizing effect of ultraviolet light and soft x rays from the sun. There are four significant concentrations of free electrons, which are known as the D, E, F1 and F2 layers. The D layer is mainly a daytime phenomenon. It acts primarily as an absorptive medium, in which lower frequencies are attenuated more than higher frequencies. High-frequency skywave signals consist of the superposition of reflections from one or more of the other layers. The critical, or cut-off, frequency is defined to be the highest frequency that will be reflected by a given layer for vertical incidence.

For nonvertical incidence, higher frequencies are reflected. Each layer is characterized by its maximum usable frequency (MUF). We will use the term MUF to refer to the ionosphere's maximum usable frequency, which is usually equal to that of the F2 layer. Inhomogeneities in the E layer (sporadic E propagation) can, however, sometimes result in MUF values as high as 80 to 90 MHz [27], which are several times higher than that expected even for the F layers. There is also a lowest usable frequency (LUF) that will provide reliable communication, because D layer absorption increases as frequency decreases. The diurnal variation of the MUF and LUF over a "typical" skywave link (of several thousand km) is shown in Fig. 3.2. The links of the ITF environment are not "typical," however, in that transmission ranges are of the order of hundreds rather than thousands of kilometers. Thus, in most cases, the MUF for transmissions within the task force will not be much greater than the critical frequency, and will usually be less than 10 MHz.

Knowledge of the portion of the HF band over which skywave propagation is supported permits the choice of an operating frequency that either uses or avoids this mode. For example, when Low Probability of Intercept (LPI) and Limited Range of Intercept (LRI) communication modes are being used, the region of the HF band that supports skywave propagation should be avoided. The choice of transmission frequency to avoid undesired skywave propagation is known as "propagation tactics" [30]. However, to achieve maximum network flexibility it would be undesirable to deny platforms the use of a substantial portion of the HF band. The effects of multipath interference can be substantially reduced via the use of spread spectrum signaling, which also provides jamming protection and multiple access capability, as will be discussed in Sec. 3.2.2 and Appendix B.

The use of LPI and LRI communication modes may not be necessary if Limited Probability of Exploitation (LPE) operation can be achieved. An LPE capability refers to the ability (with high probability) to prevent an interceptor from exploiting a received signal in any way (e.g., direction finding, signal identification, spoofing, traffic analysis), even when the signal strength at the interceptor is relatively large. If LPE operation can be achieved it would be safe, from the standpoint of interception

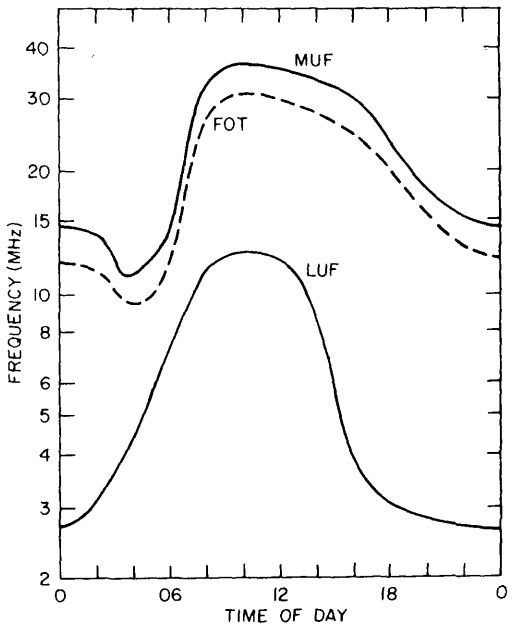


Fig. 3.2 — Diurnal variation of the maximum usable frequency (MUF), the lowest usable frequency (LUF), and the frequency of optimum transmission (FOT) on a typical long-range HF skywave link (from [26])

considerations, to operate the network in frequency subbands that support skywave propagation. However, it must be realized that interference levels, from jammers as well as other users of the HF band (including platforms within the HF ITF Network as well as those external to it) will be higher in such subbands. Considerations relating to LPE operation include the use of spread spectrum signaling and cryptography.

Typical curves, such as those of Fig. 3.2, are of limited use because the characteristics of the HF channel depend not only on frequency and time of day, but also on range, geographical location, season, and sunspot number. In addition "pathological" effects such as magnetic storms, sudden ionospheric disturbances and sporadic E layer propagation make estimation of channel characteristics difficult. Techniques for estimating the characteristics of the HF skywave channel are discussed in [27,28,31-34].

In addition to multipath propagation, the skywave signal suffers from the turbulent structure of the ionosphere that modulates the signal of each propagation mode in both amplitude and phase in a random fashion, thereby scattering the signal in frequency (time-selective fading); the signal is also spread in time (frequency-selective fading). Thus, skywave signals can experience significant levels of fading and dispersion in contrast to the well-behaved groundwave case. Such fading is minimal near the MUF; in fact, the frequency of optimum transmission (FOT) is defined to be 85% of the MUF. Fading channel models and the effects of fading on signals are discussed in our report on signaling issues for the HF ITF Network [3] as well as in [29,35].

3.1.3 Sources of Interference in the HF ITF Environment

The primary sources of HF interference in the ITF environment are: atmospheric noise, locally generated platform interference, multipath interference resulting from undesired skywave propagation, other-user interference, and hostile jamming.

A considerable amount of data is available for characterizing natural atmospheric noise in the HF band. Satisfactory techniques have been devised for computing atmospheric HF noise levels at various geographic locations and for various seasons and hours of the day [27,28,36]. The noise distributions are non-Gaussian, nonwhite, nonstationary, and highly impulsive, and are therefore difficult to characterize mathematically [26]. Noise levels in frequency bands that support skywave propagation are considerably higher at night, when the absorbing D layer disappears, than during the daytime. An example of "typical" noise-limited groundwave range was shown earlier in Fig. 2.4. This curve was used to generate the linked cluster examples of Sec. 2.2. In practice, the achievable communication range depends on frequency, transmitter power, data rate, modulation scheme, receiver structure, antenna gains or losses, other system losses, acceptable error rates, and interference levels. The effects of the other sources of interference are much greater than the effects of atmospheric noise in the stressed environment that we are assuming for the ITF Network, and so, such noise-limited communication ranges can only be considered as representative of a best-case environment, rather than a realistic one. Curves of this type are useful, however, in illustrating the dependence of communication range on frequency.

Noise and distortion considerations relating to the hardware design of a new wideband HF system architecture are discussed in [37,38]. Of the issues considered, the one most directly related to the "networking" area is that of the required separation between simultaneous transmitting and receiving frequencies on any platform; under the proposed design, it is believed that intermodulation products will not be troublesome if a minimum frequency separation of 2.5% or 100 kHz (whichever is larger) is maintained. It is also important to note that locally generated electromagnetic interference (EMI) rises as transmitter power increases, but the new wideband architecture is expected to reduce such EMI considerably.

Multipath interference is of concern whenever the undesired skywave signals are comparable in magnitude to the desired groundwave signals. There are two basic situations that may arise. If the differential time delay between groundwave and skywave signals is short relative to the symbol duration and the signals are of comparable magnitude, then the noncoherent combining of the signals may result in fading. If the delay is larger, then intersymbol interference will occur. Methods to avoid such multipath effects include spread spectrum signaling techniques (such as direct sequence and frequency hopping), which will be discussed in Sec. 3.2.2 and Appendix B, the use of channel equalizers, or avoidance of those parts of the HF band that result in such multipath.

Other-user interference is usually the principal source of interference in the HF band, and can be tens of decibels greater than the atmospheric noise level [26,39,40]. In the networking environment there are two main classes of other-user interference:

1. interference caused by platforms external to the network,

2. interference caused by other network members (or other platforms with which the network is communicating).

The main characteristic of the former is that it is not controllable; it is part of the environment in which our network must function, and will be considered to be part of the background noise level. Like atmospheric noise, other-user interference levels in frequency bands that support skywave propagation are considerably higher at night.

Interference resulting from other task force platforms is characteristic of a networking environment, and it is clear that network management schemes are needed to minimize the effects of such interference. A major part of the HF ITF networking study has in fact been directed toward this problem. Other-user interference can be avoided if orthogonality is somehow maintained among the

transmitted signals in the time domain, frequency domain, or joint time-frequency domain. In practice such orthogonality is difficult to maintain; however, there are time, frequency, and code division multiple access techniques that can achieve acceptable levels of performance in many applications as will be discussed in Sec. 4. The problem of other-user interference is especially severe in the portion of the HF band that supports skywave propagation, because in this case all members of the network can potentially interfere with each transmission, rather than the limited subset that is within groundwave propagation range of a particular platform. Point-to-point measurements are no longer adequate to assess the interference levels for a particular path, because interference can come from platforms at virtually any range (including those external to the task force, and in fact from all parts of the world).

Jamming considerations are similar to those for other-user interference. However, jammers are obviously not controllable, and are therefore not subject to network management techniques, nor can their signals be modeled simply as part of the background noise. The network must be so designed as to circumvent this form of interference. Even when only groundwave links are used in the network, the effects of jamming signals that propagate via skywaves must be considered since it is usually not feasible to separate the propagation modes at the receiver. The frequency band over which the network will be susceptible to skywave jamming signals will be determined by the relative positions of the jammer and the platforms being jammed. While the MUF for task force communication ranges is relatively low, the MUF corresponding to distant jammers is considerably higher (and would be similar to that shown in Fig. 3.2) resulting in troublesome interference over a wider part of the HF band than would be expected on the basis of the MUF for communication between task force platforms. Jamming considerations related to the HF ITF Network are discussed in Sec. 3.2.5 and Appendixes D and E, and a more detailed discussion is presented in [3].

3.2 HF Link (Point-to-Point) Communication

We now consider the problem of HF point-to-point communication in the ITF environment, neglecting for the moment the problems associated with networking issues such as other-user interference. The impact of channel characteristics discussed in Sec. 3.1 is examined further. Both narrowband (NB) and wideband (WB) signaling are discussed. Our emphasis is on wideband signaling, because of its improved AJ and LPI performance. While presently available equipment uses only narrowband signaling—there have been few changes in existing HF equipment in the past twenty years—we have assumed that a wideband capability will be available when the HF ITF network is implemented. However, since the evolution from narrowband to wideband systems is likely to occur over a period of many years, and since narrowband systems are also needed for communication with non-USN nodes (e.g., analog voice interface with civil or nontreaty organizations) and possibly for operation under benign conditions even when wideband equipment is available, the HF ITF network must be designed to use both wideband and narrowband communication.

3.2.1 Narrowband Communication

Our intent in this section is not to provide a comprehensive treatment of all narrowband signaling techniques and equipment, but rather to provide a brief overview, as well as a basis for the wideband signaling discussion of Sec. 3.2.3. The major signaling considerations include the transmission frequency, modulation technique, and AJ performance.

The signal bandwidth of HF systems currently in use is typically about 3 to 6 kHz. The choice of transmission frequency is based on the desired propagation mode (i.e., groundwave *vs* skywave) as well as the operating environment (i.e., atmospheric noise, other-user interference, and jamming). If only groundwave propagation is desired, then a good choice of frequency would be one at which: i. a strong groundwave signal is propagated; ii. there is no skywave propagation (i.e., the frequency is below the LUF or above the MUF corresponding to the particular communication path), to avoid multipath signals or other-user interference; and iii. there is little noise or other-user interference (i.e., the user

should look for quiet subbands). Alternatively, if a skywave path is desired, then a frequency near the frequency of optimum transmission (FOT, which has been defined as 85% of the MUF for the desired propagation path), at which multipath dispersion is minimal, would be best. At lower frequencies the skywave itself experiences multipath with propagation via "high" and "low" waves; at slightly higher frequencies than the FOT one would risk loss of the channel because of the possibility of fluctuations in the MUF.

A number of modulation schemes that are appropriate for narrowband communication over fading HF channels have been incorporated into the High Frequency Digital Modem (HFDM) that is currently under development by GTE/Sylvania [41]. For further information on narrowband signaling schemes that are suitable for the HF band the reader is referred to a survey of modulation techniques [42], a discussion of modulation and coding considerations for the Advanced Narrowband Digital Voice Terminal (ANDVT) [43], a description of a number of modems [44], and several Military Standards (MIL-STD-188C, MIL-STD-188-200, and MIL-STD-188-342).

Antijamming performance is discussed in detail in relation to wideband signaling in Sec. 3.2.2 and Appendixes D and E. A qualitative discussion will be sufficient for the present case of narrowband signals. The jamming protection that can be provided using narrowband signals will not be adequate for the HF ITF Network. It is straightforward for a jammer to detect the presence of a narrowband signal, and then transmit high energy narrowband jamming signals (either noise or tones) to disrupt communication.

There are methods that can provide some degree of AJ capability for narrowband signals. If diversity transmission is used (i.e., transmitting the same signal at two or more frequency subbands) then the jammer will have to jam this set of subbands. Little jamming protection would be provided by such a scheme, however, because it would not be difficult for the jammer to sense which subbands are being used and to jam them.

Another method for achieving protection from jamming is based on the use of adaptive antenna arrays to null out jammers. This approach has the advantage that it is compatible with the current narrowband HF communication architecture. Unfortunately, adaptive array techniques have several limitations that argue against exclusive reliance on this method for achieving AJ performance. Chief among these are the fact that for reasonable size arrays only a small number of jammers can be nulled out at the same time, and the fact that it is difficult to achieve protection when the jamming comes from the same direction as the desired signal. Compton [45] has recently demonstrated that an array that adapts to polarization can null an interfering signal coming from the same direction as the desired signal, if the signals have different polarizations. However, HF groundwave propagation is predominantly vertically polarized, owing to the more rapid attenuation of horizontally polarized signals in this propagation mode, and hence this technique would appear to be usable only in the unlikely circumstance that the jamming is predominantly horizontal in polarization.

3.2.2 Wideband Communication—Frequency Hopping Spread Spectrum

It was noted earlier that wideband (i.e., spread spectrum) signaling will be needed in the HF ITF Network to provide adequate protection from jamming. In this section we summarize the considerations that have led to our recommendation of frequency hopping (FH) as the spreading mechanism. Spread spectrum signaling in the HF ITF environment is discussed in greater detail in Appendix B. The basis for the choice of frequency shift keying (FSK) as the modulation technique is discussed in Sec. 3.2.3 and Appendix C. The AJ performance of FH-FSK waveforms, coding considerations relating to the HF channel, and issues relating to implementation are discussed in Sec. 3.2.5 and Appendixes D and E. However, a complete characterization of a waveform that is suitable for HF ITF communication would be far beyond the scope of this report. We are interested primarily, of course, in those aspects of signal design that will have the greatest impact on network operation.

One of the fundamental considerations in the design of a spread spectrum system is the choice of the spectrum spreading mechanism. The three forms of spread spectrum signaling that we have considered are direct sequence (DS), frequency hopping (FH), and hybrid FH-DS.

The primary criteria by which a spread spectrum system should be evaluated are its ability to provide AJ capability at acceptable data rates, its ability to function in the particular environment for which it has been designed (in our case the HF ITF environment), and the practicality of its implementation. By considering performance under each criterion we have concluded that, while each of the spreading mechanisms has its advantages, a pure FH system is the most practical choice for use in the HF ITF Network. The basis for this choice is provided in Appendix B.

The main advantages of FH signaling as compared with DS signaling are:

1. FH systems are virtually immume to the "near-far" problem, and are therefore better suited than DS systems for multiple access applications;

2. PN code acquisition (synchronization) is easier to achieve and more difficult to disrupt for FH systems;

3. FH systems are less sensitive to the dispersive nature of HF channels;

4. FH systems do not require a contiguous bandwidth; and

5. Wider bandwidths (and therefore greater processing gain) can be achieved with FH systems.

In addition, when noncoherent signaling is used (e.g., noncoherent FSK, which is proposed for the HF ITF Network) there are no carrier phase acquisition problems.

We have also considered hybrid FH-DS systems. While in certain respects they do provide some advantages over a pure FH system, they are more difficult to implement.

Thus our conclusion is that a pure FH system is most appropriate for the HF ITF Network. It is noted in Appendix B that a hopping rate of 2400 hops per second will considerably reduce the effects of fading caused by skywave interference. A high hopping rate is also advisable to prevent repeat-back jamming, as well as to facilitate coding and diversity. If the hopping rate is limited to at most several hundred hops per second, satisfactory performance is still expected in many cases. However, when operating in frequency bands that support considerable skywave propagation one would have to rely more on coding and interleaving as well as on guard times.

The next question is the choice of modulation method. Frequency Shift Keying (FSK) is generally used in pure noncoherent FH systems, and is proposed for the HF ITF Network as well. We now discuss the reasons for this choice.

3.2.3 Data Modulation Method—Noncoherent FSK

In Appendix C we discuss considerations relating to the choice of the data modulation method. The primary reasons for our recommendation to use noncoherent frequency shift keying (FSK) are:

1. Feasibility of implementation;

2. Robustness with respect to channel properties (such as fading and interference);

3. Compatibility with hopping schemes in which either several symbols are transmitted per hop, one symbol is transmitted per hop, or several hops are transmitted per symbol.

We have investigated binary and M-ary FSK. Quaternary FSK (QFSK) is well suited to the maximum anticipated data rate requirement of 2400 b/s. For example, if a hopping rate of 2400 hops per second is used, then 2400 quaternary symbols per second would be transmitted, resulting in a transmitted symbol rate equivalent to 4800 binary symbols per second. If rate 1/2 coding is used the net data rate is the desired 2400 b/s.

In Sec. 3.2.5, Appendixes D and E, and [3] we discuss in detail jamming, coding, and diversity for binary, quaternary, and 8-ary FSK. The waveform design must take into consideration the complex interrelationships among many variables, such as the adversary's jamming strategy, channel fading, M-ary signaling, diversity, coding, and interleaving. In the subsequent sections we examine these issues with respect to the HF ITF Network.

3.2.4 Link Power Budget Analysis

We now summarize a preliminary power budget analysis that illustrates the relationship between transmitted and received energy per bit as a function of frequency, range, and bit rate. The bit error rate (BER) performance of a digital system operating in additive white Gaussian noise (AWGN) is a function of E_b/N_0, the ratio between the received energy per bit and the background noise spectral density. Various modulation and coding schemes are normally compared on the basis of their BER performance as a function of E_b/N_0. Although the HF noise environment (that arises primarily from atmospheric noise and other user interference) is non-Gaussian, estimates of the required E_b/N_0 to achieve a given BER can be obtained in many cases by adding an appropriate margin to take care of the non-Gaussian effects. Jamming will of course be the most potentially disruptive source of interference in the HF ITF Network.

In the jamming environment the quantity E_b/N_0 is again of fundamental importance, although it must be redefined in terms of an equivalent energy-per-bit to noise ratio. In Sec. 3.2.5 we apply the major results of a jamming analysis by Omura [46] to the HF ITF Network environment. Mathematical results and an extensive set of performance curves are given in our report on HF ITF Network signaling issues [3]. Omura evaluated BER performance as a function of the equivalent E_b/N_0 for frequency hopped MFSK systems for a large number of cases:

1. several alphabet sizes (i.e., values of M in MFSK),

2. many values of diversity,

3. several coding schemes,

4. both hard and soft decision receivers,

5. jammer state known or unknown (i.e., in the former case the receiver knows whether or not each received symbol has been jammed), and

6. nonfading and Rayleigh fading channels.

Power Budget Equations—No Fading or Jamming

The first step in the determination of link performance is the estimation of the received power of the desired groundwave signal. The received signal power can be expressed in terms of the transmitted power and the gains and losses along the transmission path:

$$P_R = (P_T Q)/L_P$$

where,

P_R = received signal power,

P_T = transmitter power,

L_P = propagation loss,

and

Q = quantity representing net effect of system gains and losses.

Typically P_T may be about 1 kW, although the new wideband architecture will permit control of transmitter power from much smaller levels (desirable for LPI and LRI applications) to as high as 16 kW, (which may sometimes be needed to combat jamming) [38]. Propagation loss can be estimated from the curves of Fig. 3.1. The parameter Q represents the combined effect of transmitter power distribution losses, receiver processing losses, antenna pattern effects, and possibly other system losses.

First, we consider the performance of a groundwave link in an unjammed environment. The primary sources of interference are atmospheric noise and other-user interference, which we shall combine into the value N_0 for the noise spectral density. We noted that the quantity E_b/N_0 is of primary importance in digital systems. It can be expressed in terms of the received signal to noise density ratio, P_R/N_0, as follows:

$$E_b/N_0 = P_R/(RN_0)$$

where R is the information data rate in bits per second.*

Figure 3.3, which illustrates the received energy per bit for several data rates, assuming binary signaling and a transmitter power of 1 kW (and neglecting transmitter and receiver gains and losses, i.e., $Q = 1$) was obtained simply by relabeling the vertical axis of Fig. 3.1. The E_b/N_0 ratio (in dB) is then obtained by subtracting N_0 (dBW-s) from the value of E_b (dBW-s) shown on the curve. The effects of system gains or losses can be incorporated into the model by simply shifting the vertical axis in accordance with the value of the parameter Q.

The value of E_b/N_0 required to achieve a given BER is dependent on the modulation scheme. For example, for (uncoded) noncoherent binary FSK signaling in AWGN a BER of 10^{-5} is achieved for $E_b/N_0 = 13.4$ dB. If we extend this to $M = 8$-ary alphabets the required E_b/N_0 value decreases to 9.1 dB for the same BER, resulting in about 5-dB improvement on the AWGN channel [46]. To allow for the non-Gaussian nature of the interference in the HF channel we will need some additional margin, which will depend on the nature of the channel (e.g., jamming and fading characteristics and noise

*Note that while the use of coding and/or diversity will increase the number of binary symbols that are transmitted, and the use of M-ary modulation will result in fewer transmitted symbols than in a binary system, R always refers to the actual information data rate in bits per second before the application of modulation, coding, and diversity.

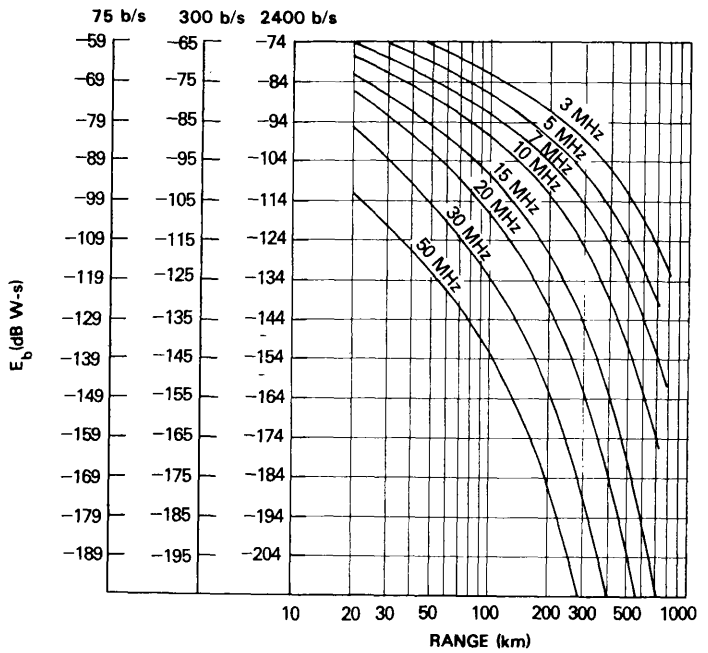


Fig. 3.3 — HF groundwave received energy per bit as a function of frequency, range, and data rate; transmitter power = 1 kW; binary signaling; omnidirectional antennas; smooth sea

statistics) and on the type of coding used as well as the amount of diversity. Estimates of achievable groundwave communication ranges (for any particular required value of BER) can easily be obtained for given bit rates and frequencies for various values of N_0 and transmitter power.

Care must be taken to ensure that an acceptable value of E_b/N_0 is maintained over the entire hopping bandwidth of a wideband HF channel. It is for this reason that we have divided the HF band into a number of subbands as discussed in Sec. 2. Over each of these subbands the propagation loss, and therefore connectivity, is relatively constant. Typically, however, the background interference levels, and therefore E_b/N_0, will vary over the frequency slots that comprise each subband. An FH signal will hop over the entire subband, and will be able to overcome the effects of a number of noisy frequency slots (and hence, lost bits) through the use of forward error correction coding, provided that an adequate E_b/N_0 is maintained in a sufficient number of frequency slots. It is also worth noting that shipboard antenna patterns can vary considerably over the bandwidth of these subbands, despite the fact that the antennas have been designed to be omnidirectional at all frequencies; e.g., nulls may exist at some frequencies resulting in greatly reduced E_b/N_0. As in the case of noisy frequency slots the use of frequency hopping provides some degree of robustness by means of frequency diversity to such frequency dependent system losses.

Estimates of communication ranges that are achievable in a benign environment are of little use to the HF ITF Network, which must be designed for operation under severe stress. The primary limitation on achievable communication range will be caused by hostile jamming, although fading is also an important concern. Therefore, it is necessary to first develop an understanding of how jamming affects communication link performance, and then develop modulation, coding and diversity techniques, including methods to adaptively vary data rates, that are suitable for operation in a jammed environment.

3.2.5 AJ Performance of FH-MFSK Signaling Over Nonfading and Rayleigh Fading Channels

An AJ communication system must provide resistance against jamming signals that have substantially more power than the desired signals. In a FH system AJ capability is achieved at the two lowest layers of the OSI model by pseudorandom hopping of the instantaneously narrowband signal across a wide frequency band, and by use of coding and diversity. The jammer may choose to jam across the entire frequency band resulting in little power in each frequency slot (broadband jamming), or he may choose to concentrate the same total power over a smaller fraction of the band (partial-band jamming) thereby placing more jamming power into each of the jammed frequency slots. In this report we consider noise jamming for both broadband and worst case partial band (WCPB) cases. Multitone jamming is also a realistic threat; its impact on link performance is a subject for future investigation.

Worst case partial band jamming is usually the most effective jamming strategy, although Omura [46] and Avidor [47] have recently demonstrated that broadband noise jamming is in fact the WCPB noise jammer in uniform Rayleigh fading channels. Further jamming protection is achieved at the Network Layer via the use of relaying and adaptive routing.

The purpose of this section is to illustrate the AJ link performance that can be obtained in an FH-MFSK system through the use of coding and diversity. We assume that noncoherent MFSK signaling is used, with one MFSK tone transmitted per hop. The basic signal parameters are:

$M = 2^K =$ alphabet size,

$K =$ number of bits per MFSK symbol, and

$R_h =$ hopping rate (hops per second).

Note that the bandwidth of each frequency slot is MR_h Hz (assuming orthogonal tone spacing, and neglecting the need for guard bands to reduce adjacent channel interference), and that $K = \log_2 M$ binary symbols are transmitted per hop.

It is assumed that the hopping rate is sufficiently fast so that repeater jamming is not possible. It is also assumed that the frequency hopping patterns are pseudorandom in nature, and cannot be predicted by the jammer.

The basic AJ system parameters are as follows:

$W =$ total spread spectrum signal bandwidth,

$R =$ information data rate in bits per second,*

$S =$ received signal power,

and

$J =$ received jammer power.

The "equivalent bit energy to noise density ratio" is defined as:

$$E_b/N_0 = \left(\frac{W}{R}\right)\left(\frac{S}{J}\right) = \frac{PG}{(J/S)},$$

where $PG = W/R$ is the processing gain, and J/S is the jammer-to-signal power ratio.

*We again note that R always refers to the actual information data rate in bits per second before the application of modulation, coding, and diversity.

This formulation is independent of the signal and jammer waveforms (although system performance would of course depend on them), and is useful because it allows the comparison of different types of AJ systems on the basis of the E_b/N_0 required for a given BER. Note that E_b again refers to the received energy per bit rather than per M-ary chip. In all of our discussions on AJ performance the term E_b/N_0 refers to the equivalent E_b/N_0. Other noise sources are neglected as they are assumed insignificant as compared with jamming.

Performance curves illustrating the effects of modulation, coding, and diversity as a function of E_b/N_0 are presented in [46] and also summarized in [3], permitting a comparison of various schemes on the basis of their performance as a function of this fundamental quantity. A brief summary of these results is also presented in Appendixes D and E. The performance curves illustrate the values of E_b/N_0 that are required to ensure a specified BER.*

Care must be used in the interpretation of the concept of processing gain in FH systems. A quantitative definition of processing gain such as that used here is valid only if the signal is hopped uniformly over the bandwidth W and the jammer is incapable of predicting the hopping pattern or following the signal as it hops from one frequency slot to another. While other definitions of processing gain are in fact possible (e.g., it is sometimes defined as the number of frequency slots over which the signal is hopped) the definition we have used is consistent with the problem formulation based on the equivalent E_b/N_0, and facilitates the comparison of a number of signaling schemes on the basis of their AJ performance.

Ultimately, we are interested in the "tolerable J/S ratio," i.e., maximum J/S ratio that can be tolerated by the AJ communication system for a specified BER:

$$J/S(dB) = PG(dB) - E_b/N_0 \text{ (dB)},$$

where the value of E_b/N_0 used in this equation is that which is required for the desired BER. Clearly, AJ performance can be improved by increasing the processing gain, which can be accomplished either by increasing the hopping bandwidth or by lowering the data rate. As an example, for a total spread bandwidth (which does not have to be contiguous for FH systems) of 5 MHz and a data rate of 2400 b/s we have $PG \doteq 33.2$ dB. Lowering the information data rate to 75 b/s increases the processing gain by a factor of 32, or 15 dB, to 48.2 dB. In a practical system the data rate, although not necessarily the hopping rate, may have to be lowered during periods of severe jamming. While the values of processing gain that are achievable at HF are considerably smaller than those at UHF, SHF, or EHF (because of the wider bandwidths achievable in those frequency bands) AJ performance can be considerably better than in the narrowband signaling case.

The AJ performance curves that are presented in this report have been generated under the assumption of an ideal soft decision receiver that can detect which of the symbols it receives have been corrupted by jamming; the same assumption has been made by a number of other researchers in this area (e.g., Viterbi [48]). The knowledge of whether or not symbols are jammed is referred to as "Jammer State Information," or J.S.I. It is expected that the performance of practical receiver structures can approach that of such an ideal receiver, although some small processing losses are expected. Omura has recently developed a new technique, based on the cutoff rate parameter, R_0, that can be used to extend the results obtained for such an ideal receiver to less intelligent receiver structures in which hard decision decoding is used and J.S.I. either is or is not available [46,3].

We have considered both nonfading and Rayleigh fading channels. It was noted earlier that HF groundwaves experience little dispersion. The main source of dispersion in groundwave links is skywave multipath propagation, much of which can be avoided at ITF ranges by hopping at 2400 hops

*It should be noted that few exact results for BER are obtainable, and most results are given in terms of upper bounds. These bounds are believed to be accurate to within a dB for BER less than 10^{-3} (i.e., the actual value of E_b/N_0 required to achieve a specified BER is within 1 dB of the value shown on the curve).

per second or faster. Since we will be relying primarily on groundwave links in the HF ITF Network, a nonfading channel model is adequate to evaluate AJ performance for most cases of interest if a hopping rate of 2400 hops per second or greater is in fact used. For frequencies at which skywave propagation is not supported, the nonfading model would be valid at all hopping rates.

Since it is expected that some skywave links may be used either within the network or for communication to points external to it, an understanding of the AJ performance over fading channels is also essential. A fading model may also be appropriate at low hopping rates when operating at frequencies at which skywave propagation is supported. While a Rician (i.e., specular-plus-Rayleigh) fading model might be more appropriate than a Rayleigh model in some cases (where the groundwave signal is the specular component and the skywave signal is the Rayleigh component), a Rayleigh model is useful because it provides a worst-case bound for Rician channel performance.

It has been demonstrated by Omura [46] and Avidor [47] that for the case of a uniform Rayleigh fading channel (i.e., one in which propagation conditions are uniform across the entire channel bandwidth) the worst case partial band jammer is in fact the broadband jammer for any of the receiver types we are considering, i.e., hard and soft decision receivers, with and without J.S.I. known.

In the following subsection we discuss some of the tradeoffs in AJ signal design for some realistic HF ITF Network link parameters. It is clear that without some form of coding and/or diversity the links of the network are not jam-resistant against the worst case partial band (WCPB) jammer. With coding and/or diversity, however, the links do achieve a reasonable amount of AJ capability.

3.2.6 Summary of AJ Performance Tradeoffs

The AJ performance of FH-MFSK signals is discussed in Appendixes D and E. Before summarizing our major results it is first useful to indicate the many variables that AJ performance is dependent upon:

$$J/S = f(M,\ m,\ r,\ W,\ R,\ \text{BER})$$

where,

M, W, and R are as defined earlier,

m = diversity per coded MFSK symbol,*

r = composite code rate (defined in Appendix E),

and the resultant bit error rate can be expressed as,

BER = $f(E_b/N_0|$ given detection technique, channel model, decision strategy, J.S.I.).

Our analyses assume noncoherent detection with and without J.S.I. and apply to worst case partial band jamming on both nonfading and Rayleigh fading channels. The results for the fading channel also apply to the nonjammed case in which the Rayleigh fading channel is affected only by AWGN, since WCPB jamming in a Rayleigh fading channel is actually broadband jamming. Both soft and hard decision receiver structures are a part of this analysis.

In order to present some AJ tradeoffs we will specify the following variables as an example:

W = 5 MHz,

R = 2400 b/s,

*The reader is hereby warned that two diversity parameters (m and L) and three code rate parameters (r, r_1, and r_0) are used in this report. The relationships among these parameters are defined in Appendix E.

soft decision receiver,

Jammer State Information (J.S.I.) known,

BER = 10^{-5} and 10^{-3}.

The two values of BER listed above correspond to high quality and medium quality data reception respectively (see Sec. 1.1.1 on requirements). The AJ performance under these two criteria differs somewhat and is discussed separately next.

AJ Performance Under a High Quality Data Reception Criterion (BER = 10^{-5})

Under the conditions described above, and using the high quality data reception criterion, the AJ performance of a FH-MFSK signaling design is shown in Fig. 3.4. Results for nonfading as well as Rayleigh fading channels are shown. In either case, it is apparent that some form of coding and/or diversity is required to make the system capable of functioning in a jammed environment. The coding and diversity improvement gains are represented by the difference between one of the upper curves and the lowermost curve in this figure. Clearly, coding is more attractive than diversity, as would be intuitively expected. However, this advantage is most apparent at lower alphabet sizes, and diminishes somewhat with increasing M. The curve illustrating the performance of a system with coding and optimum diversity represents our desired operational AJ performance, and is within 3 dB of the maximum achievable value based on the R_0 bound.

Based on the results summarized in Fig. 3.4, either the $M = 4$ or $M = 8$ signaling designs (with rate $r = 1$ coding and using diversity) represent reasonable system choices. It must be kept in mind that the use of coding and diversity, for fixed data rate R, results in faster hopping rates and therefore greater frequency slot bandwidth. In a practical system, additional diversity would normally be achieved by lowering the data rate while maintaining a fixed hopping rate.

Table 3.1 summarizes the AJ performance for binary, 4-ary, and 8-ary alphabets as a function of diversity for a fixed data rate of $R = 2400$ b/s and a hopping bandwidth of 5 MHz. The hopping rate (R_h) and frequency slot bandwidth (BW) are included in the table to illustrate the impact of the use of diversity on signal design parameters. In the nonfading case the optimum diversity is $m = 2$ for the desired BER = 10^{-5}. In the fading case it is 3 or 4, but little improvement is gained by increasing m to values greater than 2.

In Table 3.1, r_0 is the outer code rate that is discussed in Appendix E, and is the equivalent code rate if binary signaling, rather than higher order alphabets, were being used. The code rate r is the composite M-ary convolutional code rate (see Table E1).

All of these results have dealt with a 2400 b/s data rate. The AJ performance for other data rates and spread hopping bandwidths can be derived easily from these results by use of the relationship:

$$J/S = (W/R)/(E_b/N_0).$$

Once a particular modulation/coding/diversity scheme has been chosen, the required E_b/N_0 value is established. If the spread hopping bandwidth W is fixed, then J/S is inversely proportional to the data rate R. For example, if R and the hopping rate R_h are each lowered by a factor of 2 (thereby preserving the diversity value m) then the tolerable J/S ratio is increased by 3 dB. Performance for other values of m can be derived from the curves shown in Appendix E. If we allow the data rate to vary from 75 b/s to 2400 b/s, the tolerable J/S is shown in Fig. 3.5; e.g., 15 dB of J/S protection is gained by lowering the data rate from 2400 b/s to 75 b/s. It will be necessary to develop schemes that are capable of responding to channel disturbances by lowering data rates when necessary, and restoring

Table 3.1 — Tolerable J/S Protection Ratios for Noncoherent FH-MFSK; Data Rate Fixed at 2400 b/s; High Quality Data Reception (BER = 10^{-5}) (Hopping Bandwidth = W = 5 MHz; Convolutional Code of Constraint Length 7; Soft Decision Receiver; J.S.I. Known)

M	r_0	r	m	R_h	BW (Hz)	J/S (dB) WCPB Jamming	J/S (dB) Rayleigh Fading
2	1/2	1/2	1	4800	9600	22.0	18.6
			2	9600	19200	22.3*	20.0
			3	14400	28800	21.7	20.2*
4	1/2	1	1	2400	9600	23.1	19.2
			2	4800	19200	24.3*	21.4
			3	7200	28800	24.0	21.9
			4	9600	38400	23.8	22.0*
8	1/3	1	1	2400	19200	24.2	20.5
			2	4800	38400	24.9*	22.3
			3	7200	57600	24.4	22.7*

*indicates optimum value of diversity (m)

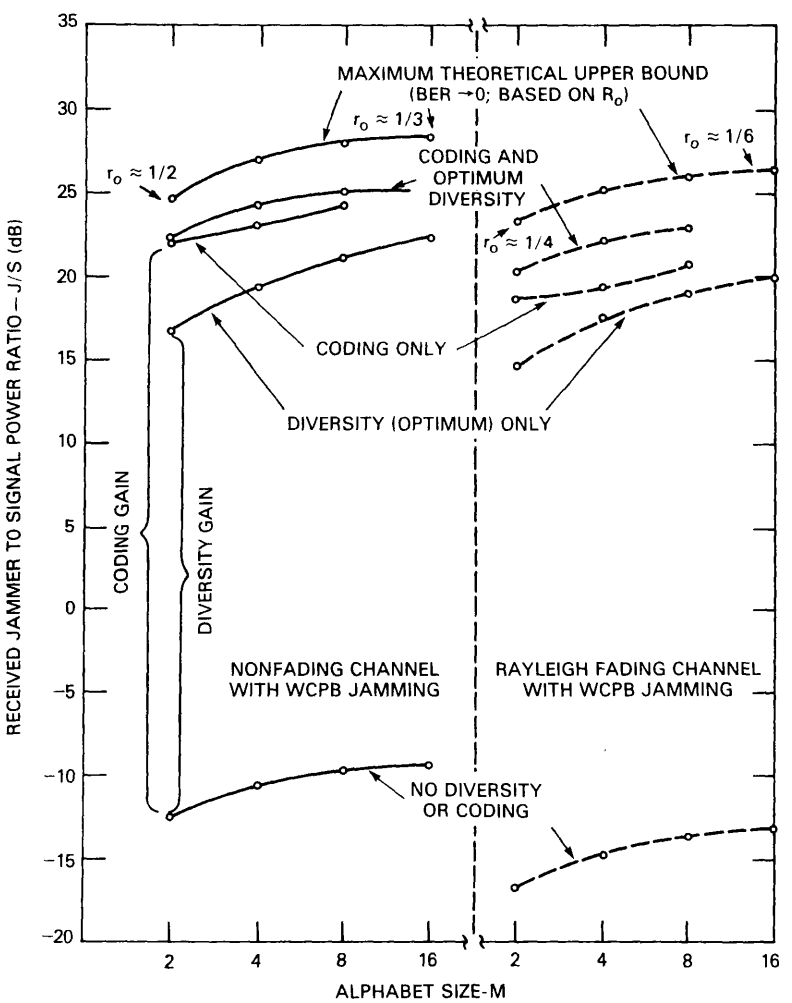


Fig. 3.4 — FH-MFSK AJ signaling tradeoffs for WCPB noise jamming on nonfading and Rayleigh fading channels under a high quality data reception criterion (BER = 10^{-5}). R = 2400 b/s; W = 5 MHz; J.S.I. known.

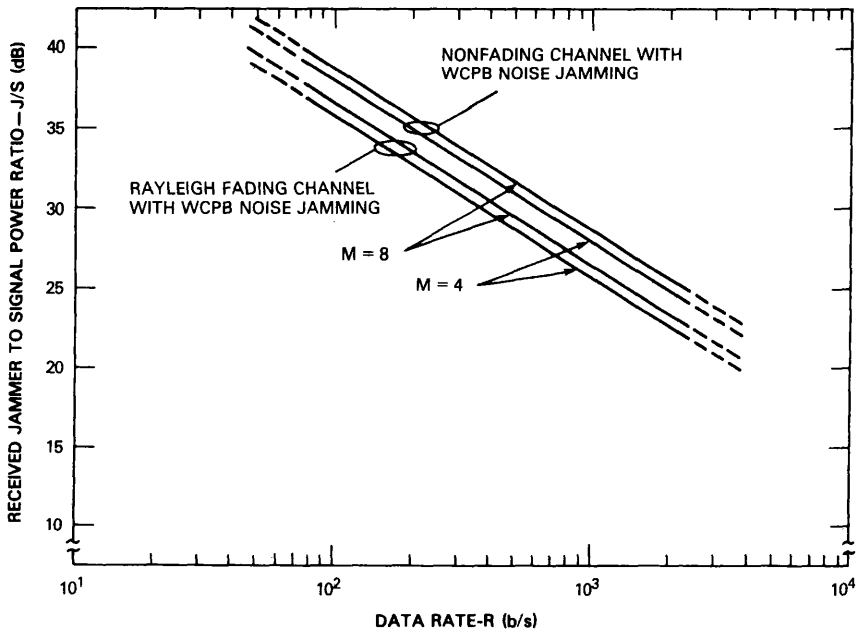


Fig. 3.5 — Maximum J/S protection ratio under a high quality data reception criterion (BER = 10^{-5}) as a function of data rate. Rate r = 1 coding and optimum diversity; W = 5 MHz; J.S.I. known.

them to higher levels whenever possible. To summarize, it is theoretically possible, when noncoherent FH 8-ary FSK signaling is used with rate $r_0 = 1/3$ convolutional coding and optimal diversity, to attain the following protection ratios for data rates between 75 b/s and 2400 b/s:

2400 b/s 75 b/s

- 24.9 dB $\leqslant$ J/S $\leqslant$ 39.9 dB (WCPB noise jamming; no fading; $m = 2$)
- 22.7 dB $\leqslant$ J/S $\leqslant$ 37.7 dB (Rayleigh fading; broadband* jamming; $m = 3$)

Some of the hopping rates and bandwidths shown in Table 3.1 may be too high to be implemented in a practical system, particularly at HF where the number of frequency slots is severely limited. Table 3.2 summarizes the AJ performance as a function of diversity for a fixed frequency slot bandwidth of 9600 Hz, and therefore a fixed hopping rate for each alphabet size, M. The diversity parameter m is inversely proportional to the data rate for the present case of a fixed hopping rate. Tradeoffs between data rate and J/S performance can easily be determined from this table.

AJ Performance Under a Medium Quality Data Reception Criterion (BER = 10^{-3})

Certain types of information transmitted within the ITF Network will not necessarily require the stringent BER performance (10^{-5}) discussed in the previous subsection. Antijamming performance results based on a medium quality (BER = 10^{-3}) data reception criterion are shown in Fig. 3.6 for nonfading and Rayleigh fading channels. The interesting distinction in this case is that some minimal

*Broadband noise jamming is WCPB noise jamming for the case of the uniform Rayleigh fading channel.

Table 3.2 — Tolerable J/S Protection Ratios for Noncoherent FH-MFSK; Frequency Slot Bandwidth Fixed at 9600 Hz; High Quality Data Reception (BER = 10^{-5}) (Hopping Bandwidth = W = 5 MHz; Convolutional Code of Constraint Length 7; Soft Decision Receiver; J.S.I. Known)

M	r_0	r	R_h	m	R (b/s)	J/S (dB) WCPB Jamming	J/S (dB) Rayleigh Fading
2	1/2	1/2	4800	1	2400	22.0	18.6
				2	1200	25.3*	23.0
				3	800	26.5	25.0*
4	1/2	1	2400	1	2400	23.1	19.2
				2	1200	27.3*	24.4
				3	800	28.8	26.7
				4	600	29.8	28.0*
8	1/3	1	1200	1	1200	27.2	23.5
				2	600	30.9*	28.3
				3	400	32.2	30.5*

*indicates optimum value of diversity (m)

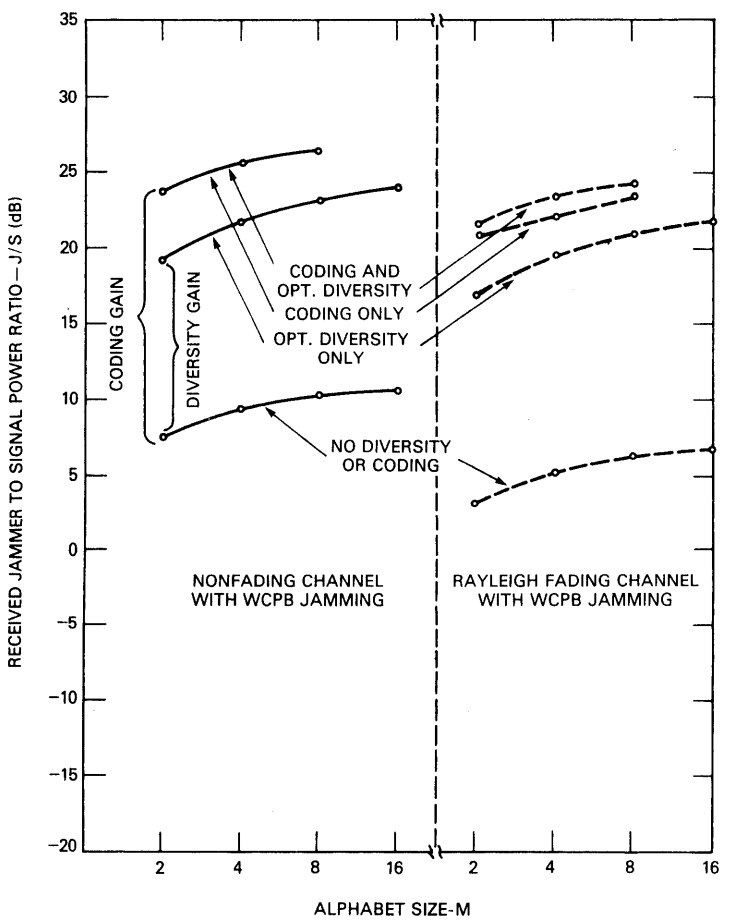


Fig. 3.6 — FH-MFSK AJ signaling tradeoffs for WCPB noise jamming on nonfading and Rayleigh fading channels under a medium quality data reception criterion (BER = 10^{-3}). R = 2400 b/s; W = 5 MHz; J.S.I. known.

protection from jamming (albeit very small) is possible without using coding or diversity. For any practical implementation, however, coding and/or diversity are recommended because of the enhanced jamming protection ratios they provide, as shown in Fig. 3.6. The coding and diversity improvement gains are represented by the difference between one of the upper curves and the lowermost curve in the figure. Clearly, these coding/diversity gains become smaller when the BER requirement is increased from 10^{-5} to 10^{-3}. This decrease in gain is evident by comparing Figs. 3.4 and 3.6 which indicate "coding only" gains of about 34 to 35 dB for BER = 10^{-5} and only 16 to 18 dB for BER = 10^{-3}. Table 3.3 summarizes the AJ performance for binary, 4-ary, and 8-ary alphabets as a function of diversity for medium quality data reception, and a data rate fixed at R = 2400 b/s.

Table 3.3 — Tolerable J/S Protection Ratios for Noncoherent FH-MFSK;
Data Rate Fixed at R = 2400 b/s; Medium Quality Data Reception (BER = 10^{-3})
(Hopping Bandwidth = W = 5 MHz;
Convolutional Code of Constraint Length 7;
Soft Decision Receiver; J.S.I. Known)

M	r_0	r	m	R_h	BW (Hz)	J/S (dB) WCPB Jamming	J/S (dB) Rayleigh Fading
2	1/2	1/2	1	4800	9600	23.8*	20.8
			2	9600	19200	23.3	21.6*
4	1/2	1	1	2400	9600	25.5*	22.0
			2	4800	19200	25.5	23.3
			3	7200	28800	24.9	23.5*
8	1/3	1	1	2400	19200	26.6*	23.5
			2	4800	38400	26.1	24.2*

*indicates optimum value of diversity (m)

This table indicates that in a coded system the use of diversity results in no performance enhancement on the WCPB noise jammed nonfading channel, and only modest improvement (about 1 dB) on the Rayleigh fading channel. This result tends to reinforce our earlier statement indicating that coding is more attractive than diversity in terms of combating WCPB noise jamming on nonfading as well as fading channels.

As in the case of high quality data reception, these results have dealt with a 2400 b/s data rate. Figure 3.7 illustrates the maximum tolerable J/S protection ratios as a function of data rate. To summarize, it is theoretically possible, when noncoherent FH 8-ary FSK signaling is used with rate r_0 = 1/3 convolutional coding and optimal diversity, to attain the following protection ratios for data rates between 75 b/s and 2400 b/s.

2400 b/s 75 b/s

- 26.6 dB $\leqslant$ J/S $\leqslant$ 41.6 dB (WCPB noise jamming; no fading; no diversity required)
- 24.2 dB $\leqslant$ J/S $\leqslant$ 39.2 dB (Rayleigh fading; broadband jamming; m = 2)

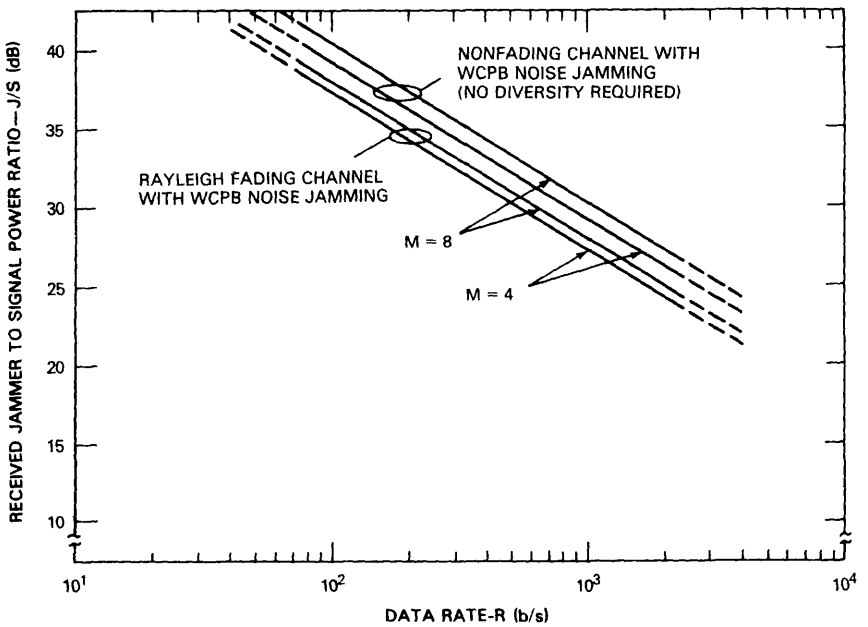


Fig. 3.7 — Maximum J/S protection ratio under a medium quality data reception criterion (BER = 10^{-3}) as a function of data rate. Rate r = 1 coding and optimum diversity; W = 5 MHz; J.S.I. known.

These protection ratios are only about 1.5 dB greater than those achievable for the BER = 10^{-5} case illustrated earlier for coded/optimum diversity FH-MFSK signal designs. Hence, allowing a higher BER does not permit the system to withstand a significantly greater jamming threat for this case of FH-MFSK signaling with coding and optimum diversity. For a signal design without either coding or diversity, however, quite the opposite is true. In this case, for BER = 10^{-5} the system is not jam-resistant, but increasing the BER to 10^{-3} does allow for some minimal protection from jamming (see Figs. 3.4 and 3.6).

Table 3.4 illustrates the tradeoffs between data rate and AJ performance for the case of a frequency slot bandwidth fixed at 9600 Hz.

Table 3.4 — Tolerable J/S Protection Ratios for Noncoherent FH-MFSK; Frequency Slot Bandwidth Fixed at 9600 Hz; Medium Quality Data Receoption (BER = 10^{-3}) (Hopping Bandwidth = W = 5 MHz; Convolutional Code of Constraint Length 7; Soft Decision Receiver; J.S.I. Known)

M	r_0	r	R_h	m	R (b/s)	J/S (dB) WCPB Jamming	J/S (dB) Rayleigh Fading
2	1/2	1/2	4800	1	2400	23.8*	20.8
				2	1200	26.3	24.6*
4	1/2	1	2400	1	2400	25.5*	22.0
				2	1200	28.5	26.3
				3	800	29.7	28.3*
8	1/3	1	1200	1	1200	29.6*	26.5
				2	600	32.1	30.2*

*indicates optimum value of diversity (m)

Based on the results presented here as well as in Appendixes D and E, the following remarks are evident:

1—Without coding or diversity:

- A FH-MFSK design provides no protection from jamming when high quality data reception (BER = 10^{-5}) is required, and only minimal protection for medium quality data reception (BER = 10^{-3}).

2—With coding* and/or diversity:

- The convolutional coding gain alone is approximately 34 to 35 dB for high quality data reception; for medium quality data reception the coding gain decreases to about 16 to 18 dB.
- Convolutional coding alone is always better (by about 2 to 5 dB) than diversity alone.
- Given that convolutional coding is used, adding diversity improves AJ performance only slightly (1 to 3 dB for the Rayleigh fading channel and 0 to 1 dB for the nonfading WCPB noise jammed channel).
- Given that convolutional coding and optimum diversity are used, the AJ performance improves only slightly (about 1.5 dB) by lowering the BER requirement from 10^{-5} to 10^{-3}.

3—Conclusion:

- Coding and/or diversity are essential to a jam-resistant HF ITF FH-MFSK signal design.
- Jamming protection ratios of the order of 25 to 40 dB are theoretically possible for data rates between 2400 b/s and 75 b/s.

The AJ performance values presented in the previous two subsections represent upper bounds on jam-resistant performance. After examining practical issues such as soft decision receiver implementation, the inability to obtain perfect jammer state information, maximum feasible hopping rates, and available spread bandwidths at HF, the above values of J/S may have to be reduced appropriately. Furthermore, channel characteristics are never uniform, and the jamming threat is highly dependent on the particular scenario and is therefore difficult to quantify. Also the combined effects of other users and jammers must be considered in order to provide a more realistic channel model. These represent further continuing study areas in our ITF Network design. However, based on our current results, it certainly appears that some modest-to-good AJ capability is possible for most links in the HF ITF Network. Coupled with the distributed control and alternate routing paths achievable through the ITF Linked Cluster architecture, we feel that the system has strong AJ and survivability potential.

3.3 HF ITF Multilink (Network) Communication

In the case of point-to-point (or single link) communication we are primarily concerned with the power budgets that must be maintained in order to obtain acceptable BER performance. Also of crucial importance, especially for spread spectrum signaling, is the issue of acquiring and maintaining synchronization.

*Assumes either r_0 = 1/2 or 1/3 convolutional coding.

In the networking (or multilink) situation the signaling issues become considerably more complex, because we must now consider the coordination of the transmissions of many communication sources. We are concerned primarily in this section with interference caused by other task-force members, and therefore potentially under network control. We discuss the problem areas that arise because of such interference, as well as possible methods to solve them.

We first address, in Sec. 3.3.1, the issues that relate to networking, as compared with point-to-point communication. While wideband (i.e., spread spectrum) signaling will be needed to provide AJ capability in the HF ITF Network, we first discuss, in Sec. 3.3.2, narrowband networking considerations. The linked cluster architecture can in fact be implemented using either narrowband or wideband signaling. This discussion serves as a basis for Sec. 3.3.3 in which we illustrate the networking implications of the use of wideband signaling as compared with narrowband signaling. While a completely wideband network would be desirable from the AJ and LPI point of view, it is clear that it will be many years before all navy platforms are fully equipped with wideband systems. An evolutionary cycle is expected in which the current narrowband equipment is gradually replaced by the future wideband equipment. As an interim measure a hybrid HF ITF Network will most likely be implemented, in which each platform will have the capability of supporting a small number of wideband links, plus a number of narrowband links. In addition, it may be desirable to operate the network in a narrowband mode whenever possible, and switch to an AJ or LPI mode, on a link-by-link basis, only when necessary. Considerations relating to such hybrid networks are discussed in Sec. 3.3.4.

3.3.1 Network vs Point-to-Point Communication Issues at HF

The dependence of groundwave propagation range on frequency is the primary reason for our decision to define a separate linked cluster network for each frequency subband of approximately a few MHz bandwidth. In the point-to-point case, where we do not explicitly consider the possibility of relaying, one would normally choose the operating frequency on the basis of factors such as the expected E_b/N_0 over the communication link, the possibility of skywave multipath interference, and the availability of a free channel. In the absence of a provision for relaying, the frequencies with better propagation characteristics (typically the lower end of the HF band which experiences less propagation loss than the higher end) would be the most attractive, and might quickly become congested. In practice, relaying will often be necessary in a task force even if the "best" frequency is used.

In the networking environment, where we can provide for relaying when necessary, there is more freedom as to the choice of operating frequency. We no longer have to choose the "best" frequency from the standpoint of propagation conditions, but can use any frequency band at which a path exists (possibly via one or more intermediate relays) from the source to the destination. It is in fact not even necessary to use the same frequency band at each hop along the way. As an example, we consider the set of linked cluster networks that simultaneously operate in different frequency bands. At the lower end of the HF band there will be a smaller number of larger clusters, and at the higher end there will be a larger number of smaller clusters. As long as it is possible to form a connected network at a given frequency band (i.e., a network in which all platforms are connected directly to a cluster head and all cluster heads are connected via the backbone network) it will be possible for any two platforms in the task force to communicate with each other via that network. The communicator's decision of which network to use will be based on overall network performance criteria such as the expected probability of correct message delivery, expected delay time, speech quality for voice, throughput, and possibly other criteria. These network performance measures are of course related to link propagation loss,

interference (mainly other-users and jammers), and congestion at the nodes (resulting in queueing delay or message loss). Intermediate nodes in a routing path may switch to a different network (i.e., frequency band) based on these network conditions.

The use of relaying provides some degree of AJ and LPI capability by giving the communicating platforms a range advantage over the potential jammer or interceptor (see e.g., [49,50]). Adaptive routing schemes can be used in some cases to route messages via platforms that, owing to their physical location, are relatively free of jamming interference; the resulting paths may be longer than some more direct paths in terms of the number of relay hops, but the better link characteristics along the more circuitous path may result in an overall improvement in performance (see e.g., [51]).

The degree of AJ performance that can be obtained is of course related to the equivalent bit energy to noise ratio E_b/N_0 that is achieved over the links of the network. During the execution of the Linked Cluster Algorithm the platform pairwise connectivities are determined and summarized in the connectivity matrix as binary entries. Connectivity (or the lack of it) must be defined in terms of achieving the desired bit error probability, and therefore a threshold value of E_b/N_0 for a given data rate. It is essential that a network that is organized under benign conditions function well while being jammed. The threshold must be set sufficiently high under benign conditions so that a sufficiently high E_b/N_0 is maintained for most expected jamming (as well as other-user interference) levels. The threshold should therefore ideally be based on knowledge of whether or not the network is being jammed at the time connectivity is tested, as well as the anticipated jamming and noise levels under stressed conditions.

3.3.2 Narrowband Network Communication

In a narrowband network a number of narrowband channels, or frequency slots, are available to be allocated among the network's users. A major network design issue is the development of link management schemes that permit the efficient apportionment of these frequency slots to the users via either dedicated or shared links.

Other-user interference will be troublesome only if two or more sources simultaneously transmit in the same narrowband frequency slot. (We again consider other-user interference to consist only of interference caused by other task force platforms; interference resulting from sources external to the task force is considered as part of the background noise level.) The problem of other-user interference can therefore be avoided if the members of the network are somehow coordinated so that their transmitted signals are orthogonal, i.e., so that no two platforms transmit in the same frequency slot at the same time. (This condition can be relaxed in some cases to permit so-called frequency re-use as long as there is little or no skywave propagation, and if the two platforms are located sufficiently far apart so that their transmissions do not interfere.)

One possible approach to avoid such interference is the assignment of a distinct narrowband frequency channel to each potential pair of communicating platforms in the network (neglecting for the moment the situation in which the relaying of messages by intermediate nodes may be necessary). The number of channels required in such a fully connected network is $N(N-1)/2$, where N is the number of platforms. For the HF ITF Network we may have $N = 100$, resulting in 4950 channels, which would be prohibitive from the point of view of bandwidth availability. In addition, even if bandwidth were not a problem, we would still have the hardware requirement of a transmitter and receiver dedicated to each of these frequency channels at every platform. As a result of such bandwidth and equipment constraints it is necessary to develop schemes that permit the efficient sharing of the available communication resources. Each narrowband channel can be shared among a number of users by using one or more of the time domain multiple access protocols that are discussed in Sec. 4.

The number of narrowband frequency channels (or slots) that are available depends on the total available bandwidth and the bandwidth needed by each signal. In Appendix C we consider a quaternary FSK (4-ary FSK or QFSK) signal hopped at 2400 hops per second, with one symbol transmitted per hop. The bandwidth nominally required by such a signal is 9600 Hz; to reduce adjacent channel interference, a channel bandwidth of approximately 20 kHz would actually be advisable. There would therefore be approximately 50 narrowband channels per MHz of spread bandwidth. In the HF ITF Network we are anticipating that the total bandwidth of each of the simultaneously operating networks under the Linked Cluster Architecture will be between 2 and 5 MHz. The total number of narrowband channels per network would therefore be between 100 and 250. In practice the number of available channels would be somewhat lower because certain parts of the HF band are dedicated to specific applications and are therefore not usable by the HF ITF Network.

As discussed in Sec. 2, the Linked Cluster Architecture provides a basis for reducing the total number of narrowband channels that are required, as compared with the totally distributed situation in which each platform maintains a link with each of its neighbors.

Normally, multiple access protocols are considered in terms of a single channel that is to be somehow allocated among a number of users. In contrast, we are considering here the sharing of a number of channels among a number of users, each of which might be limited to the use of only a single channel or a small number of channels at any given time.

It is possible to consider an HF network that uses only a single narrowband channel, rather than the many channels that we are assuming to be available. For example, LINK 11 uses a central controller to query other net members when they are to transmit data; this is known in LINK 11 terminology as ROLL-CALL [52].

The use of a single channel for HF ITF communication has also been considered by NOSC [53,54,55]. Like LINK 11 their network concept can handle data only, but it has the advantage of not needing a central controller. Our efforts at NRL have emphasized the use of multichannel networks because of our desire to support greater traffic levels as well as integrated voice and data traffic, and to provide highly survivable communication at HF.

3.3.3 Wideband Network Communication

The use of spread spectrum signaling has had a great impact on the design of the HF ITF Network. The decision to use spread spectrum signaling is based on the need to provide AJ and LPI capability. Spread spectrum signaling leads naturally to the use of Code Division Multiple Access (CDMA) techniques, since under CDMA the dual purpose of providing multiple access capability as well as AJ and LPI performance can be achieved. We use the term CDMA to include all forms of spread spectrum multiple access; CDMA can be implemented using direct sequence (DS), frequency hopping (FH), or hybrid FH-DS signaling. We are interested in FH systems for the reasons discussed in Appendix B.

To provide a sufficient degree of AJ and LPI capability, FH systems require a wide bandwidth channel over which to hop, perhaps the entire bandwidth of one of the Linked Cluster networks, i.e., about 2 to 5 MHz. One wideband channel would thus take the place of roughly 100 narrowband channels. In a narrowband system a "collision" occurs whenever two or more signals attempt to transmit simultaneously in the same channel; all signals involved in this collision are usually assumed to be destroyed (actually a pessimistic assumption). If a FH-CDMA channel were treated analogously to a time-domain channel, in the sense that only one signal were permitted to occupy it at any given time, the overall network throughput would be drastically and unacceptably reduced. By using CDMA techniques, however, the wideband FH channel can be shared among a number of simultaneous transmissions.

The purpose of this section is to address the major issues associated with FH-CDMA systems and their networking implications. Additional discussion of FH-CDMA is presented in Sec. 4.3. In particular, in this section we address the implications of using FH-CDMA in conjunction with the Linked Cluster Architecture. As in the narrowband case, there is a need to develop channel allocation schemes for the implementation of dedicated links in the backbone network and multiple access protocols for intra-cluster communication. These problem areas must be reinterpreted in the FH context, however. For example, we consider, here and in our separate report on signaling issues in the HF ITF Network [3], the following problem areas:

1. Synchronization requirements and hopping rates.

2. The generation of FH patterns.

3. Interference and multiple access in FH systems.

4. The assignment and distribution of codes (i.e., FH patterns) to platforms.

5. Contention among signals using the same code.

1—Synchronization requirements and hopping rates

In our discussion of narrowband networking considerations we noted that other-user (i.e., other task force member) interference can be avoided if the users are coordinated so that, at most, one platform transmits in any narrowband channel at any given time. It is possible in principle to achieve such an orthogonality in FH systems as well by coordinating the FH patterns of all users so that no two are scheduled to transmit simultaneously in the same frequency slot. In practice, however, the degree of synchronization required to achieve such coordination is generally not feasible, because of timing uncertainties as well as some security issues.

It would be necessary to use guard time delays at each hop to account for timing uncertainties in a synchronous network. In the HF ITF Network communication ranges from near zero to as great as 500 km may be expected, resulting in differential propagation time delays that may be as great as 1.67 ms. In addition, timing uncertainties at each platform are expected to be of the order of 1 ms. The total timing uncertainty and therefore guard time requirement is therefore close to 3 ms, which would limit hopping rates to less than 300 hops per second, if network-wide synchronization at the hop level were to be maintained.

While the lower hopping rates may in many cases be acceptable, fast hopping rates are desirable for improved AJ performance (including performance from repeat back jamming) and multipath rejection. Our goal is in fact a network design that can function satisfactorily at all feasible hopping rates, and not be dependent on either especially fast or slow hopping rates.

Although network-wide synchronization at the hop level is not feasible, such synchronization at the packet level can and should be maintained. The guard time requirement to achieve such synchronization is again of the order of 3 ms. This is a small fraction of the anticipated packet length (tens of ms) and therefore represents a small degree of added overhead. While synchronization at the packet level does not reduce the occurrence of frequency hits, it does, however, facilitate the use of network management schemes that depend on the allocation of network resources on a time division basis.

2—The Generation of FH Patterns

There are a number of methods that can be used to generate hopping patterns for asynchronous FH-CDMA applications. For example, Sarwate and Pursley have proposed a class of FH patterns based on Reed-Solomon codes that have good cross-correlation properties (i.e., they experience few frequency hits [56]), and consequently good multiple access performance. These FH patterns are not suitable for secure military applications, however; they can easily be predicted by a jammer or interceptor because they are periodic with period not greater than the number of frequency slots.

Another method that can be used to generate pseudorandom FH patterns is the use of linear feedback shift registers (LFSR's). The output of a set of m taps of the LFSR can be used to specify one of 2^m frequency slots. There exist maximal length LFSR's that generate sequences of period $2^n - 1$, where n is the number of shift register stages. For $n = 64$, for example, the period is 1.89×10^{19} binary symbols, which at first glance suggests that they may be attractive for secure spread spectrum systems. However, all future parts of the sequence can be predicted given only $2n$ bits of the pseudorandom sequence by using the Berlekamp-Massey algorithm [57]. The sequences can be made considerably more difficult to predict via the use of nonlinear output logic, i.e, by using nonlinear combinations of the shift register taps [58].

These examples were presented to illustrate two distinct approaches to the FH pattern design problem. The use of Reed-Solomon patterns is motivated by their multiple access properties, while the use of maximal length LFSR's with nonlinear output logic is motivated by security considerations. There is in fact little difference in multiple access performance between the Reed-Solomon and random FH patterns.

The methods actually used to generate secure FH patterns are of course classified, and the network designer will have little or no control over their choice. It is therefore not realistic to expect the availability of an orthogonal set of hopping patterns. The most important property of an FH pattern in a secure military application is that it appears to be random; knowledge of the frequency at any set of hops should provide no information as to the future hopping sequence. We can therefore assume that random FH patterns are being used, and that network-wide synchronization at the hop level is not possible. We can also assume that a very large family of such FH patterns exists, so that several distinct hopping patterns may be assigned to each platform. The intended receiver must of course know the hopping pattern of the transmitter, and must be able to synchronize to it.

3—Interference and Multiple Access in FH Systems

We have noted that the Linked Cluster architecture can be implemented using either narrowband or wideband signaling. As in the narrowband case, a wideband Linked Cluster network will use dedicated links (actually fractions of links allocated on a time division basis) for much of the backbone network communication. While there are similarities in the implementation of dedicated links between the narrowband and wideband cases, there are also some major differences.

The most significant difference between FH and narrowband signaling is that in the FH case there is some degree of contention even when dedicated links are used. In the case of dedicated links only a single transmitter attempts to communicate with any particular receiver at any given time, and so there is no contention for access to the intended receiver. However, as a result of the lack of orthogonality among FH patterns, frequency hits may occur because of interference from other signals (intended for other receivers) that share the same wideband channel. The question therefore arises of how many FH signals (that use random independently generated hopping patterns) can simultaneously share the same wideband channel without resulting in significant performance degradation. This problem is discussed in detail in [3]. Pursley [59] has approached this problem from the standpoint of bit error probability

derivations for nonfading and fading (nonselective and selective) multiuser channels, while Hajek [60] has approached it from the standpoint of multiple access protocol techniques. The number of users within communication range of each other that can simultaneously use the channel depends on factors such as the modulation/coding schemes, relative signal amplitudes, channel characteristics, ability (or lack of it) to detect frequency hits, and the definition of acceptable performance. Further work is needed to apply these results to the HF ITF Network, although a number of results can be presented at this point.

The most fundamental approach to this problem is in terms of the raw (prior to decoding) symbol error rate of a multiple user channel. Figure 3.8 illustrates an upper bound on the uncoded bit error probability for binary signaling as a function of E_b/N_0 for a multiple user FH system characterized by a nonfading AWGN channel and a fixed number of simultaneous users. We emphasize that each of the K users transmits continuously using its own FH pattern. It is clear from these curves that for E_b/N_0 greater than 12 dB, virtually all errors arise as a result of other-user interference rather than channel noise. The system model used to generate these curves is discussed in [3], where curves for Rician and Rayleigh fading channels are also presented. Curves of this type will be used in the future to evaluate the BER performance of coded systems.

The curves of Fig. 3.8 are valid for any relative signal amplitudes, and are pessimistic in that they assume that all hits result in a binary symbol error probability of 0.5. A tighter approximation has been obtained under the assumption of equal signal levels [59]. Further improvement would be obtained when the interfering signals are of lower amplitude than the desired signal. Frequency re-use at distant parts of the network will often result in negligible interference levels. However, we must also consider the fact that in frequency bands that support skywave propagation, the number of interfering signals will be increased. Furthermore, future efforts will consider the combined effects of other-user interference and jamming.

The problem of other-user interference in FH systems can also be approached in terms of packet error probability. Under the model discussed in [60,3] Reed-Solomon coding of rate approximately 1/2 is used to correct the burst errors caused by frequency hits in a slow FH system (i.e., one in which several bits are transmitted per hop). Figure 3.9 illustrates the probability of packet error as a function of the number of users that are transmitting simultaneously over a channel with 100 frequency slots. The channel is assumed to be noiseless in this case, and so the only source of errors is other-user interference, although a noisy channel model can also be considered. We consider two packet sizes chosen so that the data of a packet can be encoded as a single Reed-Solomon codeword. The RS-(31,15) code corresponds to a packet length of 155 bits; the packet is divided into 31 five bit bytes, one of which is transmitted at each hop. This code is capable of correcting up to eight byte errors per codeword (packet). The RS-(255,127) code corresponds to a packet length of 2040 bits, which are divided into 255 eight bit bytes. This code is capable of correcting up to 64 byte errors. Virtually all such packet errors are detectable, often permitting the subsequent retransmission of packets that are received with uncorrectable errors. The probability of an undetected packet error is less than 2×10^{-5} for the RS-(31,15) code and less than 10^{-89} for the RS-(255,127) code [61].

Three curves are shown in Fig. 3.9. The two upper curves were generated under the assumption that frequency hits are not detectable, and that they all result in byte errors. This again is a pessimistic assumption, because relatively strong signals will certainly have lower error probability. The bottom curve was generated under the assumption that frequency hits are detectable, and that the corresponding bytes can be erased. The packet error probability using the RS-(255,127) code with detectable hits is extremely low, and falls below the range of the plots. The ability to detect frequency hits and erase the corresponding bytes therefore results in a considerable increase in the number of simultaneous users that the FH channel can support. The tradeoffs between the increased complexity of such a system and its benefits must be addressed in the future.

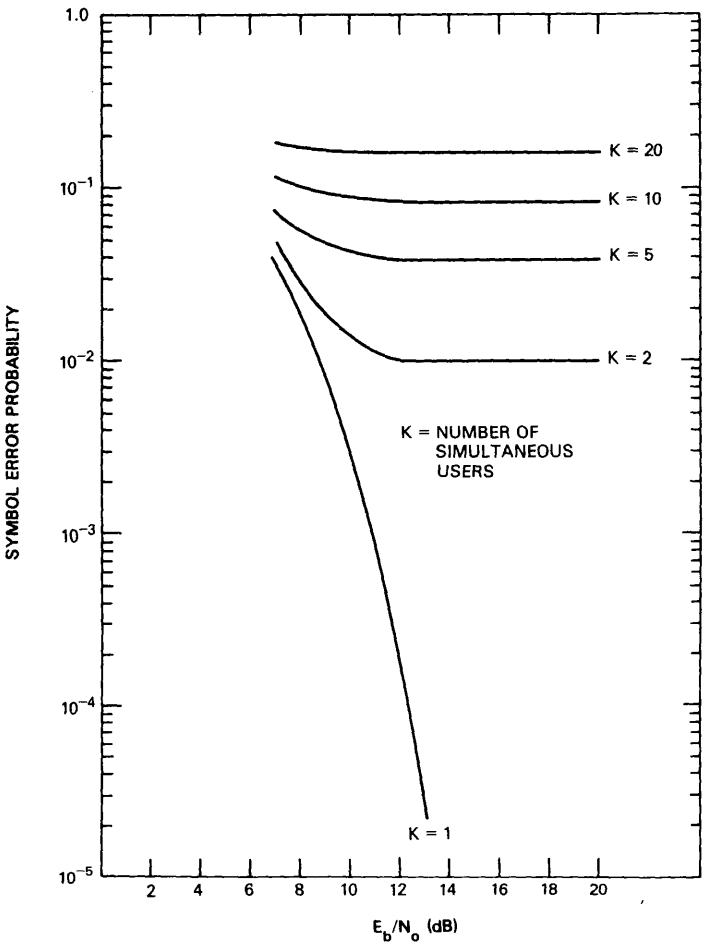


Fig. 3.8 — Raw symbol error probability for an asynchronous FH multiple-user channel; noncoherent binary signaling; $q = 100$ frequency slots; AWGN channel

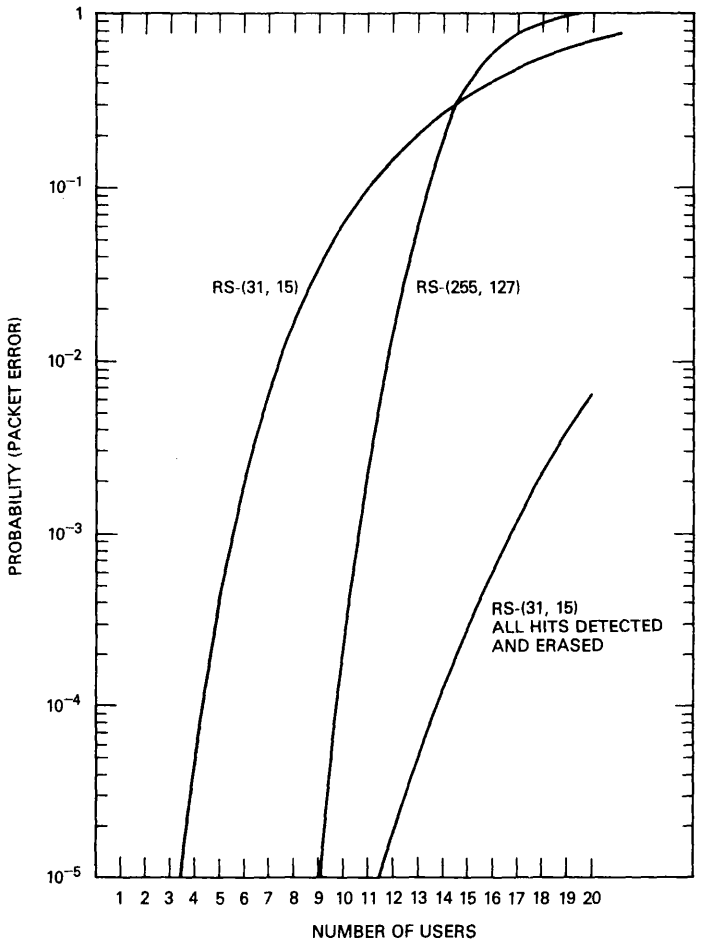


Fig. 3.9 — Packet error probability in a noiseless asynchronous FH multiple-user channel; Reed-Solomon coding; $q = 100$ frequency slots

The throughput of a FH channel of this type can be defined as the expected number of correct packets that can be delivered per time slot, where a time slot is equal to a packet duration (and is therefore different for the different codes and packet sizes used). Throughput is thus simply the product of the number of users and the probability of correct packet delivery for any given user. Under this model packets that are incorrectly received are subsequently retransmitted. We actually consider the throughput per frequency slot, expressed in terms of packets/time slot per frequency slot. The throughput achievable on a channel with 100 frequency slots when using the RS codes discussed above is shown in Fig. 3.10 for the noiseless channel, as well as for a channel in which the noise-induced byte error probability (in the absence of other-user interference) is 0.1. In the noiseless case the maximum throughput is achieved for 13 users and is 0.121 packet per time slot per frequency slot for the longer code, and 0.103 for the shorter code.

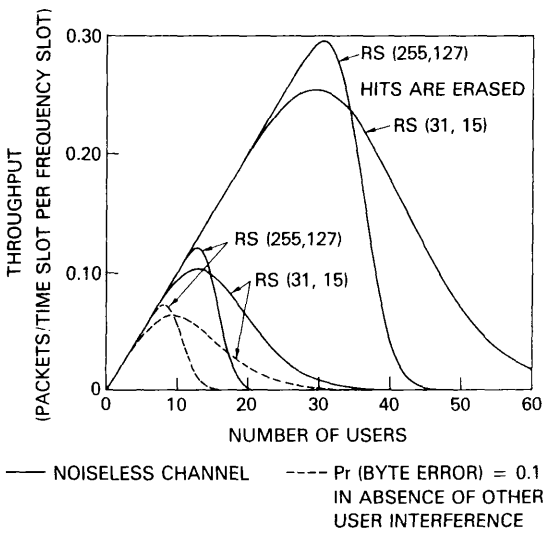


Fig. 3.10 — Throughput per frequency slot of an asynchronous FH multiple-user channel; Reed-Solomon coding used; q = 100 frequency slots

When operating at the maximum throughput level, the resulting packet error probability (and therefore retransmission probability) might be too high for some applications, e.g., those in which retransmission delays cannot be tolerated or cases in which buffer space is limited at the terminals. In such cases it may be necessary to reduce the number of users that transmit over the wideband channel simultaneously. For example, for the RS-(255,127) code the retransmission probability is 0.069 when operating at the maximum throughput level in a noiseless environment. Reducing the number of users from 13 to 10 reduces the retransmission probability to 1.9×10^{-4}, while reducing throughput from 0.121 to 0.1; this may be a favorable compromise in many cases. Further work is needed to assess the tradeoffs between retransmission probability and throughput that affect network operation.

Also shown in Fig. 3.10 is the noiseless case in which hits are recognized and erased. Throughputs of 0.294 and 0.254 packets/time slot per frequency slot are achievable using the longer and shorter code, respectively. The ability to detect hits and erase the affected bytes thus increases the achievable throughput by a factor of approximately 2.4.

Alternatively, it is possible to consider the bit error probabilities (rather than the packet error probabilities) that are associated with the use of these codes, although the transformation from packet error probability to bit error probability is not straightforward, as discussed in [3].

The use of block codes in this discussion should not be interpreted necessarily as a recommendation to use block codes (with slow frequency hopping), rather than convolutional codes, in the HF ITF

Network; such a recommendation would be premature at this point. The use of packets that consist of a single block codeword appears attractive from a performance point of view, and permits the type of multiple access discussion presented here. Similar performance could probably be achieved via the use of convolutional codes with interleaving. The use of convolutional coding is discussed in Sec. 3.2.6 and Appendix E.

The above discussion assumed the use of dedicated links, which will be used for much of the backbone network traffic and possibly other types of network links as well. We must also consider the implications of using FH-CDMA schemes for intracluster communication. There are a large variety of time-domain multiple access schemes that are suitable for narrowband intracluster communication. Further work is needed to modify them to the FH-CDMA domain. These issues are addressed in Sec. 4.

Finally, interference resulting from jammers and platforms external to the task force, and therefore not under network control, must be considered.

The other-user interference environment in the HF ITF Network is very complex, because backbone network signals, intracluster signals, and auxiliary link signals will use the same jammed wideband channel simultaneously. Methods are needed to ensure that acceptable interference levels, and therefore performance levels, are maintained. The situation becomes considerably worse at frequencies that support substantial skywave propagation, since the number of interfering signals is greatly increased. Since there is no way to coordinate the FH patterns at the hop level on a network-wide basis, the only way to reduce the degree of contention and thereby reduce error rates is to reduce the number of signals that are simultaneously transmitted within any frequency band or subband. To do so is one of the goals of the channel allocation algorithms described in Sec. 2.3 and the multiple access protocols described in Sec. 4.

4—The Assignment and Distribution of Codes to Platforms

We have noted that the network designer will have little influence over the FH patterns used in the HF ITF Network, because the primary factor in the code generation process is security, rather than multiple access capability. The most that can be assumed about the FH patterns is that they are random in nature, and that a large family of such patterns does in fact exist. The only form of network-wide coordination of hopping patterns might be at the packet level (rather than at the hop level), as discussed earlier. The major issues relating to code selection are therefore related to the distribution of a set of codes among the network's platforms, rather than the actual generation of these codes.

The basic code assignment considerations include the allocation of frequency hopping codes to users and the decision of whether to use a code associated with the transmitter or with the receiver. The four basic types of links in the network will be point-to-point links, broadcast links, random access links, and common links. Links of each of these types will share a wideband FH channel simultaneously. Considerations for these links differ, and so they will be considered individually.

Point-to-Point Links: When point-to-point links are used the FH code of either the transmitting or receiving platform may be used, as long as consistency is maintained.

Broadcast Links: In a broadcast link a single transmitter sends a common message to two or more platforms. It is therefore appropriate to use an FH pattern associated with the transmitting platform and monitored by all potential receiving platforms.

Random Access Links: In a random access link many platforms attempt to communicate with a single platform on a contention basis. An FH pattern associated with the receiver is therefore essential, because the receiver will not know a priori which platforms are attempting to communicate with it.

Common Links: A common link, monitored by all network platforms, can be used for either broadcast or random access applications. A single FH pattern would be associated with such a link.

We are now in a position to discuss the number of FH codes required to implement the HF ITF Network. To simplify the discussion, we initially assume that only a single transmitter and a single receiver are available at each platform in every subband. We shall demonstrate that it is sufficient in this case to associate one "transmitter FH code" and one "receiver FH code" with each platform in the network, and that two additional codes are needed. The total number needed in the network is therefore $2N + 2$. (This situation is of course repeated in each of the Linked Cluster networks simultaneously operating in other frequency bands.)

The types of links that are expected to be supported in the Linked Cluster architecture are as follows:

1. A channel, monitored by all platforms, to be used during the execution of the Linked Cluster Algorithm. Such a channel may be used during normal network operation as well.

2. A random access channel that is monitored by all task force nodes.

3. A broadcast channel associated with each cluster head.

4. A random access channel associated with each cluster head.

5. Dedicated links for use on the backbone network.

6. Auxiliary links.

We now discuss the FH codes that are required for the implementation of these links:

1. The use of a single common code would be adequate for the execution of the Linked Cluster Algorithm (LCA). It would not be necessary to use a unique code associated with each platform since the transmissions of each platform are inherently noninterfering because of the TDMA frame structure of the LCA.

2. The availability of a random access channel would allow a platform that is not part of the network formed by the LCA to communicate with a node that does belong to this network. This might occur, for example, when a rapidly moving aircraft or a previously radio-silent submarine wishes to communicate with a network node. Another example of such a need would be to accommodate the merger of two task forces. While equipment constraints would prohibit the continuous monitoring of such a channel, a fraction of each receiver's time slots might be used for this purpose.

3. A broadcast code would be used by a cluster head to transmit simultaneously to all members of its cluster, and each platform would have to monitor its cluster head's broadcast transmissions. In addition, since a node may be within range of several cluster heads, it might be worthwhile for it to monitor the broadcasts of other neighboring cluster heads in addition to its own; to do so would not require additional broadcast codes, but rather the ability to monitor additional codes. This would not necessarily require additional receivers, since it would be possible to monitor several cluster heads on a time division basis.

4. Intracluster communication between cluster members and their head can implemented via either a contention-based mechanism or a contention-free mechanism. A receiver-based FH code is essential wherever contention is permitted. Either receiver-based or transmitter-based FH codes can be used in the contention-free case.

5. and 6. Backbone network links and auxiliary links are point-to-point links, and therefore can be implemented using the FH code of either the transmitter or receiver.

Under our (simplifying) assumption that only one transmitter and receiver are available on each platform in every subband, these equipment resources must be allocated among links with neighboring platforms on a time division basis. The code assignment problem is therefore transformed into a combined code and time slot assignment (channel allocation) problem. Some preliminary versions of distributed channel allocation schemes have been developed for the HF ITF Network [14], and are discussed in Sec. 2.3. Such time division also helps to limit to acceptable levels the number of signals that are transmitted simultaneously. Since each platform is limited to the simultaneous use of only one transmitter and one receiver there would be no advantage gained by the assignment of a large number of codes to each platform.

We have shown that it is at least conceptually possible to implement a Linked Cluster network of N platforms, each of which has one transmitter and one receiver, by the use of $2N + 2$ frequency hopping codes in each subband.

It is straightforward to generalize the above discussion to the case in which each platform has several transmitters and receivers. It would be possible to associate a distinct code with each of them, and each platform would then be able to support additional communication links. It will be necessary to generalize the channel allocation algorithms to the case of multiple simultaneous channels per platform.

A remaining question is the procedure used to assign the frequency hopping patterns to the network platforms. The simplest approach is simply to associate a priori a pair of unique codes with each platform in the network. There would then be no need to develop a distributed scheme for the assignment of FH patterns to platforms, although of course the need for channel allocation schemes to share resources on a time division basis still exists. It is of course necessary for each platform to know the codes associated with the other network platforms. It may be possible to disseminate this information to all task force members before deployment of the task force. If not, then some mechanism will be needed to broadcast this information throughout the network. Security will be a major issue in the distribution of FH patterns, because it is essential that they are not known by an adversary.

5—Contention Among Platforms Using the Same Code

Another significant problem area is that of contention among signals that use the same code. Such a situation may arise when two or more platforms attempt to transmit to the same receiver simultaneously. We are assuming that no two receivers will use the same code, except to monitor a network-wide (or cluster-wide) random access channel or a common channel. The simplest case to consider is that of only two signals. The two basic situations that may arise are those in which the delay at the receiver between the two signals is:

a. less than the hop duration,

or,

b. greater than the hop duration.

In case (a) there is a collision that is characteristic of narrowband systems, and typically both signals will be lost, unless one is considerably greater in amplitude than the other. In case (b) it will often be possible for the receiver to acquire and maintain synchronization with the first signal to arrive. Once a

signal has captured the receiver, a delayed version of the same signal (generated by multipath propagation) or another signal that uses a delayed version of the same hopping pattern will ideally not be troublesome (although in practice synchronization can be disrupted by fading or jamming, especially when platform mobility results in varying propagation delays). Further effort is needed to evaluate the performance of contention-based FH-CDMA systems that use a common code, and to assess the implications of their use in the HF ITF Network.

3.3.4 Hybrid Network Communication

We have noted that although wideband communication is required to provide adequate AJ performance, an evolutionary cycle is expected in which the current narrowband equipment is gradually replaced by the future wideband equipment. We must therefore consider, as an interim measure, a hybrid HF ITF Network in which each platform has the capability of supporting a small number of wideband links, plus a number of narrowband links. Hybrid networks may also be used even when wideband equipment is available, because it may be desirable to operate the network in a narrowband mode whenever possible. The network might switch to an AJ or LPI mode, on a link by link basis, only when necessary.

We are primarily concerned in this section with the interference environment in a hybrid network. It is possible to consider a network in which the set of frequency slots allocated to wideband communication and the set allocated to narrowband communication are mutually exclusive. More interesting, however, and probably more realistic is the case in which narrowband signals and wideband FH signals share the same wideband channel.

We first consider the interference problem from the viewpoint of wideband signals. The presence of narrowband signals in a wideband FH channel simply results in a frequency hit whenever the FH signal enters an occupied frequency slot. As in the case of a purely FH network, forward error correction coding must be used to handle loss of data resulting from hits. It makes no difference to the wideband signal whether the hit results from interference with a wideband or narrowband signal.

Next, we consider the situation from the viewpoint of a narrowband signal that suffers hits from one or more FH signals. Typically, only a small fraction of the data will be affected, as long as the number of FH signals is not too large, and forward error correction coding can be used to correct the resulting errors.

The main point of this discussion is that FH signals can share a frequency band with narrowband signals, while maintaining acceptable performance levels among both classes of signals, as long as the number of simultaneous users is not too great. Further work is needed to quantify this performance.

4.0 MULTIPLE ACCESS IN THE HF ITF NETWORK

The communication resources of the ITF Network are assumed to consist of the full bandwidth of the HF channel. This resource must be shared by, and therefore allocated to, users of the network. Since there are many ways in which such an allocation can be made, the question naturally arises as to which method is best suited for the ITF Network. This is a major question that arises in every situation that involves sharing of a resource. It is usually referred to as multiple access. In general, the answer depends on the nature of the performance criteria and of the user's needs as well as on the architectural constraints and capabilities of the system.

In this section we review critically the main classes of multiple access methods, and emphasize the criteria to be used for their evaluation as to their suitability for the HF ITF Network. Often the term "protocol" is used to refer to a multiple access technique. We shall occasionally make such use of the

word here, but we must caution that the term is also used to describe the software or other representation of a network's rules of operation.

4.1 Frequency Domain Methods

The traditional way of allocating bandwidth is via frequency division. Each user is provided with a different portion of the entire channel resource. Each portion is dedicated to a single user for its exclusive use and is either permanently assigned or belongs to that user until reallocation is made according to some demand assignment scheme. This method has been known as frequency division multiple access (FDMA).

The philosophy of such allocation methods is that of circuit switching. This means that resources are dedicated, permanently or as needed, to individual users. We shall examine later the multiple access counterpart of the message switching philosophy, which does not dedicate any part of the resources but instead allows for their continually shared use. Unfortunately, there is no counterpart in the frequency division methods. Frequency division is inherently a circuit switched methodology.

What is wrong with frequency division? In addition to the limitations brought about by its purely circuit switched nature, there are additional disadvantages. Consider the case of five users as in Fig. 4.1. Suppose they are all within radio communication range of each other. Under frequency division there should be a total of twenty one-way channels, or ten full-duplex links. The intermodulation at each node and the mutual interference would be at substantial levels. Furthermore, the link management technique, in case of demand assignment, would require considerable sophistication particularly if it is to be implemented in a distributed fashion and if not all users are within single hop range of each other. In the latter case, even for nondemand assignment cases, the problem of efficient frequency reuse has been a major one, particularly for mobile users, and has received only recently some partially satisfactory solutions that involve the division of the communication area into hexagonal cells (e.g., [62]).

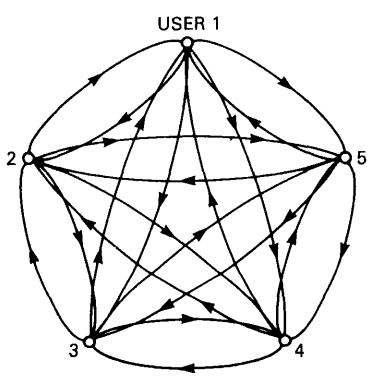


Fig. 4.1 — The use of dedicated links in a fully connected network

4.2 Time Domain Methods

4.2.1 Fixed Allocation Methods

The duality between time and frequency in communication theory makes the time division multiple access (TDMA) techniques conceptually apparent. Instead of partitioning the available bandwidth among the users, the time-of-use of the entire bandwidth can be equivalently partitioned, resulting in a capacity distribution identical to the one achieved by the FDMA method. Thus each user has exclusive

rights on the use of the entire channel during predetermined, periodically recurring time slots. These time slots are dedicated to each user creating thus a circuit switched environment. The allocation of slots need not be permanently fixed. If it is to be managed in some way a demand access environment will be created. We shall see in the subsequent subsections that demand access operation in the time domain creates many more possibilities than in the frequency domain.

Time division methods became attractive because their use results in the elimination or reduction of radio interference. Consider again the setup of Fig. 4.1 with the five users. Instead of ten full-duplex channels there is only a single channel. The price paid for this improvement is of course the need for synchronization. In the case of geostationary satellite channels the choice is clearly in favor of time-division, since it is relatively easy to maintain synchronization between earth stations via the equidistant satellite and since the large number of earth stations under frequency division could create the potential for destructive intermodulation at the transponder.

In other cases, such as in the HF channel, the synchronization problem can be handled by providing guard times between slots and by maintaining accurate time at each node. The main reasons, however, for deciding against frequency division for HF would be the flexibility of new ways in which the slots can be used in the time domain. These new ways will be described in the remaining subsections.

4.2.2 Contention Methods

Probably the most significant breakthrough in the area of multiple access methods occurred when, around 1970, Abramson conceived of a simple alternative to TDMA that he termed ALOHA [63]. Since the introduction of TDMA it had been observed that when some users had low duty cycle transmissions or when the overall traffic level was generally low, many slots were not used and as a result the channel capacity was under-utilized. The ALOHA scheme constituted a bold experimentation with an approach that was the extreme opposite of the orderly fixed allocation of slots used in TDMA. Furthermore, while still operating in the time domain it did not require synchronization. It simply postulated that every user would attempt transmission at the full channel bandwidth whenever the user chose to without regard to other users' needs. In cases of overlapping (interfering transmissions, sensed via an acknowledgment mechanism or by channel monitoring) there would be repeated retransmission attempts randomly spaced in time. The duration of each transmission was considered fixed and equal to a typical TDMA slot length. A modification of ALOHA that required synchronization was also considered and was called slotted-ALOHA. The modified version doubled the achievable throughput rate of the original one but still suffered from unstable behavior.

Several schemes were conceived by researchers in the last ten years that utilized various ingenious feedback methods to stabilize and improve upon the performance of ALOHA [64-68]. Most of these schemes perform reasonably well when traffic is mostly bursty and of low volume, and they are very simple to implement. However, it remains true that when traffic is non-bursty and/or at peak volume levels the ALOHA scheme and its variants are completely inappropriate. The value of this fundamental and perhaps revolutionary departure from classical thinking in the allocation of resources lay primarily in that it opened the way for the careful and controlled introduction of contention schemes of multiple access. Sophisticated schemes that allow for contention, that are adaptive to varying traffic patterns, and that display improved overall performance will be discussed in the next two subsections. In the early stages of the HF ITF Network effort some attempt was made to obtain a powerful means of analysis of such schemes [4].

4.2.3 Reservation Methods

In the time domain it is remarkably straightforward to implement and manage demand access methods. By allocating a separate resource, called the control, or reservation, or orderwire channel, to narrow bandwidth reservation messages it is possible to make near perfect use of the main channel by

allocating it as needed to the requesting users. The control channel may consist of a separate frequency channel or of a separate set of time slots entirely in the time domain. There are many reservation and polling schemes proposed in the literature and most of them are modifications of the same basic demand assignment scheme [69]. Where they may differ is the method specified for gaining access to the control channel. Obviously, reservations cannot be used for access to the reservation channel. Thus, one must resort to other schemes for that purpose, such as TDMA, contention-based, or hybrid schemes. Furthermore, reservation techniques are not easy to implement when there is no central controller. In [6,9] it is shown how intricate the implementation of distributed reservation schemes can be.

4.2.4 Hybrid Methods

From the preceding discussion it follows that, unless the traffic patterns generated by the users of a multiple access system fall consistently into certain categories (bursty and low volume or high duty cycle and high volume respectively) neither fixed allocation nor pure contention protocols are suitable. While the former represent the philosophy of circuit switching, the latter are examples of message or packet switching. In most practical situations, and certainly in the environment of the task force, traffic is expected to be a mixture of interactive messages, voice conversations, high speed tracking data, file transfers etc. and the average data rate is expected to vary considerably. Finally, not all users display identical traffic profiles. Thus, there is a need for protocols that combine the virtues of both extremes (namely of dedicated allocation and of sharing) and can adapt to either one as the traffic characteristics change. Although there is a wealth of imaginative schemes proposed and analyzed or simulated in the literature [70-73,9], the quest for improved multiaccess protocols remains as a major component of basic research in the area of multiuser communications. Some of the early basic research on the HF ITF Network was devoted to the search for such hybrid schemes. The Probabilistic TDMA [5] protocol and the IFFO [8,6,9,74] protocols are the products of this research.

In 1977 a method more akin to a pure contention protocol, but with a systematic (rather than purely random) retransmission strategy that has some reservation characteristics, was proposed by Capetanakis [75,76]. The Capetanakis Conflict Resolution Algorithm (CCRA), or tree algorithm, exists in several versions. The potential suitability of these schemes for the HF ITF Network was realized immediately. They are simple, distributed, secure, robust, and survivable. It is not an exaggeration to say that this approach has provided as much of an infusion of fresh thought to multiaccess research as did Abramson's conception of the ALOHA scheme over ten years ago.

Massey [77,78] has advanced the state of the art of these schemes in a number of ways. He has developed extremely tight upper and lower bounds on the time required to resolve a collision; these bounds require neither the assumption of statistical equilibrium nor the use of a specific traffic model. Massey and Amati have also developed versions of the CCRA that permit the continuous entry of additional users prior to the completion of the collision resolution process [79,80].

Contention-based methods such as ALOHA or carrier-sensing or the Capetanakis algorithm require a collision-detection or channel-monitoring mechanism in order to operate. There are several such mechanisms that work in most cases. However, when the users are so dispersed that not all of them are within single-hop range from each other it is possible for collisions to occur that cannot be detected by the transmitting terminals. This is the "hidden terminal" phenomenon, illustrated in Fig. 4.2. The circles around users A and C indicate the communication ranges for their respective transmitters. Simultaneously transmitted messages from A and C, intended for user B, will interfere without A or C being able to detect the collision since they are outside each other's ranges. If, however, all users are within single-hop range from one user (in this case user B) there are ways to solve this problem since B can then give feedback information to all users. One way is for B to emit a "busy tone" when one user is transmitting to B successfully [81]. This busy tone is universally monitored and prevents other users from interfering until the end of the successful transmission.

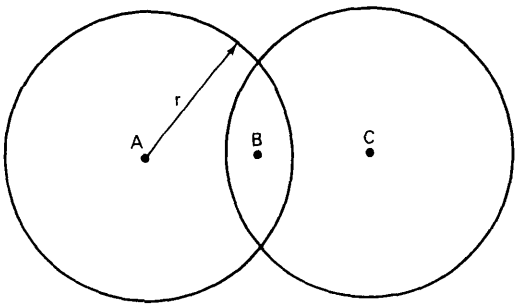


Fig. 4.2 — The hidden terminal problem

This architectural concept of a single user being, so to speak, in the center of a cluster of users and its role in solving the hidden terminal problem has played no small part in the conception of the architecture that we have proposed for the ITF Network as described in Sec. 2.

4.3 Code Domain Methods

In this section we do not intend to re-examine the spread spectrum techniques discussed in Sec. 3 and Appendix B. Instead we want to show how those techniques are part of the general multiaccess problem.

4.3.1 Fixed Allocation Methods

As with the passage from frequency division to time division, it takes a simple, direct conceptual step to visualize the channel resource modeled as a slice of the frequency-time plane (Fig. 4.3). Frequency division partitions this slice into strips parallel to the time access (Fig. 4.4a), while time division does the partition by cutting a pattern of strips parallel to the frequency axis (Fig. 4.4b). It is clear that the two-dimensional resource can be divided in other ways as well. Consider for example the mesh of Fig. 4.5 where the bandwidth has been partitioned into q bands and the time axis has been slotted. The result is a frequency hopping (FH) scheme in which each user is assigned an arbitrary sequence of frequency bands, periodic or not, as illustrated in the figure. So long as every other user is assigned a sequence that does not overlap with that of any other user the resulting partition is a form of time-varying frequency division, or code division multiple access (CDMA) since each sequence can be thought of as a code.

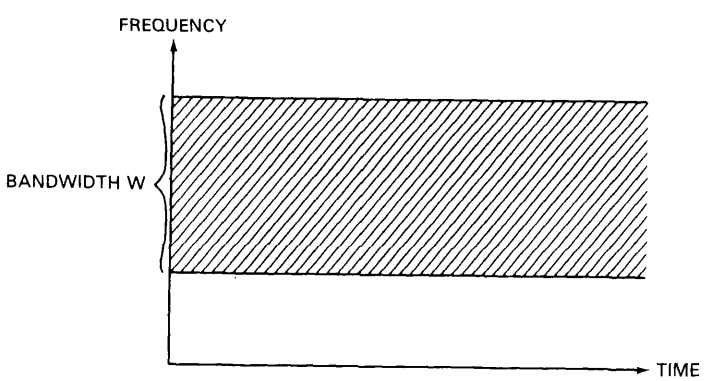
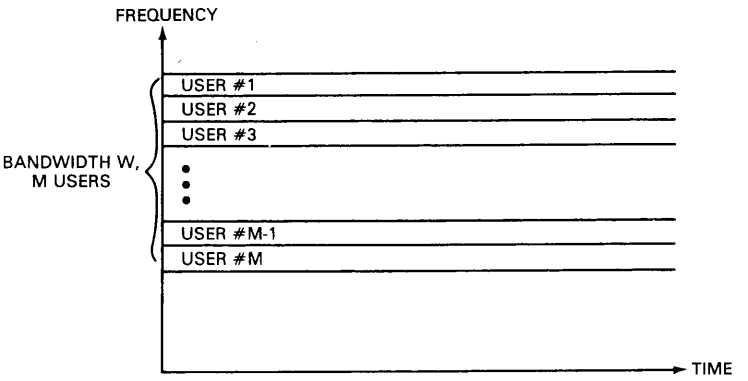
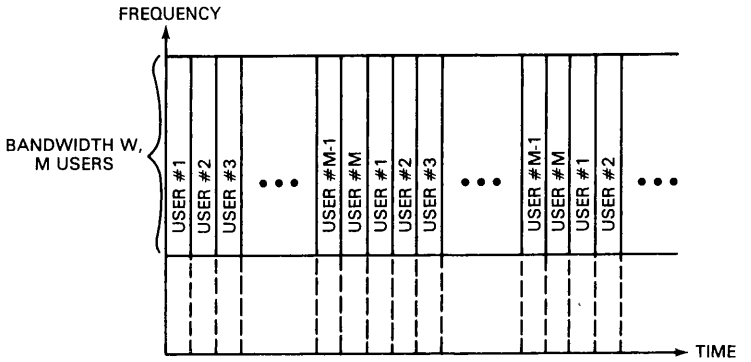


Fig. 4.3 — The channel resource



(a) Frequency Division Multiple Access (FDMA)



(b) Time Division Multiple Access (TDMA)

Fig. 4.4 — Fixed allocation multiple access methods

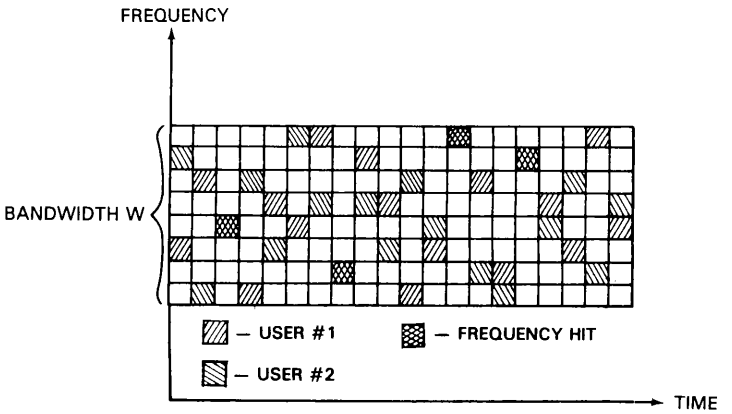


Fig. 4.5 — Simplified illustration of frequency hopping CDMA

As explained in Appendix B, there are other ways of implementing code division, such as pseudo-noise sequence modulation or hybrid forms. The frequency hopping method, however, illustrates most lucidly the equivalence (conceptually at least) of code division methods to frequency or time division ones. In practice it is usually not possible to assign hopping sequences to the users that are entirely free of overlaps (i.e., orthogonal), and as a result there are often "hits" that appear as interference and reduce the multiple access capability of this method. The use of forward error correction coding in FH multiple access systems and the throughput capability of such channels is discussed in Sec. 3.3.3. In terms of performance, FH-CDMA resembles ordinary frequency division without guardbands but, instead, with slightly overlapping frequency boundaries. The use of frequency hopping spread spectrum signaling in a cellular land-mobile radio system is discussed in [82]. The advantages and disadvantages of the use of spread spectrum signaling in such systems are discussed in [83].

4.3.2 Contention Methods

As in the time domain, it is often the case that, due to light or bursty traffic, some users will not be transmitting all the time and thus their frequency-time slots will remain unused. To counter this inefficiency it is possible to assign the same code to more than a single user, or more generally, assign codes that are not orthogonal and thus allow for hits or complete overlaps as in the case of ALOHA-type random access techniques. Only very recently have there been any attempts to model, analyze, and understand the behavior of such contention-based code division techniques [84,60]. In the Task Force environment there are additional reasons that make the use of orthogonal codes difficult. These are based on the variable propagation delay and the need for aperiodic secure codes. Most orthogonal code sets are periodic and thus subject to "decoding." More detailed discussion of code generation and related issues appears in Sec. 3.3.3.

Hajek has considered a contention-based multiple access system in which packets are assumed to be generated at random by the users, in contrast with the case considered in Sec. 3.3.3 in which each of a fixed number of users continuously transmits over the FH channel. The total channel traffic consists of newly generated packets as well as retransmitted packets that were unsuccessful at one or more earlier attempts to access the channel because of other-user interference (and possibly channel noise as well). Unsuccessful packets are retransmitted following a random time delay as in the original ALOHA studies (e.g., [63]). As in many studies of random access schemes we assume that the total channel traffic is Poisson distributed.

The throughput per frequency slot achievable by such a FH multiple access channel is plotted *vs* traffic intensity per frequency slot in Fig. 4.6, which assumes a noiseless channel in which the only source of error is other-user interference. The model used to generate this curve, as well as results for a noisy channel, are presented in [60,3]. Curves are shown for $q = 1$, 10, and an infinite number of frequency slots, and for the two Reed-Solomon codes discussed in Sec. 3.3.3. As is true for uncontrolled slotted ALOHA (which is in fact our $q = 1$ case) the curves exhibit a bistable behavior, and therefore potential instability.

An area of great interest in recent years has been the development of control schemes for random access channels that ensure stability as well as satisfactory delay and throughput performance. In the past only schemes that are suitable for time-domain channels have been considered. It is not at all straightforward to apply most of these schemes to an FH channel. Hajek has developed some new random access control schemes that are in fact suitable for use in FH multiple access channels.

Many of the control schemes that have been proposed for time-domain multiple access channels require that the users monitor the channel to determine whether there was a single (and therefore successful) transmission, two or more transmissions (all of which are usually assumed to be unsuccessful),

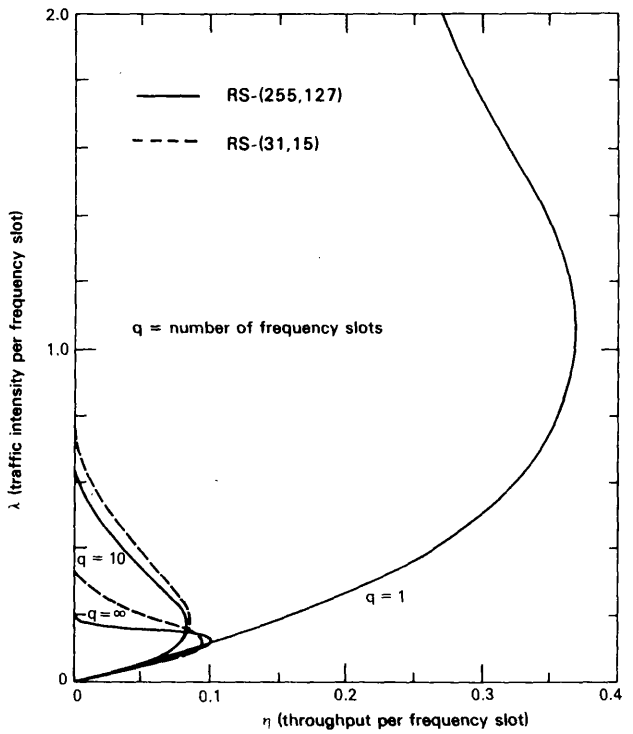


Fig. 4.6 — Throughput *vs* traffic-intensity-per-frequency-slot for frequency hopped random access. No channel noise (For $q = 1$, curves coincide.) (From [60])

or no transmissions. The situation in a FH-CDMA channel is different because several signals can in fact be successfully transmitted simultaneously. Another characteristic of FH-CDMA is that it is not feasible to monitor the success or failure of each of the individual transmissions of all other users because to do so would require the use of a separate frequency hopped receiver corresponding to the FH pattern of every user in the population.

Instead of attempting to monitor individual transmissions it is better to observe the overall FH channel. During each slot every user can use a random hopping pattern to hop a receiver among the q frequency slots. An estimate of overall channel activity can be obtained by counting the number of dwell times that the channel is in use in the monitored frequency slot. Hajek [60] has demonstrated that feedback information of this type can be used in conjunction with the techniques of [66] to implement a control policy suitable for FH random access systems.

Hajek has also developed the Acknowledgment Based Retransmission Control (ABRC) policies, a class of policies that require a minimum of feedback channel information [66]. Under these schemes a user must know only whether or not its own transmissions are successful; no additional feedback information is required. The minimal feedback requirements of the ABRC policies make them attractive for use in FH systems where feedback information is difficult to obtain.

4.4 Multiple Access Protocol Evaluation and Trade-offs

So far in this section we have outlined, and briefly described, the nature of the different methods of multiple access. There are extensive reviews in the literature that examine in detail the properties of each specific variant, its advantages and disadvantages, and the types of environments best suited for each one [9,70-73]. Our previous NRL report [1] did go into considerable depth in scrutinizing the

different multiple access protocols from the standpoint of their suitability for the ITF Network. At that time the ITF Network's architecture had not been developed and thus we were not able to determine which protocol or set of protocols would be most desirable. Now, while we are not yet in a position to finalize the selection, we are able to narrow down the choices and justify our suggestions. This will be done in the next subsection. Here we want to briefly describe the criteria that are generally used to evaluate a multiple access technique and, thus, to illustrate the complexity of the selection and trade-off procedure.

The evaluation of multiple access protocols is still a problem of basic research. Few undisputed conclusions have been reached by the scientific community so far and they are mostly qualitative. The main source of difficulty is the lack of analytical tools for the prediction of the dynamic performance of most protocols. Thus it is not easy to establish, quantitatively, the behavior of these protocols with respect to a variety of performance measures. But there are additional complicating factors. One of them is the multitude of performance criteria that are used to judge protocols. Another is the sensitive dependence of the performance of most protocols on the users' traffic statistics. Finally, most protocols are studied under simplified assumptions such as identical users, sometimes infinite number of users, infinite or zero buffer size, Poisson traffic, lack of topological or other networking constraints, "binary" type of interference (i.e., either completely successful or totally unsuccessful packet transmissions), neglect of propagation properties, and neglect of "capture" phenomena. These assumptions allow some theoretical study and permit the evaluation of the protocol in a realistic environment without substantial reliance on complex and extensive simulation.

First let us consider the performance criteria. They are usually the following:

1. Survivability

   a. robustness: this requires the maintenance of satisfactory performance over a wide range of values of the critical parameters of the network such as traffic statistics, number of users, topological layout etc.

   b. adaptability: when the critical parameters of the network are time-varying it is desirable or, sometimes, imperative to adapt the protocol to the changes in order to maintain satisfactory performance. Robustness and adaptability together constitute ingredients of survivability and graceful degradation. The latter also requires fail-safety.

   c. fail-safety: when nodes or links fail due to jamming or other reasons, the ability of the network to operate must not be impaired. This is perhaps the most fundamental requirement for certain networks such as the ITF Network. It is also an overriding criterion, since it may be incompatible with minimizing delay, maximizing throughput, and maintaining high efficiency. It requires that the protocol rules are such that no deadlocks caused by errors or data base inconsistencies occur and that no node or link is indispensable. The latter requirement often dictates a distributed control architecture (ruling out, for example, polling schemes) and it implies the former, since, under distributed control operation, it is possible that inconsistencies, instabilities, and deadlocks may occur.

2. Effectiveness

   a. average delay per message: this is defined as the average time from generation of a message to reception by the intended receiver. Obviously this time includes several "hop" cycles of queueing, processing, propagation, and transmission times if there is relaying in the network. Theoretical evaluation of delay is very difficult in realistic environments due to the highly complex nature of interacting queueing systems.

b. throughput: this is related to the delay but in a complicated way. It is defined as the average total rate of successfully delivered messages in the network. It is not clear that there are protocols that minimize delay and at the same time maximize throughput as we would like them to do.

c. stability: this is even difficult to define. Contention based protocols, such as ALOHA, sometimes display a dynamic behavior that results in total degradation of performance, namely a reduction of the throughput to the lowest levels and a simultaneous increase of the delay to intolerable levels. Such behavior is called unstable and is obviously unacceptable.

3. Efficiency

This relates to the source of the entire field of networking, namely the shared use of resources. How efficiently is the bandwidth utilized? How often are there wasted time or frequency slots caused by collisions or due to idleness of users to whom they are dedicated? This is a subtle concept not directly related to the preceding criteria.

This discussion clearly indicates that there is a need for substantial trade-offs even for a simple idealized network of identical users with single hop radio distance from each other. The reason is that the different figures of merit mentioned have a complex interrelationship that is partly antagonistic. Beyond that, when the idealized assumptions are dropped, the evaluation and the trade-offs become more difficult to accomplish. Nevertheless there are certain conclusions that can be drawn from the collective work of the scientific community on the subject as well as from the ITF network studies. These are outlined in the next section.

4.5 On the Selection of Multiple Access Protocols for the HF ITF Network

In [1] we argued that the architectural organization of the ITF Network and the multiple access protocols for it were two strongly interrelated problem areas that could nevertheless be pursued independently in the beginning phases of the network design study. In the course of our work we were pleased to see our argument verified. The Linked Cluster architecture which, on its own, meets many of the networking requirements of the Task Force, proves to be also a convenient and flexible framework for the use of a variety of multiple access techniques. In other words it does not exclude the use of any particular multiple access philosophy, nor does it disallow any particular multiple access technique. It does, however, favor the use of some of them, thereby justifying the statement made earlier that architecture and multiple access have a mutual influence effect on each other.

To begin with, the concept of clustering in our architecture was of course motivated in large part by networking considerations, but also because of its inherent ability to solve the hidden terminal problem, its potential to handle broadcasting, relaying, local polling, and local random access; that is for its flexibility as far as multiple access is concerned.

A factor that will weigh heavily in the final selection of a set of multiple access protocols is the nature and statistics of the traffic. Currently we understand that there will be a need for both voice and data communications and a combination of bursty and steady users. We also have some information on the average total traffic bit rates. Thus we have some preliminary ideas as to what protocols might be best suited to the expected demand. However, we still need to know more on the statistics before we can firm up our options.

Another factor that may limit or alter our preferences is the form of the wideband HF equipment and the signal waveforms currently under design. For example, if there are fundamental limitations in

the achievable data rates that do not permit full utilization of the bandwidth available to a node, a TDMA scheme would not be indicated because of its very low efficiency.

Our current conception is that within a cluster the existence of a cluster head within communication range from all members of the cluster provides maximum flexibility. It permits centralized polling, distributed TDMA, random access, busy-tone carrier sensing, other reservation-based schemes as well as almost any hybrid form of these. Thus intracluster communication is not a pressing problem. Almost any multiple access scheme can be implemented without affecting the network in any serious way. Care must only be exercised to avoid interference with the intercluster communication, which seems to present the more interesting situation.

If we follow the hierarchical structure of the clusters, we have the option of concentrating all the traffic that is generated inside a cluster at the cluster head and then routing it via gateways and neighboring cluster heads to its destination. This option would produce rather constant and high traffic rates over the backbone network. Thus, a circuit switched philosophy with dedicated links appears preferable. Of course, this philosophy could be implemented either in the time domain, or in the frequency domain, or in the code domain. However constraints in the numbers of receivers and in the choice of FH codes in the ITF Network preclude implementation of circuit switching strictly in the FH code domain. We already have the capability to activate dedicated links via our channel allocation method, which also allows for a demand access implementation.

However, this hierarchical routing may be unnecessarily slow and very inefficient in some cases. Consider, for example, the case of Fig. 4.7 that depicts a worst case situation. If node A1 needs to transfer a file of data to node A2, there would be a need for five hops for each packet if intercluster traffic were to use only the backbone network. It is obviously preferable to assign a dedicated link directly between A1 and A2 for such a transfer. Our channel allocation method permits the implementation of such auxiliary links. The backbone network can be used to set up this direct link between A1 and A2.

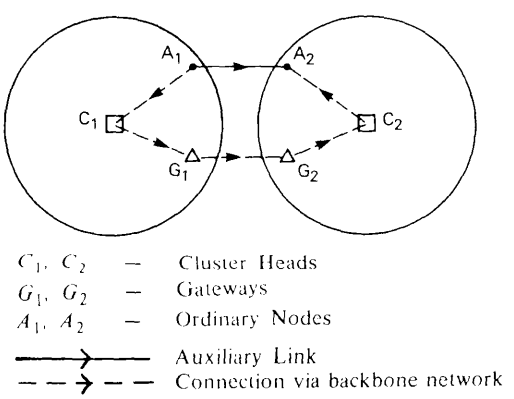


Fig. 4.7 — Example of an auxiliary link

Whether circuit-switched or packet-switched the network must operate in the code domain for antijamming reasons as explained in Sec. 3. The realization of the complex hybrid schemes in the time domain is rather well understood. However, in the code domain, even the structure of the counterparts of such schemes is ill defined. In fact part of the continuing ITF Network effort aims at clarifying and evaluating this structure.

In addition to the inter- and intracluster traffic we must consider traffic to and from aircraft as well as traffic to submarines. Tacitly, these platforms have not been considered directly as part of the main network. Random access and conflict resolution algorithms can be used for part of such traffic. In

addition, conflict resolution schemes can be used also for intracluster communication in case random access is implemented for information and/or control messages within the cluster. Unacknowledged communications can be protected by forward error correction, simulcasting, and/or flooding. Flooding would require the use of the conflict resolution algorithm as conflicts would be sure to arise. Also, in the case of aircraft, if they are not integrated into the main network in a more systematic way, a form of random access is an attractive alternative. Its use would depend on the levels of traffic that aircraft would generate.

Another consideration is the role of functional nets. An early warning functional net would most likely require flooding for the dissemination of its special purpose messages, thereby forcing the use of conflict resolution algorithms (the counterparts of which in the code domain remain not well understood, it is useful to remember). But again it is not clear that such a protocol would achieve smaller delay than ordinary prioritized hierarchical circuit switched dissemination via the backbone network. Both alternatives must be considered. As the difficulties of their analysis are formidable, they could instead be simulated. Perhaps a simplified approximate analysis could be first tried to determine whether bounds on performance can be obtained that can rank the two alternatives.

Thus, with respect to selection of multiple access protocols for the HF ITF Network, we can summarize the situation as follows: The architecture we have proposed, as well as our channel allocation method, provides considerable flexibility in accomodating a variety of multiple access techniques. Due to the complexity of the process of evaluation of multiple access schemes as well as the multitude of requirements of the ITF Network, we must compare several alternatives and preferably settle on a mixture of techniques rather than a single scheme. Multiple access must be considered in the code domain to provide protection from jamming.

In conclusion, although hard protocol choices must eventually be made, they cannot and need not be made yet. However, most of the background work for their selection has been accomplished and the choices will be forthcoming as other networking aspects (such as routing schemes) are finalized and as network parameter values (such as waveform design, and traffic statistics) and scenarios are incorporated in our study.

5.0 CONCLUSIONS AND FUTURE PLANS

5.1 Summary and Conclusions

In this report we have reviewed the work accomplished to date in the design of the HF ITF Network. This work has produced a baseline design concept for the Network and a detailed plan for the remaining steps for its completion. Both in-house and contracted efforts have contributed to the progress made thus far.

The ITF Network will consist of various platforms with markedly different characteristics, and is expected to support the traffic requirements of many diverse scenarios. The use of the HF groundwave medium is dictated by its natural survivability properties in post nuclear detonation environments and by its ELOS communication range. At the same time HF suffers from time-variable and unpredictable fading and self-interference, and as a result it is extremely difficult to obtain an accurate model for the HF channel. Consequently, the ITF Network must exhibit a high degree of robustness with respect to channel behavior uncertainties both in terms of its organization and in terms of the signaling used. Furthermore, equipment limitations place additional important constraints on the network.

The first major decision proposed for the HF ITF Network is the Linked Cluster organizational architecture. Many other design issues can easily be imbedded and studied in the framework of this architecture. Indeed, the desire to provide a framework in which other networking issues could be

evaluated motivated our early consideration of a network architecture. To assure survivability, the proposed architecture is based on the use of distributed algorithms that enable the Task Force platforms to self-organize into a reliable network structure and to continually monitor the changing connectivities for the maintenance of such a structure. This structure consists of clusters of platforms within communication range of local controllers known as cluster heads. The architectural profile of the network at any given moment consists of clusters that either overlap or are linked to each other via gateways. The set of links that interconnect the cluster heads and gateways is known as the backbone network.

Under this architecture and its implementation algorithms the network is highly survivable, self-organizing, and automatically adaptive to link or node losses. It permits the use of a variety of multiple-access switching and routing protocols with either narrowband or wideband signaling. Finally, and perhaps most importantly, the architecture takes full advantage of the apparent shortcoming of wide variation of the communication range over the HF band. This has been accomplished by partitioning the HF band into a number of subbands, each with a bandwidth of a few MHz over which the communication range for groundwaves is approximately constant. The organization algorithm is run consecutively for each subband, thus producing a set of overlaid connectivity maps that give rise to a set of simultaneously operating networks. The HF ITF Network consists of this set of individual networks that are defined in separate subbands. Network management schemes will be developed to coordinate the operation of each of the individual networks into an effective overall ITF Network structure.

It is necessary to use spread spectrum signaling in order to provide protection from jamming. We have recommended frequency hopping (FH) as the spectrum spreading mechanism and noncoherent frequency shift keying (FSK) as the modulation technique.

Bit error rate (BER) performance under worst case partial band (WCPB) noise jamming has been evaluated as a function of the equivalent signal to noise ratio for FH-MFSK signaling. Performance tradeoffs were developed for several alphabet sizes, many values of diversity, several coding schemes, both hard and soft decision receivers, known or unknown jammer state, and for nonfading as well as Rayleigh fading channels. From these results it is concluded that coding and/or diversity are essential for jamming resistance in the HF ITF Network, and that modest to good AJ capability is in fact achievable for most links in the network through the use of convolutional coding with FH-MFSK signaling.

In considering multipoint or network communication, the signaling issues become considerably more complex than in the single link (or point-to-point) case because of the potential interference among the users. In a wideband architecture, such as that envisioned for the HF ITF Network, the use of spread spectrum signaling provides an inherent natural means of multiplexing the different users with acceptable levels of interference. This is achieved via code division multiple access (CDMA) techniques in which, for the proposed choice of frequency hopping, each FH pattern corresponds to a distinct code. The use of CDMA techniques alone, however, is not sufficient to solve the network's multiple access problems. It is necessary to develop techniques to share the network's communication resources jointly in the time domain and code domain.

We propose the use of dedicated links (actually fractions of links apportioned on a contention-free time-division basis) for much of the intercluster communication over the backbone network. Distributed channel allocation algorithms for this purpose have been developed [14]. Intracluster communication consists of communication between a cluster head and its members. Communication from a cluster head to its members could be implemented either on a broadcast or a point-to-point basis, depending on the type of traffic. The multiple access protocol used by cluster members to gain access to their heads will very likely combine elements of fixed assignment, reservation, and conflict resolution. A firm commitment to the details of multiple access protocol choices is not necessary until other design issues such as routing are also addressed. The Linked Cluster Architecture is extremely flexible in that it permits the use of a wide variety of multiple access schemes.

5.2 Baseline HF ITF Network System Concept

To summarize, the work accomplished thus far in the design of the HF ITF Network has resulted in a baseline concept for the architecture of the network, for the signaling methods, and for the multiple access protocols. This provides a comfortable framework for the study of the remaining design issues. Table 5.1 indicates our recommendations for a survivable HF ITF Network design.

5.3 Future Efforts

Our future efforts will proceed within the framework provided by the baseline concept presented above. Several of the remaining design issues have been noted, e.g., the specification of multiple access protocols for intracluster communication and the continued development of link activation algorithms for distributed control. In addition, a number of network parameters still to be determined were noted, including the number of simultaneously operating networks (and related to it the bandwidth of each of these networks and therefore the frequency hopping bandwidth), and the alphabet size M for M-ary FSK signaling. A major signaling issue will be the acquisition and maintenance of synchronization of the frequency hopped signals. The tolerable J/S ratios presented here are based on an ideal receiver that uses soft decision decoding and is aware of which of the received chips have been jammed. It is straightforward to determine the AJ performance for hard decision receivers with or without such jammer state information. However, further work is needed to assess the impact of the nonideal nature of both the HF channel and the limitations imposed by practical equipment considerations.

A study plan that summarizes past, current, and future efforts is presented in Appendix A. Some of the major items to be addressed in the future include:

- the specification of multiple access protocols;
- practical considerations relating to J/S protection;
- the development of routing methods;
- AJ networking techniques (as opposed to the AJ link techniques discussed in this report);
- the development of detailed test scenarios;
- the development of a simulation test bed;
- voice/data integration;
- specification of the role of aircraft and submarines;
- internetting issues;
- acquisition and maintenance of synchronization;
- security issues (including their impact on synchronization);
- priority structures; and
- the design of network protocols up through the transport layer.

Table 5.1 — Baseline HF ITF Network System Concept

NETWORKING: Robust Network Design

- Number and types of nodes: 2 to 100; ships, aircraft and submarines.
- Task Force dispersion: approximately 500 km diameter (ELOS communication ranges).
- Network structure: overlay of several (expected to be between five and ten) networks in different portions of HF band.
- Network architecture: overlapping clusters of nodes within each of these several frequency subbands.
- Network control: hybrid (centralized local control within clusters, and distributed operation among clusters).
- Intracluster operation: protocols will include features of broadcasting, contention, and reservation. They must be compatible with frequency hopping spread spectrum signaling.
- Intercluster operation: dedicated links over backbone network and auxiliary links; a distributed algorithm for link activation is presently under development.
- Topological changes: adaptive and robust network control (continual updating of connectivities).

SIGNALING: Robust Waveform Design

- Frequency band: HF (2 to 30 MHz).
- Propagation medium: HF groundwave.
- AJ Scheme: frequency hopping spread spectrum.
- Modulation: M-ary FSK ($M = 4$ or 8 are possible choices).
- Receiver detection: noncoherent.
- Coding and/or diversity: required to combat jamming, fading, and other-user interference. Both convolutional and block coding are being considered.
- Signaling-related parameters:
  - Data rates: 75 b/s to 2400 b/s.
  - Acceptable BER for data: 10^{-3} to 10^{-5}.
  - Typical hopping bandwidth (bandwidth of one of the subbands): 2 to 5 MHz.
- Tolerable J/S ratios (convolutional coding and optimum diversity; 8-ary FSK; 5-MHz spread BW; BER = 10^{-5}; soft decision receiver; known jammer state*):

	2400 b/s	75 b/s
Worst case partial band noise jammed nonfading channel:	24.9 dB $\leqslant$ J/S $\leqslant$	39.9 dB
Rayleigh fading channel with broadband** jamming:	22.7 dB $\leqslant$ J/S $\leqslant$	37.7 dB

*i.e., receiver can detect which symbols are jammed.

**Broadband noise jamming is worst case partial band noise jamming for the Rayleigh fading channel.

ACKNOWLEDGMENTS

The authors thank Dr. J.R. Davis, D.I. Himes, and E.L. Kline of NRL for their guidance and support during this study.

The model presented in this report for antijam performance is based on a study performed by Prof. J. K. Omura of UCLA as part of the HF ITF Network task.

The model presented in this report for other-user interference in a frequency hopping environment is based on a study performed by Profs. M. B. Pursley and B. E. Hajek of the University of Illinois, also as part of the HF ITF Network task.

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Appendix A
STUDY OUTLINE FOR THE HF ITF NETWORK DESIGN TASK

In this appendix we present a study outline that summarizes our past, current, and planned efforts on the HF ITF Network task. This research has addressed many diverse technical areas such as: the identification of the network's operational requirements; the modeling of the HF channel, including propagation as well as interference considerations; the development of algorithms for network organization and channel access, and their evaluation by analysis and simulation; and the study of waveform design and coding considerations. The purpose of this outline is to demonstrate the relationship of each study area to the HF ITF Network design.

This report addresses the subject areas discussed in items 1 through 6 below. At the present time items 1 through 3 have been completed, while efforts in the remaining areas are continuing.

The HF ITF Network design study has included efforts by several university research groups and one research and development contractor in addition to those studies performed at NRL. Publications by NRL authors that have been produced by these studies are: [A1-A15]. In Sec. A.2 the contributions of the contracted studies and a discussion of their relationship to the overall research effort are discussed.

A1 STUDY OUTLINE

1. Preliminary Studies

The early HF ITF Network studies were primarily in the area of multiple access schemes that are suitable for use in mobile military radio networks [A7,A8,A10-A12,A14,A16-24].

In another early effort the applicability of the ARPANET and Packet Radio routing algorithms to the HF ITF Network environment was investigated [A25].

2. Identification of Requirements and Constraints

Operational requirements (such as variable topology, node mobility, communication modes that must be supported, survivability, security) and environmental and equipment constraints (including the military operational environment, existing *vs* proposed HF equipment, and properties of the HF channel that are relevant to network operation) were identified. The decision was made to use HF groundwaves as the primary communication medium [A1].

A number of preliminary conclusions were reached, including the need for: distributed network control and spread spectrum signaling to ensure network survivability; adaptive network control to handle changes in topology; and hybrid switching (combining features of packet and circuit switching) to handle complex traffic mixtures. High frequency ITF Network studies were divided into two major areas, i.e., network organizational structure, and the development of multiple access protocols in the spread spectrum context [A13].

3. Development of Organizational Architecture

The Linked Cluster Architecture was developed as the basis for the organizational structure of the HF ITF Network. This architecture is characterized by local network controllers known as cluster heads. Several Linked Cluster networks will operate simultaneously, each in a frequency band of several MHz bandwidth, over which the HF groundwave communication range is relatively constant. Two distributed algorithms were developed for the implementation of the Linked Cluster Architecture, viz., the Linked Cluster Algorithm (LCA) and the Alternative Linked Cluster Algorithm (ALCA). The performance of these algorithms was compared via simulation [A2-A4,A6,A9].

4. Development of Channel Allocation Methods

A key feature of the Linked Cluster Architecture is the backbone network, which will connect the network's cluster heads, often via the use of intermediate gateway nodes. Distributed algorithms have been developed for the activation of backbone network links [A5]. Related areas are the general intercluster and intracluster link management problems.

5. Multiple Access Protocol Design

Time-domain multiple access protocols (i.e., those schemes defined for time-slotted single channel systems) that are suitable for use in the HF ITF Network are to be developed. Owing to the necessity of the use of spread spectrum signaling, of critical importance is the development and analysis of the counterparts of such time-domain protocols in the time-frequency (code or spread spectrum) domain [A26-A32].

6. Spread Spectrum Signal Design

A study of spread spectrum techniques for the HF channel has led to the recommendation to use frequency hopping with noncoherent frequency shift keying (FSK). The antijamming (AJ) performance, including coding and diversity considerations, of frequency hopped M-ary FSK signals for nonfading and fading channels under worst case partial band jamming conditions has been investigated [A33]. Multiple user interference and coding for nonfading and fading channels have also been investigated [A34-A38]. The relationship between spread spectrum signaling and multiple access techniques has been addressed. A related area is the study of the impact of synchronization and acquisition times on network operation.

7. Alternative Network Architectures

Modifications to the Linked Cluster Architecture will be investigated. Of special interest are modifications that combine network connectivities at all frequency bands into a single network.

8. Development of Routing Methods

A routing metric suitable for the HF ITF Network will be developed. Routing and flow control algorithms will then be investigated. A key part of this task is the development of network measurement and updating procedures that are needed for the operation of routing and flow control algorithms.

9. HF Link Performance Studies

A link power budget analysis, including assessment of AJ performance and other-user interference levels, will be performed for the HF ITF environment. The channel model used in this study will incorporate the results of HF channel characterization measurements currently being performed. Link

performance characteristics will be related to network design and performance, including considerations such as hopping rate tradeoffs, properties of frequency hopping patterns, diversity and coding for the HF channel.

10. Development of AJ Networking Techniques

Range dependence relationships for signal strength (needed to establish link J/S ratios) will be developed from HF propagation models. Currently existing jamming models will be extended to the HF channel, where range dependence is not $1/(r^2)$. Jamming scenarios for the ITF Network will be developed, including distribution of nodes, air and surface jammers, and frequency plans.

Antijamming criteria will be developed. "Link" AJ criteria are needed to establish a model for node loss in a given scenario. "Network" AJ criteria are needed to compare performance of the entire network in jammed and unjammed modes. Link and network management and control procedures will be developed to enhance the network's AJ performance. The performance of the HF ITF Network in a jammed scenario will be evaluated by simulation via the Linked Cluster Algorithm.

11. Development of Detailed Test Scenarios

Detailed descriptions of force mixtures and traffic statistics for several test scenarios will be obtained from existing documentation.

12. Simulation Test Bed Design Plan

Methods for evaluating performance measures from simulation outputs will be specified. Simulation techniques for validating HF ITF Network design will be developed. Techniques for node emulation will be developed.

13. Intermediate System Design Concept

The results of all HF ITF Network studies to date will be integrated into a network design concept that addresses networking organization, signaling, routing, and control.

14. Development of Simulation Test Bed

Equipment and software needed for a simulation test bed will be specified and obtained. Specialized software needed for the simulator will be developed.

15. Evaluation of Network Performance

After the simulator is validated and verified, it will be used to evaluate network performance indices. The performance of alternative network architectures will be compared.

16. Incorporation of Additional Network Features

Techniques for the integration of voice and data traffic will be developed.

Methods for the implementation of auxiliary links will be developed. (Primary links consist of backbone links as well as the links between nodes and their cluster heads; other links not in these categories that may be assigned as needed are known as auxiliary links.)

Methods for the implementation of functional nets will be developed. (Functional nets are subnets embedded in the ITF Network structure that are designed to support the transmission of special types of data.)

Methods to handle the addition of platforms to the network will be developed. (This is a significant problem because our network organizing algorithms are distributed and use a fixed length TDMA structure.)

The role of aircraft and submarines in the network structure will be specified.

The internetting requirements of the HF ITF Network will be specified, and internetting schemes will be proposed. (The HF ITF Network must interface with other networks that use HF as well as other media.)

Security related issues will be specified, including their impact on synchronization. Security features will be incorporated into the network design.

Schemes to implement a priority structure will be developed.

17. Design of Network Protocols

Protocols up through the transport layer (including internetting) will be specified. (Note that the term protocol here refers to the multilayered structure of the entire network's operating rules, and not only to multiple access protocols.) Their compatibility with applicable military standards, including security, will be addressed.

18. Final System Design

The results of all network studies will be integrated to produce a final network design. This final design will be validated using the simulation test bed.

19. Plan for Transition to Fleet Use

A plan for the implementation of the HF ITF Network on naval platforms will be developed.

A2 SUMMARY OF CONTRIBUTIONS BY CONTRACTORS

It was noted at the beginning of this appendix that our HF ITF Network investigations have been supplemented by several studies performed by university and corporate contractors. The institutions and principal investigators that have participated in these studies are:

1. University of California, Los Angeles
   Principal Investigators: Profs. James L. Massey and Izhak Rubin
   Major Topic of Study: Multiple Access Protocols

2. The George Washington University
   Principal Investigator: Prof. Nicholas Kyriakopoulos
   Major Topic of Study: Multiple Access Protocols

3. Bolt Beranek and Newman, Inc.
   Principal Investigator: Dr. Anthony Culmone
   Major Topic of Study: Routing Schemes

4. The University of Illinois
   Principal Investigators: Profs. Michael B. Pursley and Bruce E. Hajek
   Major Topic of Study: Spread Spectrum Multiple Access

5. University of California, Los Angeles
   Principal Investigator: Prof. Jim K. Omura
   Major Topic of Study: AJ Performance of Coded Frequency Hopped MFSK Signals

We now discuss these contracted efforts briefly, and demonstrate their relationship to the ITF Network design.

The research performed under contracts 1 and 2 and parts of contract 4 has addressed various aspects of the multiple access protocol design problem. The many issues involved in the development of multiple access schemes for the HF ITF Network have been discussed in Sec. 4. The contractual studies have examined many of these issues, and have provided a firm basis for our continuing investigation of multiple access protocols.

1—Massey investigated the Capetanakis Conflict Resolution Algorithm (CCRA), and obtained extremely tight upper and lower bounds on the time required to resolve a collision; these bounds require neither the assumption of statistical equilibrium nor the use of a specific traffic model [A17,A18]. Massey and Amati have also developed versions of the CCRA that permit the continuous entry of additional users prior to the completion of the collision resolution process [A16,A19]. Conflict resolution algorithms will have an important role in the ITF Network, as discussed in Secs. 4.2.4 and 4.5.

Rubin investigated a number of multiple access schemes and error control procedures that have potential applicability to the ITF Network, as summarized in [A20]. His studies have addressed areas such as Automatic Repeat Request (ARQ) schemes for use over TDMA and random access channels [A22,A23], demand assignment TDMA schemes with priorities [A21], and hybrid TDMA/tree random access schemes.

2—Kyriakopoulos [A24] simulated the performance of Probabilistic TDMA [A10] and several variations of the Interleaved Frame Flush-Out (IFFO) protocols [A11,A12,A14].

3—The applicability of the ARPANET and Packet Radio routing algorithms to the HF ITF Network environment was investigated. The results of this contract will serve as a starting point for routing studies performed at NRL.

4—Pursley and Hajek have investigated frequency hopping spread spectrum multiple access techniques that are suitable for use in the HF ITF Network. Their studies during the first year of this contract are summarized in [A34]. Pursley has approached this problem from the standpoint of bit error probability derivations for coded binary FSK and DPSK signals transmitted over nonfading and fading (nonselective and selective) multi-user channels [A35-A38]. Hajek has approached this problem from the standpoint of multiple access protocol techniques [A26,A27,A30,A31]; he has also developed numerical techniques that can be used in the evaluation of multiple access protocols and routing schemes [A28,A29].

The other-user interference problem is one of the fundamental issues in a spread spectrum network. Of special importance to the network design are the question of the number of asynchronous users that can transmit over a wideband frequency hopped channel simultaneously, as well as the development of multiple access protocol techniques that can be used in a spread spectrum channel. Some of the contributions by Pursley and Hajek have been discussed in Sec. 3.3.3, and in greater detail in [A15].

5—Omura has performed an analysis of the AJ performance that can be achieved through the use of convolutionally coded frequency hopping *M*-ary frequency shift keying (MFSK) signaling in worst case partial band noise jammed channels [A33]. He has considered a large number of cases, including: several alphabet sizes (i.e., values of M in MFSK); many values of diversity; several coding schemes; both hard and soft decision receivers; jammer state known or unknown (i.e., in the former case the receiver knows whether or not each received symbol has been jammed); nonfading and Rayleigh fading channels.

The results of this study are summarized in Sec. 3.2.5 and Appendixes D and E, and in greater detail in [A15]. Omura's results have provided the basis for our models that are being used to evaluate link AJ and network AJ performance.

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Appendix B
SPREAD SPECTRUM SIGNALING IN THE HF ITF NETWORK

In this appendix we present the fundamentals of spread spectrum signaling and discuss the basis for our recommendation of frequency hopping (FH) as the spectrum spreading mechanism in the HF ITF Network.

B1 FUNDAMENTALS OF SPREAD SPECTRUM SIGNALING

A spread spectrum system is one in which the transmitted signals are spread over a frequency band that is much wider than the minimum bandwidth required to transmit the information. For example, a baseband signal with a bandwidth of only a few kilohertz may be distributed over a band that is many megahertz wide. At the receiver the wideband spread spectrum signals are remapped into the original information bandwidth and the signal is recovered.

There are four basic types of spread spectrum modulation. In the direct sequence (DS) method, the data to be transmitted modulate a higher rate pseudonoise (PN) code (or chip) sequence. The modulated PN sequence is then transmitted by a radio frequency (RF) carrier. In the frequency hopping (FH) mode the carrier shifts its frequency rapidly from one frequency slot to another using a pattern determined by a pseudorandom code sequence. In the pulsed-FM or "chirp" mode a carrier is swept over a wide bandwidth during a given pulse interval. In the time hopping mode, time slots are assigned by means of a code sequence in the same manner that frequency hopping systems are assigned frequency bands. Hybrid systems that combine two or more of these techniques are often used.

The advantages of spread spectrum signaling, as enumerated in [B1,B2] are:

1. selective addressing capability.
2. code division multiplexing for multiple access.
3. inherent message privacy/security.
4. low density power spectra for signal hiding.
5. high resolution ranging.
6. interference rejection (protection from jamming and other-user interference as well as multipath propagation).

All of the properties listed above could be used advantageously in the HF ITF Network. The first three properties are achieved through the use of quasi-orthogonal sequences, as will be discussed shortly. The interception of spread spectrum messages is difficult because the power spectral density over any narrow frequency band is extremely low. Jamming resistance results from the difficulty of jamming continuously over the entire spread bandwidth at sufficiently high power levels. Multipath signal components can be separated in DS systems using correlation or matched filter techniques, and in

FH systems by hopping at a sufficiently high rate. The use of spread spectrum techniques in a packet radio (although not HF) environment is discussed in [B3]. The basic features of DS and FH systems will now be discussed.

Direct Sequence (DS) Systems

In a DS system each receiver is equipped with a bank of matched filters, one for each particular PN sequence it is designated to receive. The PN sequences are chosen to have small cross-correlation; as a result, signals to which a filter is not matched appear as low power level noise-like interference. (If the family of PN sequences could be chosen to have zero cross-correlation, then the sequences would be orthogonal and this interference problem would be greatly reduced; however, some nonzero cross-correlation is always present in practice, and so only quasi-orthogonality is achievable.)

Selective addressing is achieved by using a PN sequence that is associated with a particular receiver. Similarly, protection from interception is achieved by using sequences that are unknown to potential eavesdroppers. Of particular importance in the network environment is Code Division Multiple Access (CDMA), which takes advantage of the fact that a number of spread spectrum signals can share the same wideband channel as long as the PN sequences used to generate them have good cross-correlation properties. The PN sequences then take on the role of codes. As the number of simultaneous transmissions (using different codes) increases, the interference level typically increases gradually, resulting in graceful degradation (rather than the catastrophic collision that is characteristic of "time-domain" contention-based multiple access systems). When all received signals are of equal power, the number of simultaneous signals that can be tolerated is approximately one tenth of the bandwidth expansion factor [B4]. The actual number varies and depends on factors such as signal to noise ratio, modulation scheme, coding, and acceptable bit error rate. When the signals are not of equal power the number will generally be considerably less, as will be discussed in Sec. B.2. Also, additional discussion of CDMA is found in Secs. 3.3.3 and 4.3.

Resistance against jamming is achieved because the jammer's waveform is poorly correlated with the spreading waveform. The AJ capability of a spread spectrum system is directly proportional to its "processing gain," which is the ratio between the bandwidth of the transmitted signal and the data rate in the information baseband channel.

Frequency Hopping (FH) Systems

In FH systems the transmitter hops from one frequency slot or subband to another, transmitting a narrowband signal at each hop. It is assumed that there is no "spectral splatter," i.e., that the spectrum of the transmitted signal is limited to its narrow band. Such an assumption is reasonable provided that appropriate pulse shaping techniques and frequency guard bands are used. (The effects of spectral splatter are discussed in Torrieri [B5].) The hopping pattern is determined by a pseudorandom code that is analogous to the PN sequence used to achieve spectrum spreading in the DS case. The hopping can be performed over the continuum of the available spread bandwidth, or alternatively distinct frequency slots can be established. In this report a frequency-slotted model is assumed because it facilitates the formulation of the FH multiple access problem.

Again, selective addressing is achieved by the transmitter via the use of the intended receiver's unique FH pattern, and interception is difficult without knowledge of the exact FH pattern. Resistance against jamming is achieved because the jammer cannot put large amounts of energy throughout the entire frequency band, and because it cannot predict the FH pattern. Partial band jamming is often used. Pseudorandom FH paterns that are unpredictable are used, as discussed in Sec. 3.3. In addition either the hopping rate must be high enough so that repeat-back jamming is not feasible, or some other

scheme must be used that is not vulnerable to repeater jamming, e.g., independent mark and space frequency tones. A FH system will be able to tolerate the loss of a number of hops (which would correspond to fractions of packets) caused by jamming if appropriate forward error correction coding or diversity is used. A discussion of antijamming (AJ) FH communication systems is presented in Sec. 3.2.5, Appendixes D and E, and [B6]. It should be noted that while DS systems are vulnerable to jamming by a sufficiently large signal (especially when it is near the center of the spread frequency band), FH systems can be disrupted only if jamming energy is placed into the frequency slot that is occupied by the signal. For example, a continuous disturbance that affects part of the spread bandwidth will appear as a continuous source of (typically low level) interference to a DS system, and as an intermittent source of (higher level) interference to a FH system.

Frequency hopping also provides some degree of robustness with respect to other disturbances and system losses that vary with frequency over the hopping bandwidth. For example, a FH signal can often overcome the effects of a number of noisy frequency slots (and therefore lost bits as in the case of jamming or fading) through the use of forward error correction coding.

As with DS systems, CDMA can be implemented. The code now corresponds to the FH pattern. The CDMA operation is usually asynchronous, and therefore it is possible for two or more users (using different hopping patterns) to transmit simultaneously at the same frequency, resulting in loss of data. The probability of such collisions (of fractions of packets in this case as compared with whole packets in the usual case of time-slotted multiple access schemes), or "hits," increases gradually as the number of users increases, another example of graceful degradation. The loss of data caused by such hits can again be handled via the use of coding and/or diversity. The question of the number of users that can transmit simultaneously in a FH channel while maintaining acceptable performance levels, as well as related coding considerations, are discussed in Sec. 3.3.3 and [B6]. Note that other-user interference occurs only when two or more signals occupy the same frequency slot simultaneously. The presence of strong signals in other frequency slots is not a problem.

Hybrid FH-DS Systems

Hybrid FH-DS signaling has also been considered for use in the HF ITF Network. In such a system the signal transmitted at each hop is no longer narrowband, but instead it is DS spread (although by a much smaller factor than in a pure DS system).

B2 ON THE CHOICE OF SPECTRUM SPREADING TECHNIQUE

One of the fundamental considerations in the design of a spread spectrum system is the choice of the spectrum spreading mechanism. The three forms of spread spectrum signaling that we have considered are direct sequence (DS), frequency hopping (FH), and hybrid FH-DS.

The primary criteria by which a spread spectrum system should be evaluated are its ability to provide AJ capability at acceptable data rates, its ability to function in the particular environment for which it has been designed (in our case the HF ITF environment), and the practicality of its implementation. By considering performance under each criterion we have concluded that, while each of the spreading mechanisms has its advantages, a pure FH system is the most practical choice for use in the HF ITF Network. We now summarize the considerations related to the choice of spectrum spreading technique. A more complete discussion is presented in [B6].

Processing Gain—Bandwidth Considerations

As mentioned earlier, the AJ capability of a spread spectrum system is directly proportional to its "processing gain," which is the ratio between the bandwidth of the transmitted spread spectrum signal and the data rate in the information baseband channel. It is possible to achieve considerably greater

processing gain through the use of FH as compared with DS signaling. Although signals with large instantaneous bandwidths (up to as great as 1 MHz) can be supported over groundwave links, the skywave channel is much more restrictive. Instantaneous bandwidths are usually limited to at most 100 kHz, because of the dispersive nature of the skywave medium, thus limiting the processing gain that can be achieved in a DS system. In contrast, FH signals can hop over the entire bandwidth of the Linked Cluster networks (perhaps 2 to 5 MHz) or in fact the entire HF band. FH signaling also provides additional flexibility, because the spread bandwidth does not have to be contiguous.

Multipath Considerations

Since skywave signals are being considered mainly as multipath interference that often results in the fading of the desired signal as well as in intersymbol interference, it is desirable to select a spectrum spreading method that minimizes such effects. Fortunately, spread spectrum signals have an inherent antimultipath capability. Direct sequence systems provide finer time resolution than FH systems; however, the frequency selective nature of the HF channel is apparent at the large instantaneous bandwidths characteristic of DS systems, often resulting in severe degradation in performance.

To avoid fading caused by skywave interference an FH receiver must hop out of the frequency slot before the skywave signal arrives. From the standpoint of multipath protection, it is best to hop at the fastest possible hop rate, which is anticipated to be at least 2400 hops per second for the proposed HF equipment. In [B6] it is shown that a hop rate of 2400 hops per second will be sufficient to avoid all F-layer skywave reflections at ranges of less than 300 km. While E-layer reflections may still be present, they will usually be considerably smaller than the groundwave or F-layer skywave signals, and will therefore often not be troublesome, although fading may result in some cases. Coding and/or diversity will of course be required to achieve acceptable performance.

Synchronization of PN Codes

Rapid acquisition of timing synchronization is the most critical problem in the operation of spread spectrum systems. The receiver must first of all know the PN sequence that was used to spread the signal. This replica of the spreading signal is then used to de-spread the waveform into its original baseband format. The acquisition and maintenance of timing synchronization is generally much more difficult for DS systems than for FH systems.

Rapid synchronization is especially important in the packet communication network environment since individual transmissions are of short duration. An inefficient synchronization scheme would therefore result in a large fraction of the transmitted bit stream being devoted to the synchronization process (i.e., high overhead).

Multiple Access Capability

The improved AJ performance of spread spectrum signals is gained at the expense of greatly increased bandwidth. Since the HF ITF Network will have to support communication among a large number of users, each wideband channel will have to be shared via Code Division Multiple Access (CDMA). While CDMA techniques can be implemented for either DS or FH systems, the former are highly susceptible to differences in received signal power levels (the "near-far" problem) while the latter are not.

Robustness

Robustness refers to the ability of the system to operate satisfactorily in a variety of hostile environments. In general, FH systems are more robust than DS systems. The following five items have been addressed earlier in this section, but merit repetition here:

1. FH systems are virtually immume to the "near-far" problem, and are therefore better suited than DS systems for multiple access applications;

2. PN code acquisition (synchronization) is easier to achieve and more difficult to disrupt for FH systems;

3. FH systems are less sensitive to the dispersive nature of HF channels;

4. FH systems do not require a contiguous bandwidth; and

5. Wider bandwidths (and therefore greater processing gain) can be achieved with FH systems.

In addition, when noncoherent signaling is used (e.g., noncoherent FSK, which is proposed for the HF ITF Network) there are no carrier phase acquisition problems.

Hybrid FH-DS *vs* FH and DS

The discussion in this section so far, especially as summarized under "Robustness" above, has indicated that FH is clearly preferable over DS as the spreading mechanism in the HF ITF Network. It was in fact concluded by Torrieri that FH is preferable in most military networks [B7].

The remaining candidate spreading mechanism is the hybrid FH-DS system. One of its advantages over pure DS is that much shorter PN sequences can be used in the hybrid system since part of the interference rejection capability is provided by the frequency hopping; the use of shorter PN sequences results in easier signal acquisition than for DS systems. Also, like FH systems, FH-DS systems are less dependent on the relative power levels of signals at the receiver than are DS systems.

The primary advantage of FH-DS over pure FH is that improved multipath rejection can be obtained at lower hopping rates. There are a number of disadvantages, however, of the hybrid FH-DS system. These include more difficult synchronization than for pure FH, more complex equipment, and a reduced number of frequency slots available for CDMA operation. It must be mentioned, however, that we have not done a definitive quantitative performance comparison between FH and hybrid FH-DS.

Our conclusion is that a pure FH system is most appropriate for the HF ITF Network. It was noted that a hopping rate of 2400 hops per second will considerably reduce the effects of fading caused by skywave interference. A high hopping rate is also advisable to prevent repeat-back jamming, as well as to facilitate coding and diversity. If, however, the hopping rate is limited to at most several hundred hops per second, satisfactory performance is still expected in many cases. However, we would then have to rely more on coding, interleaving, and guard times in frequency bands that support considerable skywave propagation.

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Appendix C
DATA MODULATION METHOD: NONCOHERENT FSK

In this appendix we address considerations relating to the choice of the data modulation method, and we present the basis for our recommendation of the use of noncoherent frequency shift keying (FSK). Binary and M-ary signaling are considered.

The first choice to be made regarding the modulation method is between coherent and noncoherent schemes for the modulation and detection of the FH signal. An FH system is said to be coherent if the dehopper at the receiver maintains phase coherence with the received signal. It is noncoherent if such coherence cannot be maintained. Coherent FH systems are much more difficult to implement than noncoherent systems. In the case of the HF channel the dispersive nature of the medium would in fact preclude the use of coherent FH systems because of frequency selective fading; i.e., it would not be possible to maintain the relative phases among the different frequencies.

Another choice to be made is that of the hopping rate. It was noted earlier that it is generally advisable to hop as fast as possible (with respect to channel and equipment limitations) in order to obtain multipath rejection and to avoid repeater jammers. A hopping rate of 2400 hops per second is assumed in many of the examples in Sec. 3.2.5 and Appendixes D and E. Fast FH systems (i.e., more than one hop per bit) permit the use of diversity (i.e., multiple transmissions of the same symbols) and/or the use of lower rate codes; in either case, improved interference rejection is achieved. In the case of skywave signals, hopping rates will probably be limited to at most several hundred hops per second because of the dependence of propagation path (and therefore propagation delay) on frequency. In the case of groundwave signals, however, it is possible to use considerably higher hopping rates that are limited primarily by equipment and bandwidth availability constraints, rather than the properties of the medium.

The most practical data modulation scheme for noncoherent FH systems that hop one or more times per symbol is frequency shift keying (FSK). The simplest form of FSK is binary FSK (BFSK), under which each encoded bit is transmitted as one of two frequency tones; one frequency corresponds to a "mark" (a logical 1) and the other to a "space" (a logical 0). Figure C1 illustrates a noncoherent receiver for FH-BFSK. The receiver bases its decisions on the relative energy contained in the two frequency tone positions. No phase information is required, and each bit is independently detected; FSK is therefore highly robust in terms of fading and interference. In narrowband FSK systems the two frequency tone positions remain constant. In an FH-BFSK system the narrow band containing the two frequencies is hopped according to the FH pattern.

To avoid spectral overlap the two tones are usually separated by the "orthogonal spacing," which is $1/T_b$ Hz for rectangular pulses (and also raised cosine pulses), where T_b is the bit duration as shown in Fig. C2. The bandwidth required to contain both the mark and space frequency tones is therefore $2/T_b$. For a bit rate of 2400 b/s, this bandwidth is then 4.8 kHz. It is often advisable to allow frequency guard bands between channels, especially when there are large power differentials among signals in the network. For example, a channel bandwidth of $4/T_b$ might be used for binary signaling.

When two or more symbols are transmitted per hop, differentially encoded modulation schemes such as DPSK, DQPSK, or minimum shift keying (MSK) are possible alternatives to FSK [C1]. Under

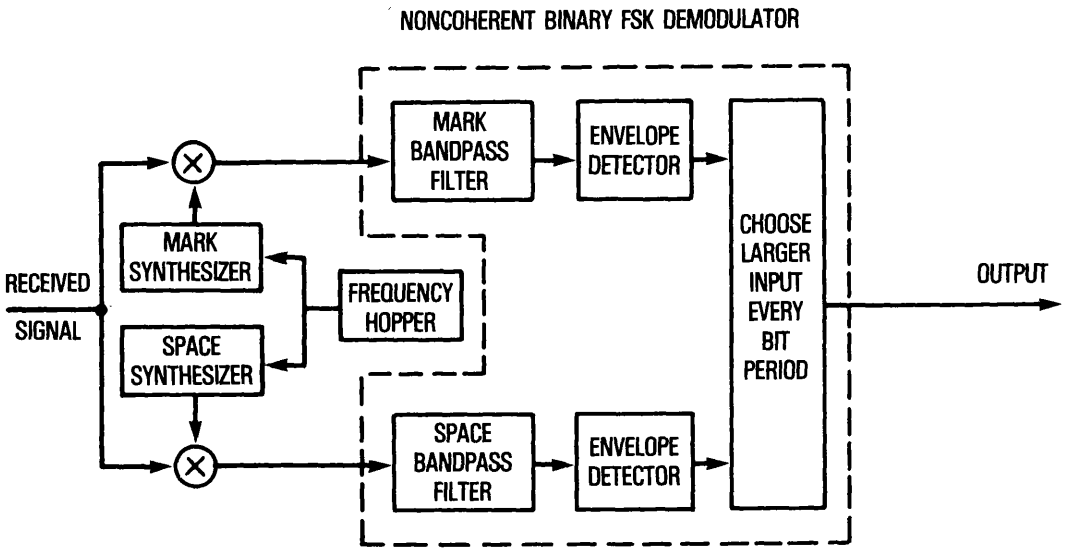

Fig. C1 — Frequency-hopping receiver

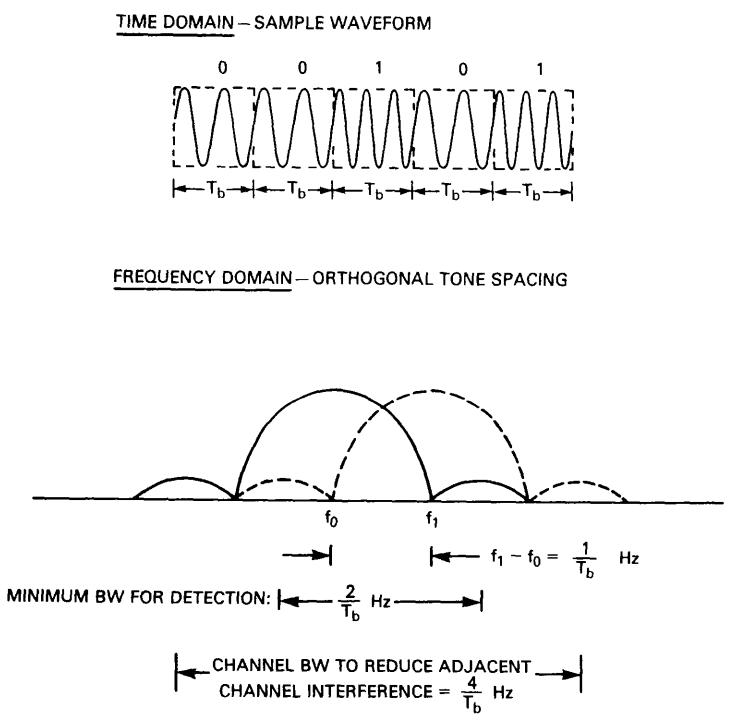

Fig. C2 — Binary frequency shift keying (BFSK)