Resistance to HF Jamming Interference in Mobile Radio Networks by an Adaptive, Distributed Reconfiguration Technique

D. J. BAKER, J. E. WIESELTHIER, A. EPHREMIDES,
AND D. N. MCGREGOR

Comunmication Systems Engineering Branch
Information Technology Division

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In radio communication, interference (and in particular jamming) represents an important limitation to the rate and range of information transfer. In a radio network environment, a combination of relaying and other classes of interference-combatting methods, such as spread spectrum signaling, may achieve highly robust resistance to jamming. Since the presence of relays is an inherent characteristic of a network, it is possible to use some nodes as relays when previously existing direct links are disabled as a result of jamming. The purpose of this report is to show how a distributed algorithm can enable an HF radio network to reconfigure itself to combat various jamming threats. We present models for the communication range that is achievable through the use of HF groundwave signals under both benign and stressed conditions and for cases of narrowband and wideband signaling. The models are used in our simulations. These simulations show that the choice of best frequency for communication in an HF network should not depend solely on communication range in a benign environment.

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CONTENTS

RESISTANCE TO HF JAMMING INTERFERENCE IN MOBILE RADIO NETWORKS BY AN ADAPTIVE, DISTRIBUTED RECONFIGURATION TECHNIQUE

1. INTRODUCTION

In radio communication, interference (and in particular jamming) represents an important limitation to the rate and range of information transfer. Interference may be combatted by three classes of methods. One class consists of antenna configurations that provide highly directive reception capability. This class includes a variety of adaptive array techniques that provide for side-lobe cancellation. The main disadvantages of these techniques are that generally they are not effective when the interfering signal is coming from the same direction as the desired signal; they do not provide for multiple access capability [1]; and they generally require the use of narrowband signaling schemes. Another class consists of waveform design techniques that include spread spectrum (wideband) signaling and related modulation and coding considerations. These techniques achieve substantial resistance to interference regardless of the direction from which it originates. They also provide inherent multiple access capability, a feature that is desirable in radio network environments [2,3]. The third class consists of the addition of relays along the communication path. The presence of such relays increases the effective range of a transmitter in the presence of interference [4-6] and can be used with both narrowband and wideband signaling schemes.

In a radio network environment, a combination of relaying and other classes of interference-combatting methods may achieve highly robust resistance to jamming. In fact, the presence of relays is an inherent characteristic of a network because intermediate nodes can serve as relays whenever necessary. Thus, if the network's design is based on a control concept that provides for an adaptive reconfiguration capability, it is possible to use some nodes as relays when previously existing direct links are disabled as a result of jamming [7].

In this report, we show how such a radio network can respond to interference. The network model considered here consists of N nodes, where N may range up to approximately 50. The nodes may be dispersed over a region with diameter ranging up to 500 km. The HF channel (2 to 30 MHz) is used for communication. We assume that the network must operate under a variety of stress conditions and must, above all, be survivable. This model closely resembles the HF Intratask Force (ITF) Network currently under design study at the Naval Research Laboratory [8,9]. We emphasize here the antijamming (AJ) behavior of this network resulting from the inherent presence of relays in a networking environment. Both narrowband and spread spectrum signaling examples are included. We do not consider here antenna configuration techniques.

We consider a network consisting of a known number of mobile nodes that use the HF channel for communication. The main characteristic of this network is its variable topology, which is caused by many factors including node mobility, hostile jamming, antenna orientation, and HF propagation conditions. The latter are subject to substantial variations that involve both ground and sky waves. For the organization and adaptive reconfiguration of this network, a fully distributed algorithm is used as described in fuller detail in the next section and in Refs. 10 and 11. This algorithm consists of two parts, a communication part that allows neighboring nodes to exchange messages involving local connectivity information and a computation part that organizes the nodes into a connected network based on an architecture of linked node-clusters.

We assume that the network must withstand a variety of interference threats including multiple jammers, standoff jamming, intermittent jamming, worst case partial band (WCPB) jamming, etc. The key idea is that jamming in any form causes the loss of communication links, and as a result it creates topological changes. Since our network is organized by executing an algorithm designed to react to topological changes and reconfigures itself adaptively in response to such changes, it is capable of resisting jamming threats as well.

This report is organized as follows. In Section 2, the network system and control concept is briefly described. In Section 3, the HF propagation model and narrowband and wideband signaling waveform designs are considered. The resultant model allows the determination of communication range for the HF groundwave for both benign and jammed environments. This evaluation is necessary to determine the connectivities among the nodes. In Section 4, it is shown how the network structure is inherently robust vis-a-vis these threats. Extensive simulation results are also reported that demonstrate the predicted ability of the network to reconfigure itself and discover alternative paths in the presence of jammers. An interesting result of these simulations is that the choice of best frequency for communication in an HF network should not depend solely on the communication range achievable in a benign environment.

2. SYSTEM AND CONTROL CONCEPT OF THE NETWORK

A basic architecture is outlined here for an HF radio network consisting of a fixed number of mobile nodes numbered consecutively from 1 through N. This architecture can be developed by a fully distributed algorithm that results in a hierarchical structure of node-clusters, each locally controlled by a clusterhead node and linked to each other by gateway nodes (Fig. 1). The portion of the network that consists of clusterheads, gateways, and the links that connect them is known as the backbone network. This architecture is flexible; it allows and is compatible with a number of choices for network operation, such as routing, flow and error control, multiple access schemes, etc. It represents primarily a survivable means of self-organization and self-adaptation to changing connectivities that arise from variations in the topology of the network.
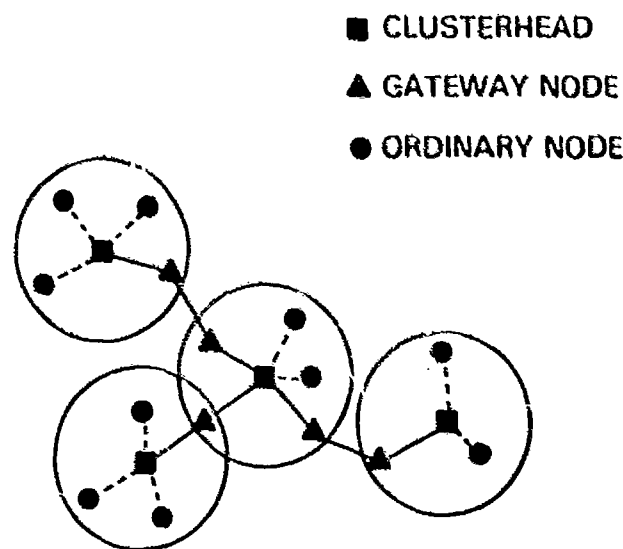

Fig. 1 — Example of linked cluster structure

The basic algorithm has been called the LCA (Linked Cluster Algorithm) and is described in detail elsewhere [11].* The LCA requires both communication and computation. Communication consists of neighboring nodes exchanging control messages; computation consists of each node determining the existing connectivities and the achievable linked cluster structure.

A time division multiple access (TDMA) protocol controls communication during the execution of the LCA. The LCA requires two TDMA frames, each of which consists of N time slots (Fig. 2). During the jth slot of either frame, the jth node broadcasts all the connectivity information available to it at that time, while the other nodes listen for node j's transmissions. Thus, in the first frame the jth node simply broadcasts an early tentative portion of its connectivity information concerning neighbors with identities less than j. In the second frame, the jth node broadcast includes the entire connectivity information concerning all two-way neighbors, namely those for which communication in both directions is possible. Bidirectional connectivity can be determined by checking whether node j's identity is in the list of node i's neighbors that is received by node j. Only bidirectional links are considered for possible inclusion in the backbone network.
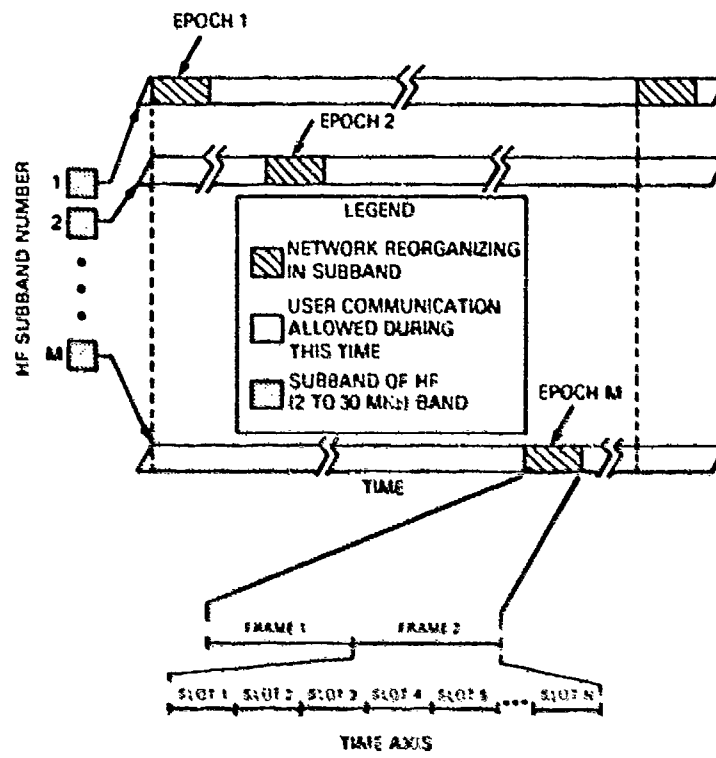

Fig. 2 — Timing for network reorganization

At the end of the second frame, the data base accumulated at each node consists of the identities of its neighbors and of those of its neighbors' neighbors. A set of rules, operating on connectivity and other control information exchanged during the second frame, allows the unambiguous selection of clusterhead and gateway nodes. As a result, each node can determine its status, namely whether it is to become a clusterhead or not. If not, it can determine which of its neighbors are to become clusterheads and whether or not it should become a gateway node for linking any pair of clusters. We emphasize that the LCA can produce a connected network whenever the connectivities required to do

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*All results in this report are based on a version of the Linked Cluster Algorithm called the ALCA, which is described in detail in Ref. 11.

so are present. In this network structure each platform is connected directly to a clusterhead, and all clusterheads are connected to each other through the backbone network — other links, not shown in Fig. 1, may provide additional connectivities.

Since the medium assumed here is the HF channel and since communication range for HF groundwaves is highly variable, the LCA has been extended to take this variability into account. This strong frequency dependence is explained in the next section. In fact the variability of range, which at first appears to be a disadvantage, can be turned around and can be exploited by the LCA to the network's benefit. Thus, the HF band is partitioned into M subbands, over each of which the propagation range is approximately constant. Time contains fixed periods that we call epochs. Each epoch consists of two TDMA frames, as described previously. There are M nonoverlapping epochs that periodically repeat themselves. During the $\hbar$h epoch of any cycle, a structured exchange of messages is taking place at the $\hbar$h subband, which organizes a network at that subband. Thus we create an overlay of M networks for the same set of nodes, one for each subband. At any given instant, the nodes are engaged in a reconfiguration effort for at most one of the networks while communicating regularly in all of the other subbands (see Fig. 2).

Overall, this architecture achieves the following objectives which are basic for the operation of any mobile radio network:

- communication path establishment between every pair of nodes;

- a convenient structure for network-wide broadcasts;

- avoidance of the hidden terminal problem [12] associated with multiple access in multi-hop environments;

- robustness with respect to node losses and connectivity changes.

Issues such as the precise way in which the network operates, that is, the details of how link activation [13] and routing are effected, how multiple access is achieved, how often the configuration is updated, etc., can be considered within the framework of this basic architecture. For the HF ITF network, there are many possible choices consistent with the requirements and constraints that this architecture places upon the network. These choices are not addressed here because they do not directly affect network reconfiguration in response to jamming. (Demonstration of resistance to jamming is the primary goal of this paper. The interested reader should consult Ref. 9 for further details on the HF ITF n   ation.)

In the next section, we establish models to determine the communication range of an HF link for both narrowband and wideband signaling schemes. We use those models in the simulation of the network's behavior that is reported in a later section. We must emphasize, however, that in the case of an actual implementation of the LCA, this model is not necessary, since the connectivities at each node are determined in a totally adaptive fashion based on the probing messages exchanged during the reorganization process.

3. COMMUNICATION OVER NETWORK LINKS

In this section, we present models for the communication range that is achievable through the use of HF groundwave signals under both benign and stressed conditions. Both narrowband and wideband signaling schemes are considered. In the benign case, communication range is limited primarily by atmospheric noise and other-user interference. In the stressed case, the primary source of interference is hostile jamming. The basic waveform considered is noncoherent frequency shift keying (FSK) with convolutional coding used to correct errors caused by jamming or other interference. For the wideband (spread spectrum) signaling case, this basic waveform is frequency hopped (FH) over a wide band of

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several megahertz. The jammer is assumed to operate as a Gaussian noise jammer for the narrowband signaling case and as a worst case partial band (WCPB) Gaussian noise jammer for the wideband case.

HF Groundwave Medium

The HF medium is suitable for extended line-of-sight (ELOS) communication, largely because of the propagation ranges (up to several hundred kilometers) of HF groundwaves. Another advantage of HF groundwave propagation is that it is only minimally affected by severe atmospheric disturbances. In addition, the use of HF groundwaves avoids the need to use relays outside the task force, such as geo-stationary satellites (operating at SHF and EHF), that are potentially vulnerable to physical attack.

HF groundwaves (unlike HF skywaves) experience little dispersion, although they are subject to skywave multipath interference, high levels of atmospheric noise, and other-user interference that can propagate from distant sources via HF skywaves. Another disadvantage of HF compared to higher frequency bands is that there is a limited bandwidth, and therefore only relatively low data rates can be achieved. Despite these disadvantages, however, the ability to communicate at ELOS ranges and the reliability of the medium make the HF groundwave well suited for applications such as intratask force communication.

The attenuation of HF groundwaves as a function of distance is considerably greater than inverse-square law. Therefore, previously derived communication/jamming range relationships that illustrate the region in which the jammer is effective as a function of various system parameters do not apply here (e.g., those developed by Cook [4,5]). Typical groundwave path loss over a very rough sea (sea state 6), evaluated using Barrick's model [14]), is illustrated in Fig. 3 as a function of distance and as frequency is varied between 3 and 30 MHz. It is clear from this figure that groundwave attenuation as well as attenuation rate (i.e., the slope of the attenuation curves) are increasing functions of frequency. Reference 14 also shows that propagation loss increases as sea state increases, and increasingly so as frequency also increases.

The strong dependence of propagation loss (and therefore communication range) on frequency has led to the development of the network management procedure described in section 2. This procedure requires a set of simultaneously operating networks, each defined in a frequency band over which the communication range is relatively constant.

The achievable communciation range is a complex function of transmitted signal power, propagation loss, system losses, data rate, and noise level, as well as modulation and coding schemes, tolerable bit error rate (BER), and receiver structure. Here, for both the narrowband and wideband signaling cases, we assume a transmitted power level of 1 kW, path loss corresponding to sea state 6 (extremely rough sea), data rates of 75 and 2400 bps, noncoherent binary frequency shift keying (FSK), rate 1/2 convolutional coding with constraint length 7, a soft decision receiver structure, interleaving to combat burst errors, and BER $= 10^{-5}$. For the case of wideband FH signaling in WCPB noise jamming, we make the additional assumption that we know which received symbols are jammed (known as jammer state information, or JSI).

Communication Range in a Benign Environment

While propagation loss is fairly well predicted by Barrick's model, it is still difficult to predict the achievable communication range. This is because of variable (and highly non-Gaussian) interference, as well as uncertainties in system losses, including deviations from nominally omnidirectional antenna patterns. Shipboard HF antenna patterns can vary considerably over a frequency range of several hundred kilohertz; e.g., nulls may exist at some frequencies resulting in greatly reduced signal levels. The
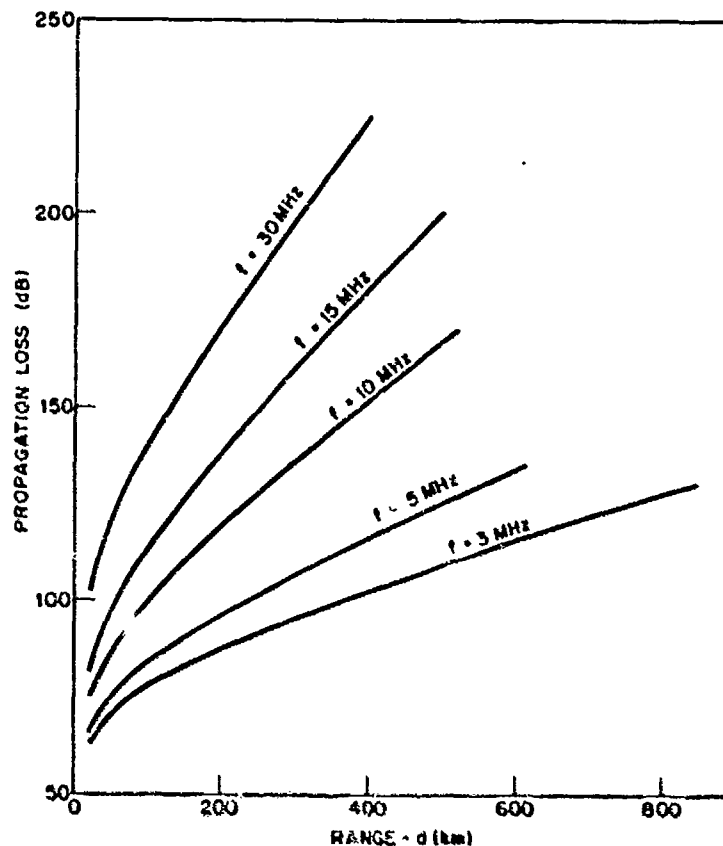
Fig. 3 — Groundwave path loss over rough sea (sea state 5) as
a function of distance for several frequencies in the HF band

use of frequency hopping (FH) with coding provides some degree of robustness with respect to frequency-dependent system losses by providing some degree of frequency diversity. Frequency hopping multiple access considerations related to mobile HF radio networks are addressed in more detail in Refs. 9 and 15.

In this report, we assume that the only losses are propagation loss and miscellaneous system losses. The former are evaluated directly from Barrick's curves (Fig. 3), and the latter are assumed to be 3 dB. The same range model is used for both narrowband and wideband signaling. The received signal energy per bit, E_b, is simply the received power divided by the data rate. Background noise levels, which include atmospheric noise as well as interference from other users of the HF band, vary considerably as a function of frequency, location, and time of day [16,17]. Here, we do not consider interference caused by other network users to be part of the background noise level. For the case of narrowband signaling, we implicitly assume that network management schemes ensure that neighboring users do not transmit simultaneously in the same frequency channel. For the case of wideband signaling, a number of users with independent pseudorandom FH patterns can share the channel simultaneously if appropriate coding is employed to correct errors caused by frequency "hits" [15]. Future studies will generate a more comprehensive range model. This model will consider other-user interference in addition to jamming and background noise. It will also address the relationships between modulation and coding schemes and the network's organizational structure and protocols.

The signal design parameters, sea state, BER, and system losses were defined earlier in this section. For rate 1/2 convolutional coding with constraint length 7, the required E_s/N_0 in a Gaussian

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noise environment is 9.7 dB [19], which we round up to 10 dB. The noise density N_0 is chosen based on one of the noise occupancy distributions presented in Ref. 17. The resulting communication range model is illustrated in Fig. 4 as a function of frequency for data rates of 75 and 2400 bps. This model should be considered representative of a region characterized by relatively high noise levels, rather than a definitive or worst-case model for HF groundwave propagation over seawater. Noise levels in quiet areas are typically tens of decibels lower than those that have been assumed in this study. The main purpose of this report is to demonstrate the ability of a network to reconfigure itself in response to connectivity changes caused by jamming. Therefore, we emphasize the execution of the recently developed distributed algorithm for network organization, rather than modeling precisely the effects of interference.
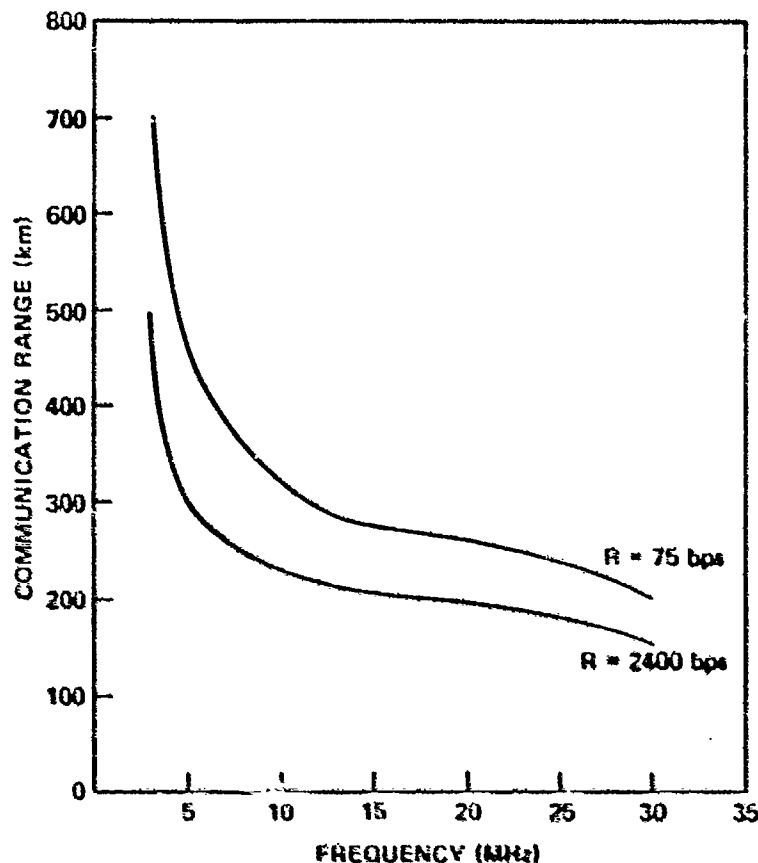

Fig. 4 — Communication range example for HF groundwave

Communication Range in a Jammed Environment

An antijamming (AJ) communication system must provide resistance against jamming signals that have much more power than the desired signals. Over an individual link, only limited AJ performance can be obtained with narrowband signaling. Thus the use of spread spectrum signaling is necessary in many (especially military) applications. We show in section 4, however, that some degree of network AJ capability can be obtained even when individual links are extremely vulnerable to jamming. In Ref. 9 we concluded that noncoherent frequency hopping (FH) with frequency shift keying (FSK) is the most practical spreading/modulation choice for mobile HF radio networks. In FH systems, protection from jamming is achieved through the pseudorandom hopping of the instantaneously narrowband signal

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across a wide frequency band, e.g., the entire bandwidth of one of the M subbands into which the HF band is divided. In addition, loss of data is countered by the use of coding and diversity. Further AJ capability results from the use of adaptive relaying and network restructuring, which is precisely what this report demonstrates.

Narrowband Signaling

We first consider the AJ performance of narrowband noncoherent binary FSK signaling. A Gaussian noise jammer with constant noise density over the signal bandwidth is assumed. The basic AJ signaling parameters are:

W is signal bandwidth,

R is information data rate in bps,[*]

S is received signal power, and

J is received jammer power (in signal bandwidth W).

The resulting bit energy-to-noise density ratio is easily expressed as

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

For noncoherent binary FSK, the orthogonal tone spacing is $1/T_s$, where T_s is the binary symbol duration. A total bandwidth of $W = 2/T_s$ is thus needed to contain the mark and space tones. The data rate can be expressed as $R = r/T_s$, where r is the code rate. For such a signaling scheme with no diversity (beyond that inherently provided by the coding process), we have

$$W/R = 2/r.$$

For a rate 1/2 code we therefore have $W/R=4$.

Background noise is neglected in this phase of the analysis but will be introduced later. Besides, such interference is generally much weaker than the jamming signal in regions where the jammer poses a significant threat. The maximum J/S ratio that can be tolerated by the rate 1/2 coded noncoherent narrowband communication system considered here is

$$(J/S)_{max} = 4/(E_b/N_0),$$

where the value of E_b/N_0 used in this equation is that which is required for the desired BER. The value of E_b/N_0 required to achieve a BER of 10^{-5} for the coding modulation scheme considered is approximately 10 dB, which results in

$$(J/S)_{max} = -4 \text{ dB}[†]$$

Thus, narrowband links are extremely vulnerable to jamming.

Wideband Signaling

We now consider a wideband FH system. It is assumed that the hopping rate is sufficiently fast so that repeater jamming is not possible. It is also assumed that the FH patterns are pseudorandom in

---

[*]Note that while the use of coding increases the number of binary symbols that are transmitted, R always refers to the actual information data rate in bps before the application of modulation, coding, and diversity.
[†]This result is valid for any data rate. Note that the signal bandwidth is proportional to the data rate, and the jammer power is in all cases assumed to be uniformly distributed over the signal bandwidth.

nature and cannot be predicted by the jammer. The basic AJ signaling parameters were presented earlier in the discussion of narrowband signaling. We must reinterpret two of them for the wideband case as:

W is the total spread spectrum signal bandwidth

J is the received jammer power (in spread hopping bandwidth W).

Realistic jamming threats include multitone jamming and worst case partial band (WCPB) Gaussian noise. In the latter case, the jammer concentrates its energy on the fraction of the signal-hopping bandwidth that will produce the most severe disruption of communication. In this report, we consider only WCPB Gaussian noise jamming, for which extensive results for convolutionally coded M-ary FSK signals have recently been obtained by Omura [20]. The former case could pose a somewhat greater threat, but it is not expected to have a great impact on the achievable communication range.

For a FH system in a WCPB Gaussian noise environment, the equivalent bit energy-to-noise density ratio is defined as

$$E_b/N_0 = (W/R)(S/J) = PG/(J/S),$$

where $PG = W/R$ is the processing gain.* As in the narrowband case, we neglect background noise. The maximum J/S ratio that can be tolerated by the AJ communication system is

$$(J/S)_{max} = PG/(E_b/N_0),$$

where the value of E_b/N_0 used in this equation is that which is required for the desired BER.

It is shown in Ref. 20 that a BER of 10^{-5} can be achieved in a noncoherent FH binary FSK system under WCPB noise jamming for $E_b/N_0 = 11.2$ dB if rate 1/2 convolutional coding is used with a soft decision receiver that can detect which received symbols are jammed. Such an ideal receiver is assumed in this report, although the performance of other receiver structures can also be evaluated.†

We assume that the signal is hopped over the entire bandwidth of one of the M frequency subbands. For example, for a hopping bandwidth of $W = 5$ MHz, the achievable AJ performance for the signaling scheme described here [9] is

$$(J/S)_{max} = \begin{cases} 22 \text{ dB for } R = 2400 \text{ bps} \\ 37 \text{ dB for } R = 75 \text{ bps} \end{cases}$$

Improved link AJ performance may be obtained by increasing the spread hopping bandwidth. However, the dependence of the attenuation characteristics of the HF groundwave signals on frequency suggests that subbands of much greater than 5 MHz bandwidth may not be advisable.

Evaluating the Communication Range

The next step is to translate the achievable J/S ratios into communication ranges. The J/S ratio is easily expressed in terms of transmitted power levels, propagation losses, and other system losses:

$$J/S = L_a(P_{tj}/L_j)/(P_{ts}/L_s),$$

---

*Alternative definitions of processing gain have been used elsewhere. The present definition permits a consistent formulation of the AJ link performance measures for coded systems [9,20].

†For a hard decision receiver, the required E_b/N_0 is 12.6 dB if such jammer state information (JSI) is available and 17.8 dB if it is not. Omura has demonstrated the inadvisability of using a soft decision receiver if JSI is not available [20].

where the following parameter values have been assumed:

P_{tj} = transmitted jammer power = 10 kW,

P_{ts} = transmitted signal power = 1 kW,

L_j = path loss of jammer,

L_s = path loss of desired signal, and

L_a = additional system losses = 3 dB.

These parameter values result in

$$J/S = 20 \ L_s/L_j.$$

Successful communication (i.e., BER $< 10^{-5}$) can take place as long as J/S does not exceed the tolerable level $(J/S)_{max}$ discussed earlier.

Figure 5 illustrates the geometry of a transmitter, receiver, and jammer; d is the distance from the transmitter to the receiver and d_j is the distance from the jammer to the receiver. Note that for this case of a single receiver, there is circular symmetry about the receiver. We define $d_{jmin}(d)$ as the minimum value of d_j that can be tolerated for a given d, or in other words the radius of the circle within which the jammer disrupts communication.

TRANSMIT

JAMMER

d

d_j

RECEIVER

$d_{jmin}(d)$

JAMMER WILL CAUSE
DISRUPTION ONLY WHEN
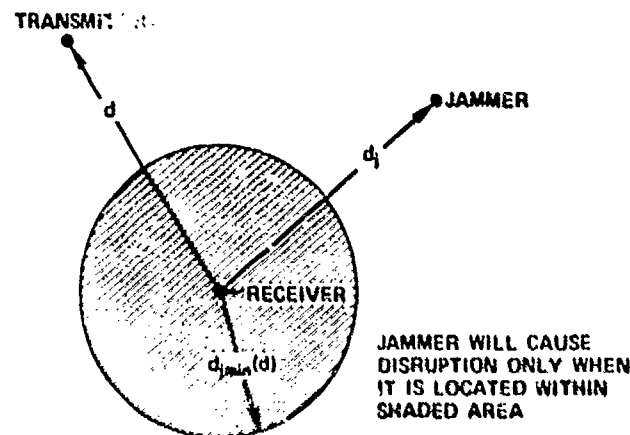IT IS LOCATED WITHIN
SHADED AREA

Fig. 5 -- Transmitter-receiver-jammer geometry

The examples given in this report are based on the assumption that all platforms (transmitting, receiving, and jamming) are surface vessels and all propagation is via groundwaves. Therefore Barrick's curves for groundwave propagation loss over seawater, shown earlier in Fig. 4, can again be used.

The AJ capability that has been achieved by frequency hopping and coding, again for sea state 6, is illustrated in Fig. 6. In this figure, $d_{jmin}(d)$ is plotted as a function of d for the system parameters discussed above. We note that $d_{jmin}(d)$ is less than d, despite the 10 dB power advantage that the jammer has over the transmitted signal. The curves of Fig. 6 are based on the simplifying assumption that attenuation is constant over a 5-MHz bandwidth centered at the frequencies shown. The degree of AJ capability is most pronounced at the lower end of the HF band for the examples shown. Lowering the data rate from 2400 bps to 75 bps improves AJ performance by increasing the tolerable J/S ratio $(J/S)_{max}$ and thereby reducing the size of the circle in which the jammer is disruptive. This effect is also especially pronounced at the lower end of the HF band. Conversely, if $(J/S)_{max}$ is decreased (e.g., by raising the data rate or decreasing the hopping bandwidth) the disruption region is increased.
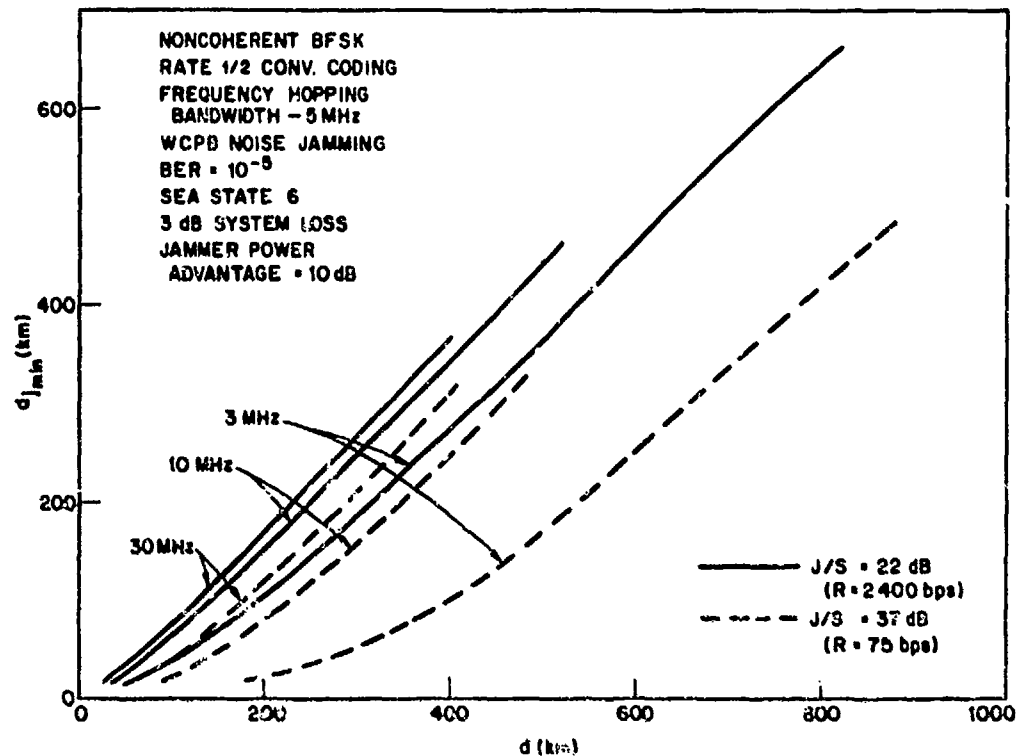
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Fig. 6 — $d_{jmin}(d)$ vs d for HF groundwave model and wideband signaling

In the narrowband signaling case with rate 1/2 coding, for which $(J/S)_{max} = -4$ dB, there is little AJ capability, as shown in Fig. 7. We now have $d_{jmin}(d) > d$. Thus, the jammer can disrupt communication even when it is farther from the receiver than is the friendly transmitter. We also see that AJ capability is higher at the upper end of the HF band for this non-AJ system, unlike the FH system discussed above. The propagation loss curves of Fig. 3 provide the reason behind the improved AJ capabilities at the higher frequencies for non-AJ signaling schemes. These curves show that the rate of attenuation increases with increasing frequency. Consequently, if the jammer is at a range disadvantage, i.e., if the receiver is closer to the source transmitter than to the jammer, then the higher the frequency the greater the additional propagation loss experienced by the jamming interference. Conversely, if the jammer has the range advantage, the use of low frequencies is preferred.

We note that if system parameters are such that $[(J/S)_{max} - L_o]$ is equal to the jammer's transmitted power advantage (10 dB in our examples), then the curves for all frequencies are of unity slope, in which case $d_{jmin}(d) = d$. Thus the jammer will disrupt communication if (and only if) it is closer to the receiver than the friendly transmitter. We illustrate this case in Fig. 7, although we have not associated it with any particular signaling scheme.

Background noise has been neglected in the evaluation of $d_{jmin}(d)$. Therefore, the curves of Figs. 6 and 7 depend only on the attenuation predicted by Barrick's model for groundwave propagation loss over seawater (for given waveform/coding design, transmitted power levels, and sea state), not on the background noise environment. These curves are therefore valid only for values of d that are less than maximum achievable noise-limited values (such as those predicted by the curves of Fig. 4).

Under benign operating conditions, the communication ranges presented in Fig. 4 provide a model for determining network platform connectivities, and therefore for determining a network organizational structure by means of the Linked Cluster Algorithm. Under jammed conditions, communication ranges are decreased. This disrupts platform connectivities and necessitates network reorganization.
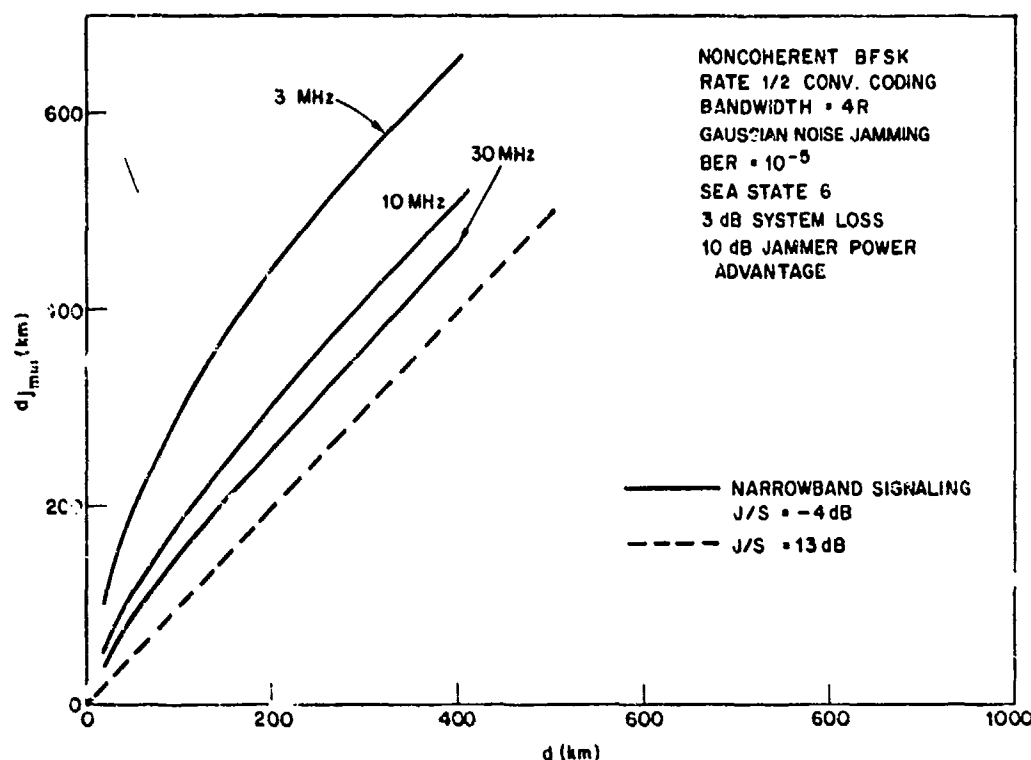
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Fig. 7 — d_{jm} (d) vs d for HF groundwave model and narrowband signaling

For each pair of platforms connected in the benign environment, connectivity in the jammed environment is examined by computing the J/S ratio at the receiver, or equivalently, by examining Figs. 6 and 7. (We neglect the case in which the combined background noise plus jamming causes loss of links, while neither is sufficient to do so alone.) Note that while all links that exist in the benign environment are two-way links (under the assumption of equal transmitter powers and uniform interference conditions throughout the network) the presence of jammers can result in one-way links. This distinction is important, because one-way links are equivalent to lost links in the LCA. Further studies will address possible schemes for the use of such one-way links, as well as asymmetrical links that can support a higher data rate in one direction than in the other. We reiterate that even though the range calculations described above are useful in their own right and are for the simulation of the algorithm, they are not needed for the actual operation of the algorithm. This is because the probing messages exchanged among the nodes determine fully whatever connectivities may exist at a given time.

Connectivity (or the lack of it) must be defined in terms of the desired bit error probability (and therefore a threshold value of E_b/N_0 for a given data rate) and the probability of achieving this level of performance. The goal of the Linked Cluster Algorithm is to form a network structure that is robust to all jamming, and therefore only links for which there is a high probability that the threshold value of E_b/N_0 can be achieved should be used to form this structure. In the case of intermittent jamming, a node may decide that a link is unreliable, even though the received signal exceeds the threshold level whenever jamming does not occur. Consequently, the linked cluster structure may be formed as though the unreliable link were lost. On the other hand, although the LCA might not use such unreliable links to form the backbone network, their use for other purposes is not excluded.

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4. SIMULATION RESULTS

In Section 2 we outlined a procedure, called the Linked Cluster Algorithm (LCA), by which a mobile radio network can determine its connectivities and organize itself into a structure of linked node-clusters. Each node is bidirectionally linked to a clusterhead, and clusterheads are bidirectionally connected via gateways nodes, thus forming a connected network. In Section 3 we described two models for determining the connectivities of a network both with and without jammers present—the first model assumed narrowband signaling and the second model assumed a wideband FH signaling scheme. In the present section, we show how application of the LCA can combat jamming by dynamically forming a connected network, structured into linked node-clusters, using only those links which are not broken by jamming. We also give examples showing that the preferred portion of the HF band within which to operate the network greatly depends on the jamming scenario and whether narrowband or wideband signaling is used.

Mobile Jammer

Our first example, shown in Fig. 8, represents a relatively small task force. However, it is large enough to illustrate the results of applying our network structuring algorithm. Larger networks are examined in subsequent examples. For this example, the connectivities* shown in Fig. 8a are for the case of a 10 MHz operating frequency, a 2400 bps information rate, and no jammers present. Other signaling parameters are the same as those cited in the previous section. Also, in this and in subsequent examples, we have used the noise model described in the previous section. That model gives a maximum communication range of approximately 230 km at 10 MHz (see Fig. 4).† To emphasize the capabilities of the network to combat jamming by reorganizing, we first consider the extreme, but unlikely, case in which the jammer is passing through the task force. Subsequent examples treat more realistic and more complicated scenarios.

In the absence of jamming, the network organizes into the set of node clusters shown in Fig. 8b; nodes 1, 3, and 5 have become clusterheads, and every node is connected to one of these heads. Nodes 2 and 8 have become gateways (relays) to join the clusterheads, thus forming the backbone network. In Fig. 8b, and in all subsequent figures depicting network structures, we show the backbone network as well as the links between each node and its own clusterhead.

The sequence of frames c through i in Fig. 8 illustrates how the network restructures itself in response to a mobile jammer for the case where spread spectrum (wideband) signaling is used. The jammer path is as shown in Fig. 8b, and subsequent frames correspond to jammer positions indicated by the solid dots on the path also shown in Fig. 8b. For this, as well as our other examples, each jammer is assumed to radiate 10 kW, while task force nodes radiate only 1 kW. The jammers are assumed to be shipboard, and we consider only groundwave propagation.

To understand the results shown in Fig. 8, we need only refer to Fig. 6. This figure shows that at 10 MHz the jammer must be within approximately 70% of the transmitter-to-receiver range before that link is broken. For example, when the jammer is at the location shown in Fig. 8c, node 7 is prevented from hearing node 3, and node 6 is prevented from hearing either 3 or 8. Consequently, nodes 6 and 7 are no longer bidirectionally connected to clusterhead 3, as they were in Fig. 8b. The network responds by forming an additional clusterhead at node 6; also, node 4 becomes a gateway to link this new head to the rest of the backbone network.

As the jammer approaches nodes 4, 6, and 7, the link from 3 to 4 is lost. This results in node 4 becoming a clusterhead, as shown in Fig. 8d. This in turn causes 7 to become a clusterhead and 6 to become a gateway. Note that the use of link (3,4) has been avoided while still maintaining a connected network.

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*In all of our examples, nodes that are joined by a solid line are bidirectionally linked.
†Examples that do not include a jammer are applicable to both narrowband and wideband signaling cases.
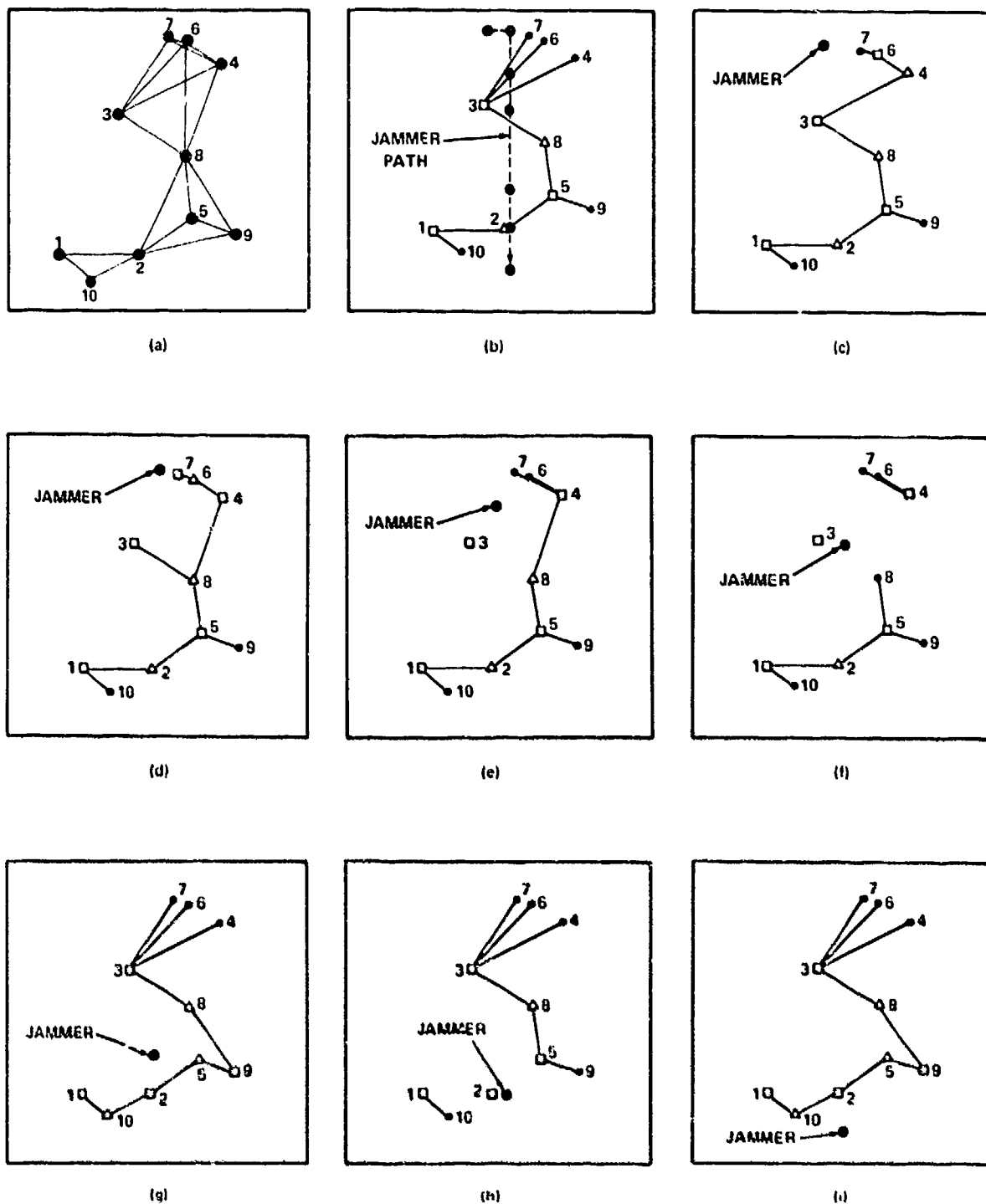
Fig. 8 — Example of a network restructuring itself to combat a mobile jammer (10 MHz wideband)

Approaching node 3 (see Fig. 8e), the jammer is successful in isolating this node; however, the rest of the network remains connected.

In Fig. 8f, the jammer is near the critical node 8. This is a critical node in the sense that its loss will disconnect the network, as can be seen by examining the connectivities shown in Fig. 8a. Splitting does in fact occur, as shown in Fig. 8f. At this point, only a repositioning of the nodes can achieve relaying that will reconnect the network. Of course, if additional link AJ capability can be obtained, for example, by reducing the information rate or switching to a frequency with more favorable propagation characteristics, then our network structuring algorithm will use the new links to form a connected network.

When the jammer moves away from nodes 3 and 8 to the position shown in Fig. 8g, the network is able to return to the connected state. However, as the jammer approaches 2, the ability to use this node for relaying is lost, and the network becomes disconnected again as illustrated in Fig. 8h. The network is able to recover to the connected state after there is a moderate separation between the jammer and node 2, as shown in Fig. 8i.

Multiple Jammers and the Loss of a Central Node

Our second example is for the case of 24-node network. This example is slightly more realistic because the jammers do not penetrate deeply into the task force. In addition, we examine the combined effects of multiple jammers and node loss. As in the previous case, the operating frequency is 10 MHz, the information rate is 2400 bps (corresponding to a 4800 bps transmission rate with rate 1/2 coding), and wideband signaling is assumed. Figure 9a shows how the network organizes in the absence of jammers. Five clusters are formed: clusterhead node 1 with cluster members 2, 3, 11, 13, 14, 15, and 16; clusterhead node 4 with cluster members 7, 12, 17, and 18; clusterhead node 5 with cluster members 9, 19, and 20; clusterhead node 6 with cluster members 10, 21, and 22; and clusterhead node 8 with cluster members 23 and 24. (Here we have used the convention that if an "ordinary" node is bidirectionally connected to more than one clusterhead, it is a member of the cluster with the lowest numbered head.) Node 15 becomes a gateway to link clusterheads 1 and 4; node 13 becomes a gateway to link heads 1 and 5; gateway node 12 links heads 4 and 5; gateway 3 links heads 1 and 6; gateway 2 links heads 1 and 8; and gateway node 3 links clusterheads 6 and 8. We see from Fig. 9a that a connected network has been formed. Next, we examine how the network restructures itself in response to three jammers and the loss of what appears to be a key node, i.e., node 1.

The links that make up the network structure shown in Fig. 9a and which are lost when jamming occurs and node 1 is disabled are shown in Fig. 9b as dashed lines. However, as this figure shows, upon reorganization a new network structure is formed that avoids the use of any of the failed links. For example, with the exception of node 14, all the nodes that formerly had node 1 as their clusterhead now belong to the cluster with clusterhead 2. Node 14 now joins the cluster with clusterhead 6, and node 12 becomes a clusterhead—but without any other cluster members. Clusterheads 2 and 8 are connected by a new gateway relay node 11. Node 15 also becomes a gateway, conveniently linking heads: 5 and 12, 2 and 12, 4 and 12, and 2 and 4. Gateway node 13 provides the linkage between the new clusterhead 2 and clusterhead 5. Two hops are now required for head 6 to reach the nearest clusterhead, i.e., node 2, and nodes 3 and 14 both become gateways to provide this linkage. However, despite the loss of many links, the network remains connected. In general, if bidirectional links exist that permit the formation of a connected network, the linked cluster algorithm will in fact discover such links and produce a connected network structure.

Jamming at 5 MHz and 30 MHz

The previous examples demonstrate the ability of the network to combat jamming and node loss by periodically reorganizing. Now we examine the benefits of establishing backbone networks in more
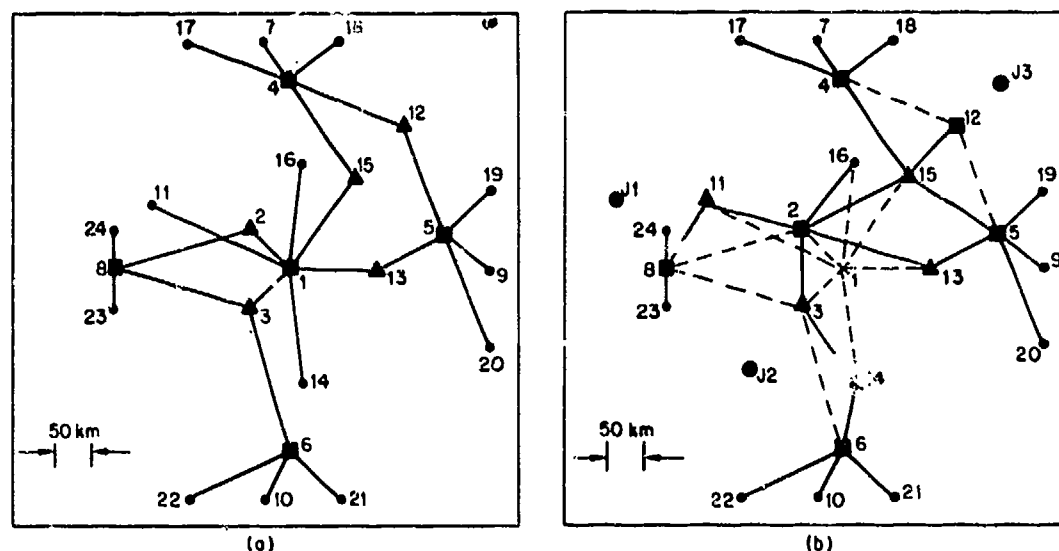
Fig. 9 — Example of a network restructuring itself to combat three jammers
(J1, J2, and J3) and loss of a central node (10 MHz wideband)

than one HF subband, and we compare results for both narrowband and spread spectrum (wideband) signaling schemes. Again we consider the 24-node network of the previous example, but this time the network performs periodic reorganizations at 3 MHz and at 30 MHz. We chose these frequencies because they represent communication range extremes in Fig. 4.

For the case of no jamming, a 2400 bps information rate, and operating frequencies of 3 and 30 MHz, the results of running the LCA are shown in frames (a) and (b) of Fig. 10. As one would expect, fewer hops are needed to form most communication paths in the 3 MHz network than in the 30 MHz net. Figures 10a and 10b corroborate this. The reason is that the communication range is generally much greater at 3 MHz than at 30 MHz (500 km vs 160 km in our model).

However, the advantage of operating a network at 3 MHz rather than at 30 MHz is not so apparent for the case of wideband signaling and the three-jammer scenario shown in Figs. 10c and 10d. Comparison with the case of no jamming reveals that considerable restructuring of the network has occurred at 3 MHz; additional clusterheads have appeared at nodes 7, 8, 10, and 12, and nodes 2, 5, 6, and 15 are now gateways. Gateway node 2 links heads 1 and 7, 1 and 8, and 7 and 8; gateway nodes 5, 6, and 15 link heads 1 and 12, 1 and 10 and 7 and 12, respectively. In contrast, at 30 MHz, only the role of node 18 has changed from that of gateway to ordinary node. Our example shows that at the lower frequency there are still fewer relays needed than at the higher frequency; however, the network remains connected at both frequencies, despite the jamming.

On the other hand, for the case of the narrowband system, relying exclusively on the low frequency portion of the HF band could be disastrous in this scenario, as Fig. 10e clearly shows. For the narrowband case and at 3 MHz, the network is almost totally disconnected; only a single bidirectional link remains, connecting nodes 4 and 7. To understand what is happening in Fig. 10e, consider J/S at nodes 4 and 17 arising from a transmission from node 7 and jamming from J1 and J3. Since J/S must be less than -7 dB to meet our data communication requirements of BER $= 10^{-5}$ at 2400 bps (-4 dB for $(J/S)_{max}$ and -3 dB for system losses), and since we have assumed that the jammer has a 10 dB power advantage, the propagation loss experienced by the jammer's signal must be at least 17 dB
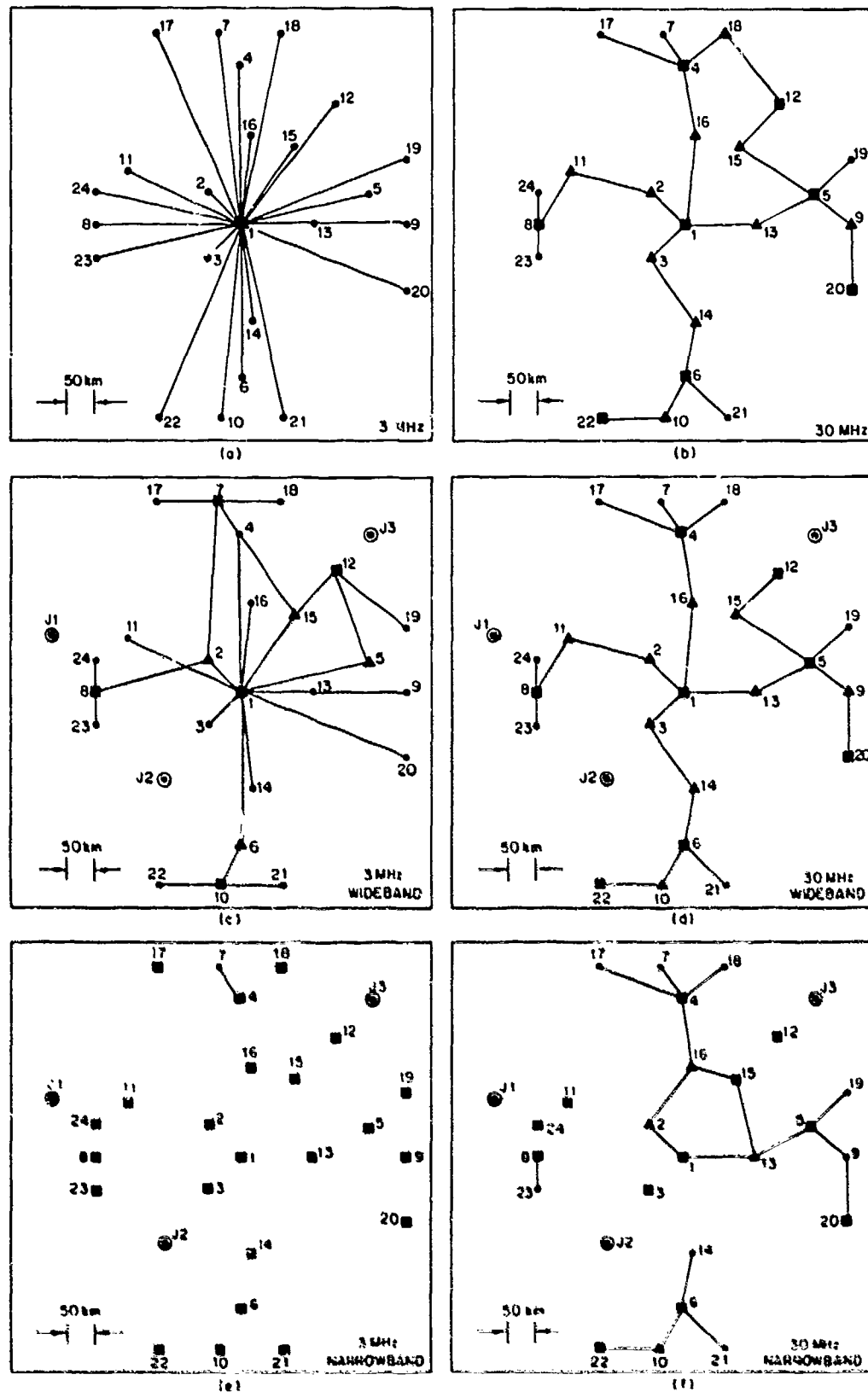
Fig. 10 — Example of a network restructuring itself at two frequencies and for two signaling schemes in response to interference from three jammers (J1, J2, and J3)

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greater than that experienced by the desired signal to maintain a link. For example, at 3 MHz, the path losses obtained from Fig. 3 are as follows:

node 7 to node 4:	73.3 dB,
J3 to node 4:	90.4 dB,
node 7 to node 17:	78.6 dB, and
J1 to node 17:	95.0 dB.

Thus, at node 4 the jamming signal experiences an additional path loss of 17.1 dB relative to the signal from node 7, whereas at node 17 the jamming signal is reduced by only 16.4 dB relative to the signal from node 7. Since the jamming signal must be reduced by at least 17 dB, the jammer is successful in breaking link (17 to 4) but not link (7 to 4).

However, the results are not nearly so bleak at 30 MHz. At 30 MHz, the corresponding path losses are:

node 7 to node 4:	128 dB,
J3 to node 4:	182 dB,
node 7 to node 17:	144 dB, and
J1 to node 17:	199 dB.

These values give additional reductions of the jamming interference relative to the signal level of 54 dB at node 4 and 55 dB at node 17. Therefore, at 30 MHz neither link (7 to 4) nor (7 to 17) is lost because of jamming. In fact, considerable connectivity remains at 30 MHz for this scenario, as shown in Fig. 10f.

Whether it is better to use frequencies in the upper or lower portion of the HF band depends on the sign of the quantity

$$(J/S)_{max} - L_a - \text{(jammer's transmitted power advantage)},$$

where all quantities are expressed in decibel units. If this quantity is positive (e.g., in the case of spread spectrum signaling), it represents the amount that the jamming interference must be increased (relative to the desired signal) at the receiver before a link can be successfully jammed. Since, as Fig. 3 shows, the rate of propagation loss increases with increasing frequency, operating the network in the lower portion of the HF band would necessitate the jammer penetrating farthest into the task force. On the other hand, if this quantity is negative (e.g., in the case of narrowband signaling), it represents the amount the desired signal must be increased (relative to the jamming interference) at the receiver to prevent successful jamming of a link. In the latter case, it is better to operate the network at the higher frequencies to make maximum use of any range advantage that the task force nodes might have over the jammer.

All of our examples are for the case when the transmitters are at the earth's surface. If, for example, the jammer were a high-flying aircraft, the propagation loss curves would differ significantly from those shown in Fig. 3, and our comments regarding the advantage of using high vs low frequencies would not apply. (However, it would be difficult for an aircraft-mounted HF transmitter to radiate 10 kW of vertically polarized interference.) Also, if network connectivities can be maintained at the lower frequencies even in the presence of jamming, there are advantages to be gained by using the lower frequencies, for example, a reduced need for relaying. Consequently, in an HF intratask force network, it is likely to be advantageous to use multiple backbone networks, which are formed at both high and low frequencies in the HF band.

5. CONCLUSIONS

We have shown how networking can be used to enhance the antijamming performance of a naval intratask force HF communication system. To reap the full benefits of using relaying to combat jamming, we use a network architecture that provides for the automated selection of relay nodes and the

linking of these nodes to form a backbone network. The network self-organizes without the need for a central controller, and the reorganization process is repeated periodically; thus, the network can adapt to a changing jamming threat.

We have given examples to show how such an intratask force network adaptively restructures itself in response to mobile jamming threats typifying large, shipborne jammers and for cases of both narrowband and wideband signaling. To achieve these results, we developed realistic groundwave propagation and atmospheric noise models, and we derived communication range curves for the case of jamming of both narrowband and wideband systems. We showed that when the quantity

$$(J/S)_{max} - L_a - \text{(jammer's transmitted power advantage)}$$

is positive (e.g., for wideband signaling), using frequencies in the lower portion of the HF band provides greater protection against shipborne jammers, whereas when this quantity is negative (e.g., for narrowband signaling), the use of frequencies in the upper portion of the HF band is preferred.

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