USE OF ALE AND PACKET RADIO FOR HF NETWORKS

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Abstract

Considerable interest in HF networking has been generated by recent advances in Automatic Link Establishment (ALE) and packet radio techniques.

This paper includes a brief description of current ALE and packet radio techniques. ALE integrates selective calling, automatic linking, and link quality analysis to provide reliable "telephone-like" service for HF voice and data users. Standardization and federal acceptance have recently been accomplished through the release of MIL-STD-188-141A and FED-STD-1045. In contrast, packet radio has evolved from line-of-sight applications, and its use on HF links has been pioneered by the amateur radio community.

The focus of this paper is the use of packet radio and MIL-STD-188-141A techniques in HF networks. Many of the shortcomings of existing fixed channel HF packet radio systems can be overcome by the use the robust ALE waveform described in the MIL-STD. The network related aspects of the standard are highlighted. Receive scan and selective call are shown to be effective tools for contacting both individual and multiple network members. Design examples are given for the configuration and interconnection of network participants. Packet structures are described which will support higher level network functions, such as internetting, routing, and store-and-forward switching. The areas currently under consideration for standardization in the higher level FED-STD-104X documents are discussed.

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1. INTRODUCTION

Traditionally, high levels of operator skill have been required to obtain satisfactory HF communications because of the variability of the propagation and the congested channel conditions. Reliable automatic frequency selection and link establishment procedures have recently been developed which can effectively automate these tasks. Two new standards have been released, MIL-STD-188-141A and FED-STD-1045, which describe a robust interoperable waveform for Automatic Link Establishment (ALE) and Link Quality Analysis (LQA). These standards are the basis for a new generation of adaptive HF radio systems, such as the Harris RF-7200 Autolink II, which make HF reliable and easy to use.

Now that these standards are established, further improvements can be foreseen by the application of networking techniques to HF systems. The potential benefits of networking include greater connectivity, improved reliability, and more efficient use of frequencies.

Much of the current interest in HF networking has developed as an extension of well established line-of-sight packet radio technology. However, HF networks have very different characteristics to their line-of-sight counterparts and in many respects require the use of different techniques. In particular, the use of automatic frequency management and link establishment techniques is considered essential for reliable network operation.

This paper examines the use of the new ALE standards and packet radio techniques in HF networks.

2. HF NETWORK PHILOSOPHY

2.1 General

In comparison with other forms of transmission, the capacity of an HF link is limited. It can vary from a few bits per second up to 2400 bits per second depending upon the channel conditions. Networking significantly reduces this capacity because of the overhead introduced by the network protocol and the need to forward traffic. Therefore, the real requirements and motivation for HF

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networking need to be understood.

One important reason for considering HF networking is to enhance connectivity. Direct communications may not always be possible between all of the stations in a network due to a combination of propagation and frequency allocation constraints. Networking provides a means of obtaining full logical connectivity by relaying messages or parts of messages (packets) through intermediate stations which are able to communicate directly with one another.

Networking can also provide a number of performance enhancements. It can be used to circumvent link outages and in some circumstances it can be used to select routes which have higher capacities than direct point-to-point connections.

However, the use of networking should be minimized because of the limited HF channel capacity. The facility for networking can usefully be provided to overcome situations where communications would otherwise not be possible but maximum advantage should always be taken of the inherent characteristics of HF propagation. The fact that HF signals can propagate over large distances should be used wherever possible for direct point-to-point communications, and the ability of an HF signal to be received simultaneously by a number of stations should be exploited for multi-point communications.

2.2 Network Frequency Requirements

A critical requirement for any network is that it is connected. Any station must be able to communicate with any other station, either directly or via one or more intermediate stations. The connectivity of an HF network is determined by a combination of factors; the operating frequencies of the stations, the prevailing propagation conditions, and the effects of co-channel interference. These factors can vary unpredictably and they create fundamental difficulties with the management of a network.

The operating frequencies of the stations are possibly the most important parameters that must be selected. They must follow the diurnal variations in the propagation conditions and they may require frequent changing to avoid co-channel interference. Their influence on network connectivity is discussed below.

The usable frequency range of an HF link lies between the MUF (Maximum Usable Frequency), which is the highest frequency returned by the ionosphere, and the LUF (Lowest Usable Frequency), which is the lowest frequency providing the required signal-to-noise ratio. Both the MUF and the LUF exhibit large diurnal variations. They also depend upon path length, geographical location, season, solar activity, and various system parameters.

The dependence of the usable frequency range on path length is a significant factor in the design of an HF network. Figure 1 shows the results of an analysis to investigate this dependence using the IONCAP propagation prediction program. The time of year and the orientation of the path have been chosen to show the most significant variations in the MUF and LUF.

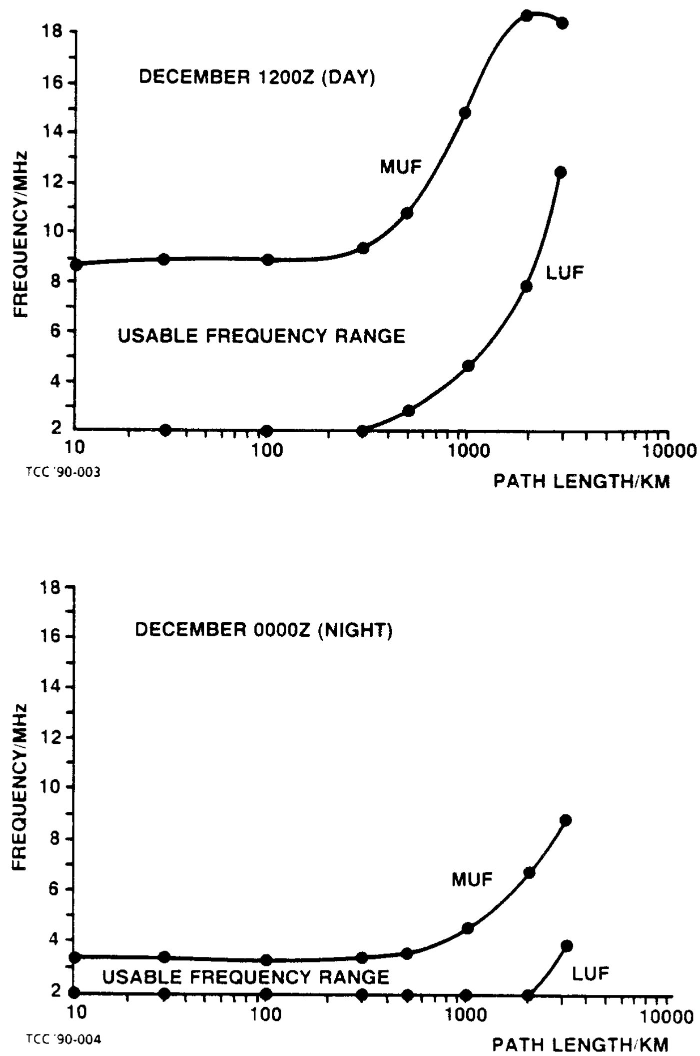

Figure 1. Variation of usable frequency range with distance

It is possible to choose operating frequencies that will yield a fully connected network if the network is confined to an area less than 1000 km in diameter, as shown in Figures 2(a) and 2(b). In some circumstances, a connected network can still be produced if the operating frequency is above the MUFs of some of the shorter paths. This situation is shown in Figure 2(c). However, if the operating frequency is too high a fragmented network will result, as shown in Figure 2(d), and communications will be lost with some stations.

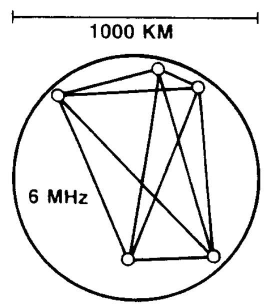

Fig. 2(a) Fully connected network (day)

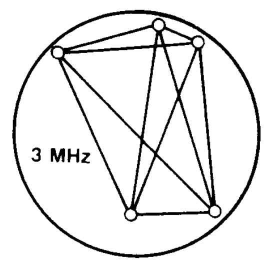

Fig. 2(b) Fully connected network (night)

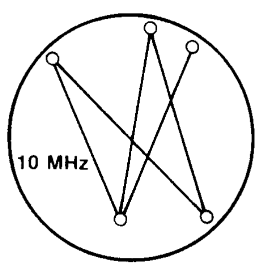

Fig. 2(c) Connected network

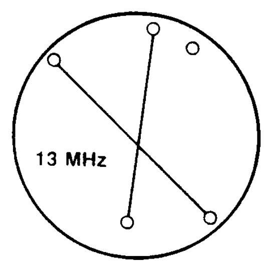

Fig. 2(d) Fragmented network

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Figure 2. HF Network Connectivities

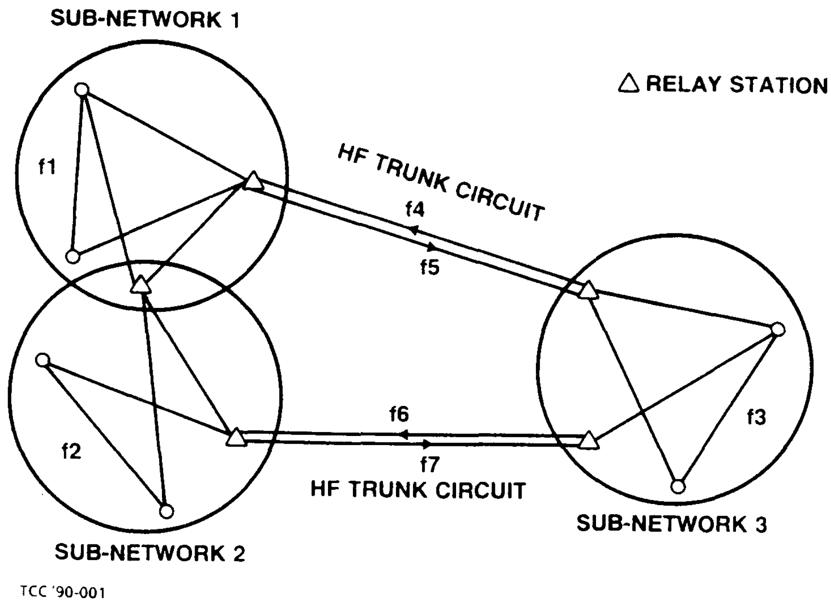

Figure 3. Linked-Cluster Network

Larger networks require the use of several operating frequencies for the various links in the network. Although, it is possible that a common operating frequency can be found for networks considerably larger than those described above (1000 km in diameter), such networks are usually not viable at all times of the day, the year, and throughout the solar cycle. It is necessary to divide larger networks into a number of smaller connected sub-networks ("clusters"), each one operating on its own frequency. The sub-networks are connected by separate point-to-point HF circuits ("links") and relay stations. This type of "linked-cluster" network is shown in Figure 3.

Automatic frequency management is essential for the reliable operation of HF networks. The manner in which frequency management is accomplished depends upon the way in which the network is operated.

2.3 <u>Network Operation</u>

Networks may be operated in a variety of different ways. Appropriate to HF usage, are star, mesh, and store-and-forward operation.

2.3.1 <u>Star Network Operation</u>

A star network is established in such a

way that it is capable of real-time forwarding of traffic between a master station and a number of slave stations which do not necessarily link directly together. All traffic is forwarded through the master station.

Selecting the network operating frequency and establishing the various link connections can be performed automatically using the FED-STD-1045 star net call procedure, described in section 3.1.2.

The star network is most suited to applications with a limited number of stations because of the volume of traffic forwarded by the master station. The network is vulnerable to a failure of the master station but in normal operation it is capable of high reliability since its connectivity is well defined and it is responsive to rapidly changing channel conditions.

2.3.2 Mesh Network Operation

In a mesh network, stations are linked together by whatever propagation exists between them. Forwarding occurs in real-time between connected stations. The degree to which the network is connected depends upon the propagation conditions and the choice of operating frequencies. The connectivity is normally greater than that of a star network but it is less well-defined and network management is more complicated.

For small geographical areas, up to 1000 km in diameter, it is possible to envisage a connected network operating on a single frequency. In this case, the FED-STD-1045 star net call procedure is likely to indirectly yield a highly connected mesh network and is an ideal means of setting up the network.

As the network size increases, the star net call link set-up procedure is less likely to result in a well connected mesh network. More complicated frequency selection and link establishment procedures involving the proposed FED-STD-1046 group calls and connectivity exchanges are required to set the network up on the best frequency and determine the resulting connectivity.

Ultimately, single frequency operation of a large network is not possible and it must be divided into smaller sub-networks, of the "Linked-Cluster" type. Frequency selection and link establishment is performed independently in each of the sub-networks.

2.3.3 Store-and-Forward Operation

To some extent, the difficulties of maintaining HF network connectivity can be mitigated by the use of store-and-forward techniques. If a network is fragmented due to propagation or co-channel interference, traffic can be stored at the stations until the required connectivity is available.

Networks of this type tend to exhibit long delays (of the order of 12 hours) in delivering traffic because of the relatively slow changes that occur in propagation conditions. However, global coverage can be achieved with a modest number of stations.

Each link can be established as required by conventional automatic link establishment (ALE) techniques. The lack of coordination between the stations means that this type of operation is only suitable for low traffic densities. Higher traffic loads require centralized network frequency management or time synchronized operation of the stations.

3. NETWORKING WITH THE FEDERAL STANDARDS

3.1 Networking with FED-STD-1045

FED-STD-1045 has four useful tools for HF networking:

1. Receive channel scan
2. Individual and Net Calls
3. Link quality analysis (LQA)
4. Orderwire Messages

The first three items deal with link establishment and are discussed below. The fourth item, orderwire, deals with data exchanges and is covered later in Section 4.1.

3.1.1. Receive Channel Scan

The default condition of the ALE controller is receive scan. Channels are examined for incoming calls and LQAs. FED-STD-1045 requires scan rates of five and two channels per second, with a design objective of ten channels per second. The faster scan rates can either be used to oversample incoming signals or allow incoming calls to have shorter stop scan portions.

3.1.2 Individual and Star Net Calls

The individual call is used to form a point-to-point link between two units. A three part handshake is used, consisting of a "call", "response" and "acknowledgement". The call stops the scan of the target unit (by identifying him specifically) and identifies the caller. The response by the target notifies the caller that the call message was received. The acknowledgement by the caller confirms reception of the response and finalizes the link. The link is then available for voice or data traffic.

The star net call establishes a link between the calling node and all other net members. The protocol is similar to the individual call, except responses come back from the net members in time slotted fashion. The net is a prearranged grouping of individuals with a common net address and knowledge of net parameters (like the connect time slot in which to respond). The star net call is ideal for establishing conference calls, making broadcasts or performing roll call functions.

3.1.3 Link Quality Analysis

ALE controllers can link effectively and quickly on the best available HF frequency, only if accurate and timely link quality analysis (LQA) techniques are employed. LQA consists of three basic components:

1. Transmitting on-air signals so that distant units have the opportunity to evaluate unilateral (or "one-way") paths.

2. Measurement by ALE controllers of receive signal quality.

3. Transmitting (or reporting) measured scores so that other ALE controllers can tell how well their transmissions were received (required for bilateral or "two-way" scoring).

FED-STD-1045 performs the above functions through the use of three types of on-air exchanges; sounding, LQA exchange and star net LQA. Examples of these exchanges are shown in Figures 4 and 5. Sounding is a beacon-like transmission on one or more frequencies, allowing distant stations to measure unilateral path quality. The LQA exchange is a three transmission

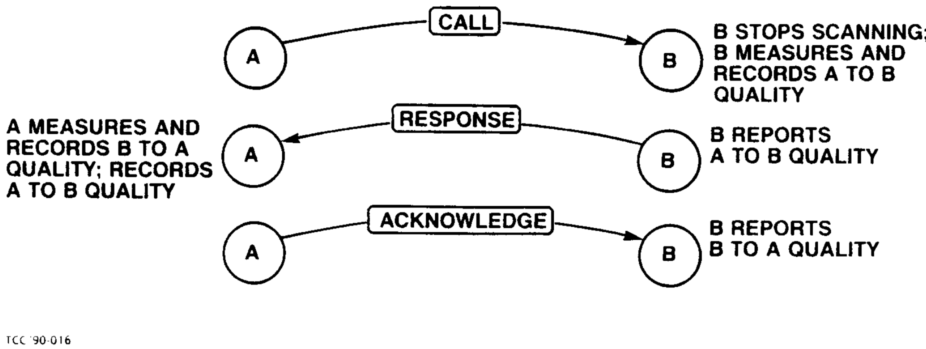

Figure 4. Individual LQA Exchange

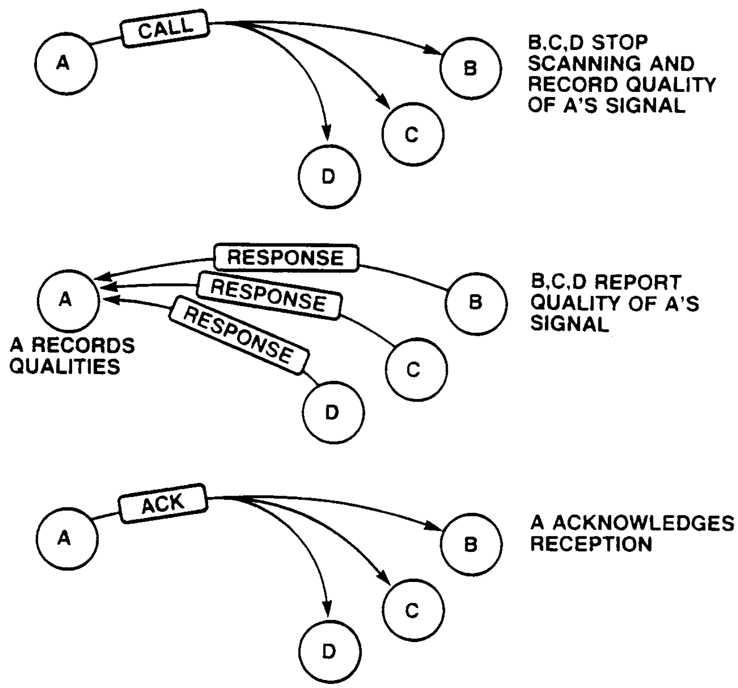

Figure 5. Star Net/Group LQA

Table 1. Summary of Scoring

LQA TYPE	UNILATERAL SCORING	BILATERAL SCORING
Sounding	At all but sounder	None
LQA Exchange	At eavesdroppers	At two participants
Star Net LQA	At all but initiator	At initiator

exchange which causes both of the two units involved to measure and report (to the other) the link quality. The star net LQA is initiated by a transmission from the "center" of the star topology and causes each of the outer stations of the net to respond in a time slotted manner, reporting how well the "center" was received.

A design example will emphasize the relative merits of these techniques. Assume for this simple example that the ALE nodes are only interested in the unilateral link quality with their one hop neighbors. Each node has an LQA table similar to the one at Node 1, shown in Figure 6 below:

LINK QUALITY WITH NODE...

	2	3	4	...	N
Channel 1	Score	Score	Score	...	Score
Channel 2	Score	Score	Score	...	Score
:	:	:	:	...	:
Channel C	Score	Score	Score	...	Score

Figure 6. Node 1 LQA Table

Table 2. LQA Times

LQA TEST METHOD	NUMBER OF TESTS PERFORMED		SECONDS PER CHANNEL		NUMBER OF CHANNELS	MINUTES FOR C=10 CHANNELS N=10 NODES
Sounding	N	x	.784C+2.78	x	C = NC(.784C+2.78)	17.7
LQA Exchange	N/2	x	.784C+6.70	x	C = NC(.392C+3.35)	12.1
Star Net	1	x	.784C+2.22N+7.36	x	C = C(.784C+2.22N+7.36)	6.2

Each node needs (N-1)C scores to fill its table and the entire network has n(N-1)C scores. For a 10 node, 10 channel example, this implies 900 scores. Table 2 above compares the use of different LQA methods to fill the entire network's tables.

These approximate time calculations assume three (or less) characters per address, two seconds to check for a clear channel and tune, a dwell time per channel of .784 seconds and that all units eavesdrop on transmissions whenever possible. The times above can be cut in half if the network's scan rate is five channels per second and the scan call time is reduced to one scan period. However, this will also reduce the probability of linking due to the reduced time allowed for signal detection.

With this simple example, LQA times are bearable. The next level of sophistication would be to desire bilateral scores between all one hop neighbors or collection of scores for two hop neighbors (i.e., neighbors neighbors). Either of these goals could be accomplished by initiating LQA exchanges on every link or having each node initiate a star net LQA. In the LQA exchange case, the number of LQAs jumps from N/2 to N(N-1)/2, and with 10 nodes and 10 frequencies, this would take about 109 minutes. Note that all the LQAs must be done sequentially so all nodes can eavesdrop. In the star net case, the number jumps from one to N, which would now take 62 minutes in the example. Even with a faster scan rate cutting the times in half, this is still unacceptable. The only hope for the network would be to reduce the number of frequencies (which reduces connectivity and reliability), breaking the network into smaller clusters (reducing one hope connectivity) or backing down on the need to know global network LQA data.

Here are four practical rules for using the LQA protocols:

1. Use sounding only at unsophisticated nodes which cannot support LQA exchanges or star net LQAs.

2. Use star net LQAs whenever possible due to their time efficiency. The initiator must be well heard by others because participation depends on it.

3. Use LQA exchanges only to fill in gaps

in the LQA table or where bilateral scores are required.

4. Eavesdrop whenever possible, and do not perform a test if recent scores exist.

3.2 Networking with FED-STD-1046

The intent of FED-STD-1046 is to standardize "HF Radio Automatic Networking". The standard is currently being drafted by the U.S. government, so its contents are not yet public. However, certain ALE techniques of great use in HF networking are anticipated to be in the standard:

1. Star Group Calls and LQAs (MIL-STD-188-141A, paragraph 70.6.3)

2. Polling

3. Connectivity Exchange

4. Message Relay

5. Engineering Orderwire (see MIL-STD-188-141A, paragraph 80.3-80.5)

The sections below describe the first four techniques to the author's best ability. Because the standard is under development, the descriptions should by no means be considered absolute or final. The fifth technique, engineering orderwire, is covered in Section 4.1.

3.2.1 Star Group Calls and LQAs

Star group calls and LQAs are very similar to star net calls and LQAs except that a group is a nonprearranged set of individuals (recall that a net is prearranged). As with a star net call, the star group call is basically composed of three portions: the call by the initiator, responses from those called and an acknowledgement by the initiator. Unlike the star net call, which uses a net callsign to address those called, the star group call must include the address of each of the individuals in the group. The individuals being called use the sequence of the transmitted individual addresses to derive the order in which they should send responses. Group sizes will probably be limited to five to twelve addresses.

When judged on efficiency in gathering LQA information, the star group LQA can be faster or slower than a net LQA, depending on the make up of the group. If the group and the net have the same number of members, the group exchanges take a little longer than the net exchanges, due to the need to include all of the group individual addresses. On the other hand, group testing can go faster than the net if the group call is selective in which nodes get tested and, thereby, fewer individuals than are in the net. As it was seen in the Section 3.1.3 ten node/ten channel example, times are excessive if LQA is performed on all links just for completeness. The star group LQA is an efficient tool for gathering just the information which is needed.

3.2.2 Polling

When the polling command is used within the link establishment protocol, the caller can extract LQA data from another network node. The called node responds with a list of channels, and associated LQA scores, for those channels which propagate between the two units. The polling technique is ideal for retrieving data from neighbors, in cases where the data has been lost at the local node. Another use is for retrieving data to allow the local node to supplement its unilateral scores with data suitable for creation of bilateral scores. An example of polling is shown in Figure 7.

3.2.3 Connectivity Exchange

The connectivity command allows a calling node to ask the question: "With which nodes can you connect and how good are the connections?" The called unit responds with information (addresses and LQA scores) for both one hop and multi-hop connections. The data is very useful for establishing a routing table on the fly without having to initiate any LQA tests. An example of a connectivity exchange is shown in Figure 8.

3.2.4 Message Relay

This calling protocol allows the initiator of a message to specify the destination of a message and the intermediate nodes (or hops) through which the message is expected to pass. Once this information is transmitted by the initiator in the call portion of the exchange, the identified nodes send time slotted responses (similar to star group call) which report their ability to pass the message along to the final destination. The initiator then selects the most advantageous node and passes the message to it. As a message is passed along, the relaying nodes attach their address to the message so that the routing history of the message is recorded. An example of the message relay procedure is shown in Figure 9.

3.3 Higher Level Federal Standards

There are currently plans for three more federal standards relating to HF standardization. They are listed below for completeness, but are beyond the scope of this paper.

- o FED-STD-1047 HF Radio Automatic Message Store and Forward
- o FED-STD-1048 HF Radio Automatic Networking to Multimedia
- o FED-STD-1049 HF Radio Automatic Operation in Stressed Environments
    - o Section 1 Link Protection
    - o Section 2 Anti-Interference
    - o Section 3 Encryption
    - o Section 4 Other Functions

3.4 Application of FED-STD Techniques

The FED-STD networking tools described in the preceding sections offer the HF network designer a great deal of flexibility in establishing communication links and gathering LQA information. The primary concern of those involved with the use of FED-STD ALE is the proper balance between communication link establishment and LQA. The examples presented in Section 3.1.3 showed that time spent gathering LQA data can grow to the point where there is no time left for communication.

The keys to gathering LQA data without compromising communication time are to take advantage of passive, efficient and custom techniques:

- o Monitor and record all LQAs and calls encountered, not just the ones to the local node. Use on-air traffic to fill out the LQA and connectivity matrix at no cost.
- o Piggyback LQA and connectivity data on other communication exchanges to avoid the need for multiple link establishments.

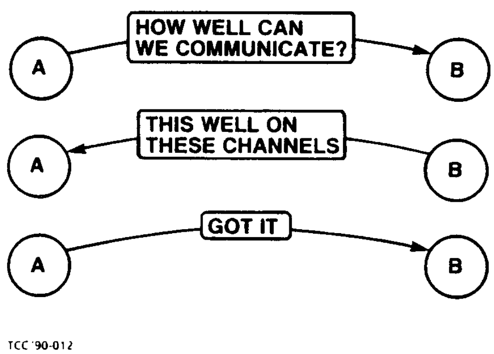

Figure 7. Polling

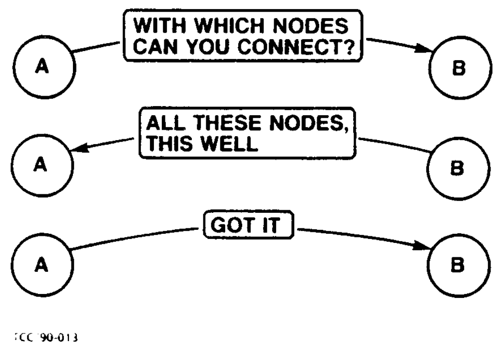

Figure 8. Connectivity Exchange

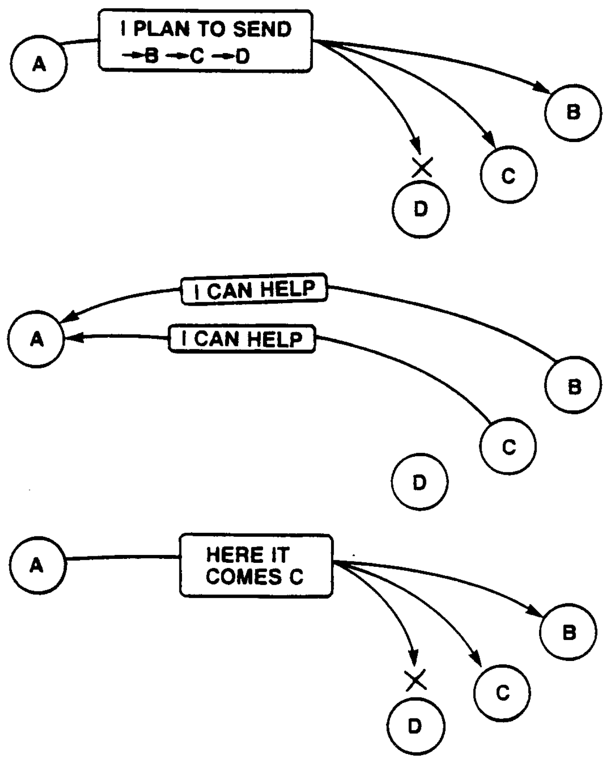

Figure 9. Message Relay

- o Record the routing history appended during the message relay process and fill out routing tables at no cost.

- o Gather and maintain LQA and connectivity data only for those nodes which are regular contacts and request infrequently needed data from neighbors on an as needed basis. Use selective techniques like star group LQAs.

- o Take advantage of the flexibility of the FED-STD protocols to create faster, custom LQA techniques which could then become part of the standard.

4.0 DATA TRANSMISSION TECHNIQUES

Once a link has been established on the best available HF channel, the HF user has a number of methods to pass data to one or more nodes. The sections below focus on four of those techniques; namely:

- o The Engineering Orderwire capability of FED-STD-1045/1046

- o The MIL-STD-188-110 Change Notice 2 (CN2) Modem

- o Commercially available HF packet radio controllers (AX.25)

4.1 FED-STD-1045/46 EOW

The only mandatory order wire capability in FED-STD-1045 is automatic message display (AMD). This protocol allows short (less than 90 characters) ASCII messages to be transmitted between ALE controllers, displayed on the controller's front panel, and saved. Messages can be input from the controller front panel or attached DTE depending on implementation.

It is anticipated the FED-STD-1046 will require the use of the data text message (DTM) and data block message (DBM) for orderwire. Both of these techniques are described in detail in FED-STD-1045, but appear to be optional. The DTM allows ASCII or binary data messages thousands of characters long to be communicated in a format similar to the ALE protocol. The DBM is similar to the DTM, but allows longer messages and uses deeply interleaved blocks. Both modes typically use an attached DTE for message input and display and have the capability of working in constant transmission or ARQ mode. Throughput will tend to be in the tens of bits per second.

All of the FED-STD-1045/1046 orderwire messages use the same internal 8-ary FSK modem and error correction techniques as are used in link establishment.

4.2 MIL-STD-188-110 CN2 Modem

The modem uses two, four and eight-ary PSK modulation, channel equalization, interleaving and convolutional coding to produce an extremely robust data waveform. The modem can be operated in negative SNRs (3kHz noise bandwidth), even with five milliseconds of multipath at the 75 bps rate. Throughput rates of 75, 150, 300, 600, 1200 and 2400 bps can be selected. Some modems, such as the Harris RF-5254C, allow uncoded throughputs of 4800 bps. One very advantageous feature is automatic bit rate selection at the receive site, based on the bit rate of the incoming signal. This allows adaptive bit rate techniques to be used without coordination at the receive site.

The MIL-STD-188-110 CN2 waveform is optimized for message transmission and it is not suitable for packet or burst operation because of the long synchronization preamble that must accompany each transmission. The related NATO STANAG 4285 waveform is, however, suitable for packet transmission and is provided in the Harris RF-5254C modem.

4.3 HF Packet Controllers (AX.25)

The amateur radio community has developed a packet radio protocol called AX.25. This protocol closely resembles the CCITT X.25 data link layer protocol, except that the address fields have been expanded to accommodate the amateur callsigns and every packet contains complete data link address information. The protocol also contains facilities for explicit routing through specified intermediaries.

The transmission standard for HF use is 2 FSK (200 Hz frequency shift) sent at a rate of 300 baud. This type of modulation provides very little tolerance to multipath and satisfactory performance can only be expected on channels exhibiting less than 1ms multipath spread. Since, the maximum multipath spread is a function of path length, with greater multipath spreads occurring at shorter ranges, satisfactory results are generally only obtained on long distance links.

Channel access is controlled by a simple signal detection scheme (energy based) in conjunction with an exponentially weighted re-try counter to avoid collisions.

The transmitted packets are delineated by 8-bit flag bytes. Full addressing information, control data, and a 16-bit CRC error check are sent with every packet. Only error-free packets are accepted by the receiving equipment. However, HF channels are often characterized by medium/high densities of errors and some form of forward error correction coding (FEC) is needed to avoid having to frequently re-transmit packets.

An important feature of AX.25 is that it provides similar data link layer services as X.25 and a wide variety of higher level protocols, such as TCP/IP, can be readily transmitted over it.

The daily operation of many thousands of amateur packet radio stations provides valuable information for the design of HF packet networks. To date, the most significant observations are:

- o greater multipath protection is required for the operation of short/medium range links.
- o a more robust packet structure is required for HF operation.
- o FEC is needed to improve efficiency under medium/high error rate conditions.
- o robust modem and frame sync preambles/postambles are required for operation on poor channels.
- o stop-and-wait ARQ protocols offer higher efficiencies than the sliding-window ARQ protocol used in AX.25.
- o short packets (less than 3 seconds long) are required for effective sharing of channels.
- o signal fading and co-channel interference render simple channel access schemes based on energy

detection ineffective. More complex approaches using preamble recognition are needed.

5. SUMMARY

HF packet radio networks promise unrestricted connectivity, enhanced reliability, and support for new forms of data communications. The performance of such networks depends critically upon the validity of the network designs, effective frequency management, and the use of reliable methods of data transmission.

Networks must be designed so that their connectivity can be maintained over a wide range of propagation and interference conditions. A detailed propagation analysis is an essential part of the design of any network that spans distances in excess of 1000 miles.

The recently approved FED-STD-1045 and MIL-STD-188-141A automatic link establishment standards are ideal building blocks for developing effective network frequency management procedures. However, consideration must be given to ways of reducing the transmission time for the LQA and connectivity exchanges.

There is a real need for a robust HF packet radio protocol. Existing and planned FED-STDs do not address this requirement and the current AX.25 standard is not robust enough for general application.

However, AX.25 has proved to be a remarkably flexible protocol and it has been used in a wide variety of applications. The functionality provided by AX.25 appears to be an ideal model for a more robust protocol to follow.