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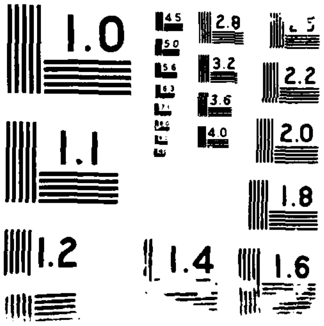
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NAVAL POSTGRADUATE SCHOOL

Monterey, California

THESIS

LONG HAUL COMMUNICATIONS
IN THE HF SPECTRUM
UTILIZING HIGH SPEED MODEMS

by

Robert H. Ellis

March 1988

Thesis Advisor: M.H. Hoever

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In the past ten years reliable high-speed satellite systems have pushed slower less reliable communication systems to the bottom of the list for development programs. Concern over reduced budgets, vulnerability of expensive satellite systems, and recent advances in HF technology are creating new interest in upgrading existing HF communication systems.

Nondevelopment Items (NDI) are defined as the use of off-the-shelf commercial items instead of costly, time-consuming conventional research and development programs. The Navy Department's current policies are designed to insure the maximum use of NDI to fulfull Navy requirements.

The speed of HF systems can be improved using current signaling and modulation techniques, and reliability can be increased by error-correcting codes or error detection used in conjunction with automatic repeat request (ARQ) schemes. Improved HF systems not only provide survivable back-up capability, but increased capacity for present communication needs.

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Long Haul Communications in the HF Spectrum Utilizing High Speed Modems

by

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Lieutenant, United States Navy
B.S., University of Washington, 1978

submitted in partial fulfillment of the
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In the past ten years reliable high-speed satellite systems have pushed slower less reliable HF communication systems to the bottom of the list for development programs. Concern over reduced budgets, vulnerability of expensive satellite systems, and recent advances in HF technology are creating new interest in upgrading existing HF communication systems.

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I. INTRODUCTION

A. PURPOSE

This thesis examines the environmental effects and proposed techniques impacting multi-channel high-speed communications in the HF spectrum (2 - 30Mhz). Primary emphasis will be the examination of the environmental effects which impact multi-channel high-speed communications in the HF spectrum. Secondary emphasis will be the examination of nondevelopmental items (NDI), or off-the-shelf modems, which are available to upgrade current long haul HF systems.

B. RESEARCH QUESTIONS

Can currently available technology in high-speed modems for HF communications provide enhanced flexibility, redundancy, and robustness necessary to augment and back up satellite circuits? Can we improve HF communication speed and reliability to the required level today with currently available modems or is further development required? Additional questions to be discussed in this thesis include:

- What are the strengths and weaknesses of the HF spectrum?
- How does multipath propagation of the HF signal [i.e., sky wave and direct path] affect the error rates associated with high-speed modems?
- What types of data rates and propagation losses are evident when utilizing currently available high-speed modems?
- What modem techniques offer improved performance for present day and future HF communication systems?
- What are the advantages and disadvantages of serial vs parallel modem techniques?
- Do current high-speed modem techniques provide resistance to jamming?

C. SCOPE OF THESIS

This thesis does not attempt to solve the problems associated with high-speed HF, but rather attempts to familiarize the communication planners and managers with the characteristics of the HF spectrum, the current advances and available techniques in high-speed HF communications.

II. NONDEVELOPMENTAL ITEMS (NDI)

Before a communication planner and manager begins the acquisition process for new and improved equipment, he must understand the purpose and necessity of NDI. In this chapter NDI, its history, current DOD policies and its suitability for HF systems improvement, are presented.

A. DEFINITION

Nondevelopmental Items (NDI) are defined as hardware or software material available which require little or no government research and development. These include:

- Items commercially available.
- Items previously developed and in use by the Navy, other military services, or foreign military services/government.
- Items currently being produced, but not yet available commercially.
- Items available from the above sources that could be easily modified to meet acquisition requirements. [Ref. 1]

There are two primary categories of NDI: (1) off-the-shelf items - Items procured from any of the above sources and used "as is" without modification, and (2) modified off-the-shelf items - Items which require modification or augmentation to hardware or software in order to meet DOD requirements for operational use. These modifications include but are not limited to environmental protection, nuclear hardening, and military electrical power sources.

B. BACKGROUND

NDI provides three major advantages over the typical DOD research and development process:

- Research and development cost, start-up production cost, testing and evaluation time are all minimized.
- Time for delivery to the fleet is decreased substantially.
- State-of-the-art technology may be used to meet operational requirements. [Ref. 2]

Potential disadvantages of NDI include:

- Cost and performance tradeoffs may be necessary in some instances in order to utilize NDI technology.
- Integrated logistics support (ILS) programs may have to be modified to meet anticipated delivery dates for NDI.
- The use of NDI may increase the number of items that are nonstandard, not interoperable and/or incompatible with existing systems within DOD.
- Existing safety margins may be reduced when utilizing NDI not specifically built for operations in a military environment. [Ref. 2]

C. POLICY

In 1972 the Commission on Government Procurement recommended that acquisition of commercial items become the leading policy in developing new systems. Four years later, the commission's recommendation became policy at the Office of Federal Procurement Policy (OFPP). The main thrust of OFPP's policy was to have government agencies purchase commercially off-the-shelf items which would meet their requirements. OFPP also emphasized using existing commercial distribution channels for delivery of such items. Lastly, OFPP stated that performance and reliability of commercial products should be established through marketing research programs.

The U.S. Army took the lead within DOD in shifting greater priority to the use of NDI in the development of new weapon systems and subsystems. The Army published the first NDI handbook for acquisition management in the early 80's. In 1986, the Packard Commission in its final report to the President of the United States stated:

> Rather than relying on excessively rigid military specification, DOD should make greater use of components, systems, and services available 'off-the-shelf.' It should develop new or custom-made items only when it has been established that those readily available are clearly inadequate to meet military requirements. [Ref. 3]

The Defense Authorization Act for fiscal year 1987 directs DOD to state the requirements for supplies in terms of: (1) functions to be performed, (2) performance required, and (3) essential physical characteristics. These requirements must be fulfilled through the procurement of nondevelopmental items to the maximum extent possible. [Ref. 2]

In 1986 The Secretary of the Navy instituted a policy intended to make the consideration and use of nondevelopmental items (NDI) during the acquisition process the rule, not the exception.

> The procurement of NDI has been proposed for many years as a way to reduce program costs, shorten the time required to field operational equipment and reduce program risk. Although there has been considerable evidence of the benefits of procuring NDI, the Navy has not yet formulated systematic, aggressive procedures and programs for capitalizing on the use of NDI. Changing economic and political conditions, coupled with rapid technological advances in the commercial sector, dictate that the Navy explore NDI solutions and implement those solutions when it is in our best interest to do so. [Ref. 4]

D. NDI FOR HF SYSTEMS

HF communication equipment is the perfect example of where the use of NDI should be very beneficial and cost-effective. The expansion of allied and civilian markets has improved the state-of-the-art in HF equipment substantially in the last 10 years. In order to prevent a proliferation of non-standard high-speed modems in the fleet, the Secretary of Defense in 1987, placed a moratorium on purchases of such modems pending the approval of a DOD HF high-speed modem standard. It is the author's opinion that the advantages of reduced cost, timely delivery to the fleet, and state-of-the-art technology, far outweigh the interservice concerns over establishing an "official standard" for various components prior to upgrading any HF system. It seems that a closer scrutiny of HF NDI and DOD specifications is warranted.

Several Agencies have conducted test and evaluation of currently available commercial HF modems. Commands also have used discretionary funds to procure commercial modems for operational use.

III. BACKGROUND

This chapter provides a review of the history of naval HF, the characteristics of the HF medium, and how fading, multipath, noise and errors affect transmission data throughput rates. A basic understanding of these characteristics is essential before a communication planner or manager can begin to evaluate competing HF technologies when upgrading current or future HF systems.

A. BRIEF HISTORY OF NAVAL HF COMMUNICATIONS

Until the 20th century, a naval force operated in total isolation after sailing over the horizon. As a result major battles have been fought after peace treaties were signed. The early experiments of Marconi and others led the way for the development of the Navy's first truly "over-the-horizon" communication system. Until 1926, the Navy considered HF to be too unreliable and unpredictable for operational use [Ref. 5:p. 43]. The limitations on telegraphic transmission speeds and the unpredictable nature of HF propagation were recognized and documented but not fully understood. By 1932 the existence of the reflective ionized "layers" of the upper atmosphere, the ionosphere, were confirmed.

Long haul HF voice communications were well established prior to WWII, providing longer distances, wider bandwiths and lower cost systems than earlier low frequency (LF) systems. The threat of destruction posed by war to trans-Atlantic cable circuits provided the necessary emphasis for renewed efforts to improve the reliability and efficiency of HF telegraph circuits. Little was accomplished in this area until the development of the first automatic error detection and correction system by Van Duren in 1953. [Ref. 6:p. 5]

In past decades, the Navy has used the HF sky wave propagation extensively for long haul communication requirements. Despite HF's prime advantages of low cost and robustness of the propagation medium, the poor reliability due to the variations and short term unpredictability of the ionosphere resulted in the increased development and use of high quality, high data rate, satellite or landline systems. During the development of present day satellite systems, HF radio communications were viewed as backup communication systems. Given the higher priority and reliability of satellites during peacetime operations, HF techniques and equipment are vintage 1960! Furthermore, operator skills have declined to a point where HF communication circuits are extremely difficult to maintain. [Ref. 7: p. 2]

> Too much is being attempted with too little by poorly qualified personnel. The Fleet Communications Plan cannot be carried out with the diversified, incongruous radio installations existent within the fleet.... Theory is far ahead of material improvements. Destroyers have obsolete apparatus.... Existing regulations require a uniformity and versatility of procedure beyond which the equipment is capable.... An impracticable number of communication channels are now required.[1] [Ref. 8: p. 384]

Recently, the realization of the vulnerability of satellites , the observed limited channel capacity of satellite systems during times of stress and the difficulty in maintaining command and control when operating without satellite systems, has regenerated the development of HF systems . Until now, HF has primarily been used for voice and low-speed teletype. Today high-speed (1200-2400 bits per second) data-transmission rates are required for computer data links, digital secure voice, and message transmission.

Advances in microcircuitry have led to the development of new HF modems that use signal processing techniques to improve data throughput. HF remains vital to long haul communications.

---

[1] Though this looks like a quotation from a recent communications exercise report, it is in fact from a **1923** fleet commander's report! After 55 years of technology some things never change.

B. CHARACTERISTICS OF LONG HAUL HF PROPAGATION

The HF or short-wave spectrum lies between 2Mhz and 30Mhz and is utilized worldwide for long-haul communications. HF communications can be divided into two primary categories, ground waves and sky waves. Ground waves follow the earth's curvature and are most effectively utilized for communications under 300 miles. Long distance communications is made possible by the sky wave component radiating into the ionosphere and returning to earth. The ionosphere is composed of highly ionized gases surrounding the earth's upper atmosphere from an altitude of 40 miles above the earth and extending to 250 miles. It is known that the atmosphere is under constant bombardment by radiation and particle showers from the sun as well as by cosmic rays. The capability to refract or bend sky waves back to earth depends on the concentration of free electrons within the ionosphere due to the ultraviolet radiation of the sun.

One factor influencing the density of ionization is the 11-year cycle of sunspots across the surface of the sun. These spots, which vary up to 80,000 miles in diameter, are created by whirling eruptions of electrified gas. The greater the number of sun spots, the greater the intensity of ultraviolet radiation, and the greater the ionization. Other factors influencing ionization are the varying amounts of radiation striking the northern or southern hemisphere as the earth tilts on its axis while it moves around the sun in its yearly cycle and the daily rotation of the earth upon its axis.

During daylight hours, the ionosphere has 4 distinct layers, D, E, F1, F2, with each layer having a varying concentration of free electrons. The D layer, the lowest in ionization and altitude, absorbs radio waves from the lower end of HF spectrum. The waves from a higher frequency although somewhat weakened by the D layer, will still pass through and be refracted by the E layer. The "E" layer exists at altitudes between 50 and 90 miles. It is a well-defined layer with greatest density at an altitude of about 70 miles. This layer is strongest during daylight hours and is also present, but much weaker, at night. The maximum density of the E layer appears at about mid-day. During this part of the day, the ionization of the E layer is sometimes sufficient to refract frequencies in the upper HF band back to earth. This action is of great importance to daylight transmissions for distances up to 1,500 miles. Waves toward the upper end of the HF spectrum will pass through the D layer with low absorption and refract back to earth from the F layers. The F layer extends approximately from the 90-mile level to the upper limits of the ionosphere. During daylight hours the F layer is divided into two sections: the F1 and the F2 layers. Figure 1 shows the various layers associated with the ionosphere at night and during the day.

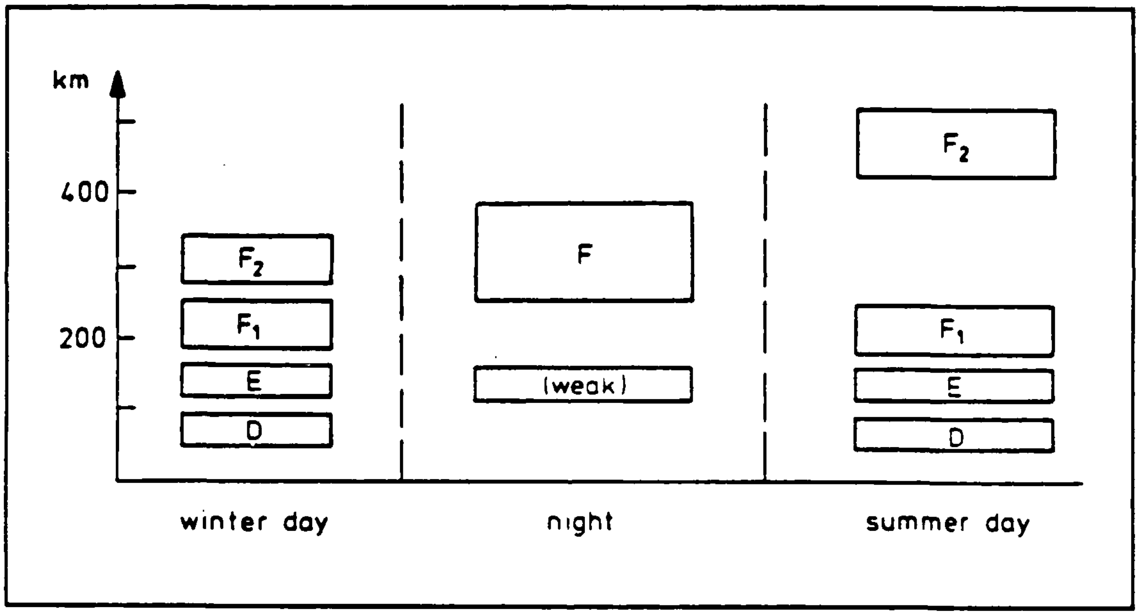

Figure 1. The Ionosphere [Ref. 9:p. 26]

Occasional and unpredictable highly-ionized regions referred to as sporadic E will develop beneath the E layer. These cloud-like masses drifting at speeds of up to 250 mph cause some frequencies to refract in an unexpected manner. Some of the waves that pass through the E layer, may be refracted back to earth at the F1 layer. But often the waves will continue on through the F1 layer to the F2 layer. F2 because of its higher altitude and denser ionization has the greatest occurrence of refraction and provides the longest communication path.

Regardless of the time of day, the lower the angle at which a radio wave penetrates the ionosphere the better the chances for refraction. As day turns to night, the decrease in ultraviolet radiation striking the ionosphere causes decrease in density of ionization. The D layer diminishes and no longer has an effect on radio wave propagation. The E layer is no longer significant and shortly after sunset F1 and F2 combine into a single less-densely ionized layer. Nighttime's decreased ionization density causes radio waves near the 2Mhz level to refract successfully back to earth while the waves from the upper end of the HF spectrum pass into space. This is just the opposite of what happens during daylight hours when the layers reappear and waves in the upper end of the spectrum refract most successfully.

The ability of the ionosphere to return a radio wave to the earth depends upon the angle at which the sky wave strikes the ionosphere, the frequency of the radio wave, and the ion density. When the wave from an antenna strikes the ionosphere at an angle, the wave begins to bend. If the frequency and angle are correct and the ionosphere is sufficiently dense, the wave will eventually emerge from the ionosphere and return to earth.

C. HF TRANSMISSION CHARACTERISTICS WHICH ADVERSELY AFFECT HIGH-SPEED HF DATA RATES

1. Introduction

In this section the effects of fading, multipath, noise and errors will be presented. Before the communication manager can use HF systems effectively, he must understand the strengths as well as the weaknesses of the spectrum. A partial list is shown in Table 1.

Three factors determine the ability of a receiver system to successfully interpret an incoming signal:

- Signal-to-noise ratio (S/N) at the receiver input
- Data rate
- Bandwidth.

The performance of a system is determined by the probability of error, a function of the received (S/N) and its data rate. In general the following relationships hold true (all other factors constant):

- Increased data rates increase bit error rates.
- Increased bandwidth allows increases in data rates.
- Increased S/N decreases bit error rate. [Ref. 10: p. 69]

Propagation in the HF spectrum is accomplished through a combination of ground-wave and sky-wave paths. Although all HF circuits experience multi-component propagation, on some circuits the effects are negligible, particularly on those with single hop paths. Figure 2 illustrates a variety of typical HF paths.

TABLE 1. STRENGTHS AND WEAKNESSES OF HF [Ref. 11:p. 4-1]

Strengths of the HF Medium

1. The ionosphere is a robust propagation medium which recovers rapidly after major perturbations, e.g., polar cap events (PCE's), sudden ionospheric disturbances (SID's) and high-altitude nuclear burst.
2. Long-term (monthly mean) propagation parameters arepredictable with reasonable accuracy.
3. Each communication link exhibits unique characteristics, e.g., fade rates and depths, multipath structures, noise levels, etc, which potentially can be used to isolate that path from the effects of other transmissions in the HF band.
4. Only simple equipment and operating procedures are necessary to achieve access to the medium; this allows it to be exploited by simple mobile terminals.
5. Equipment costs are low in comparison with those of other types of long-range communication systems.

Weaknesses of the HF Medium

1. The ionosphere is subject to sudden unpredictable disturbances such as polar-cap events (PCE's) and sudden ionospheric disturbances (SID's).
2. Although the long-term parameters of the propagation path are relatively predictable, significant departures from such predictions can be expected in the short term (day-to-day).
3. Levels of man-made interference are high, particularly at night, and the nature of such interference is inadequately characterized.
4. A high level of system availability and reliability requires considerable user expertise in manually-controlled systems.
5. The available capacity of a nominal 3Khz HF channel is limited to a maximum of a few kbits/s; data rates of, at most, a few hundreds of bits/s are more realistic if high levels of availability and reliability are necessary.

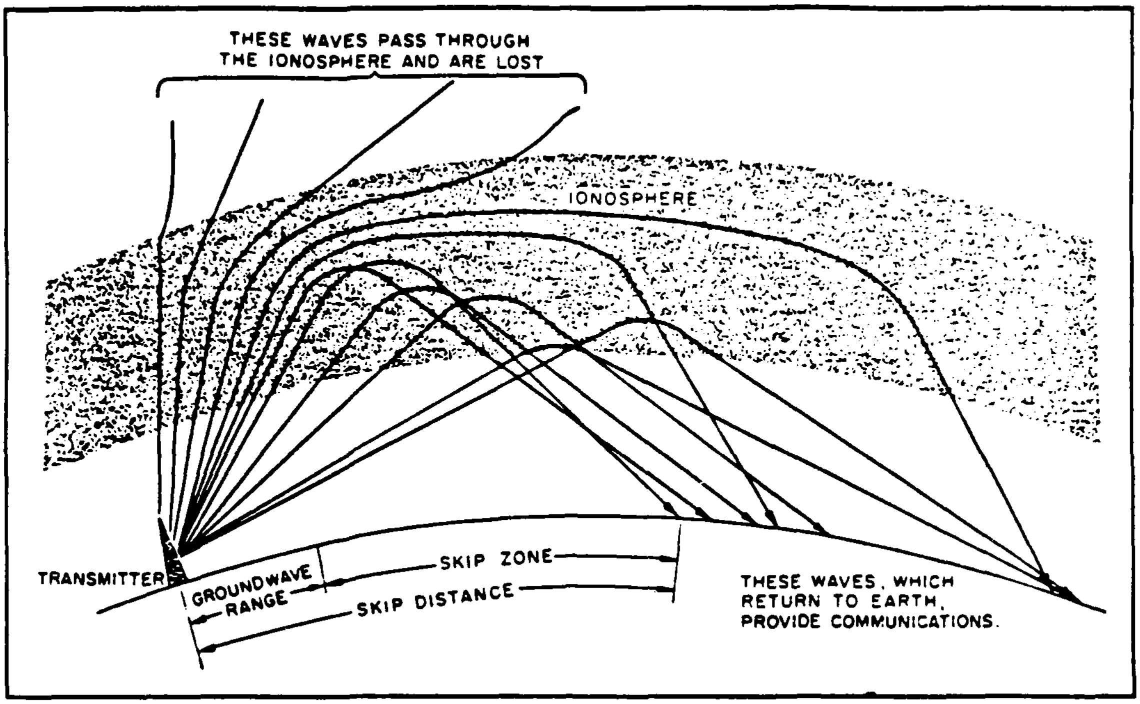

Figure 2. Typical HF Paths [Ref. 12: p. 6-8]

Multiple hop paths may experience increased absorption, fading, and distortion, but also allow for greater distances as shown in Figure 3.

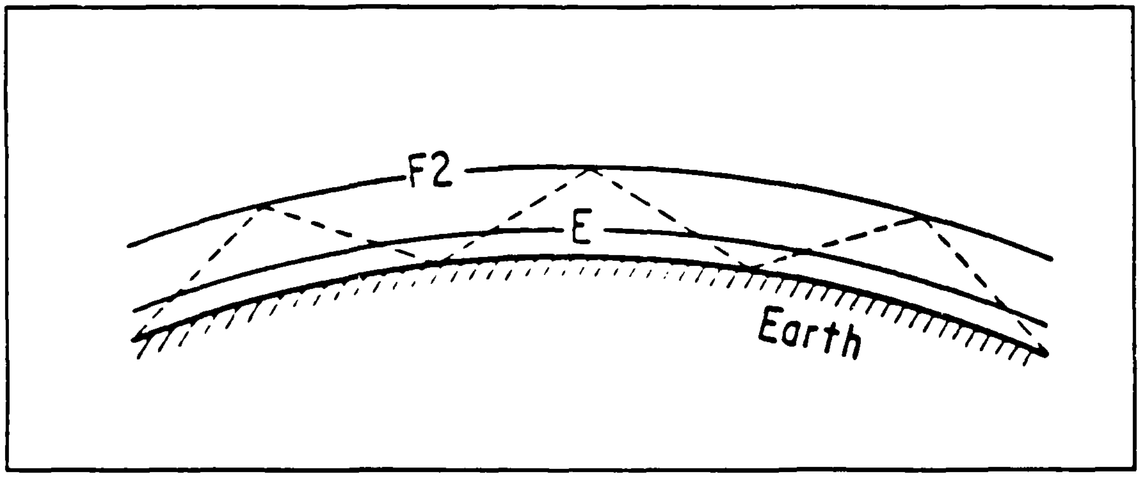

Figure 3. Multiple Hop Paths [Ref. 12: p. 6-9]

The maximum usable frequency that can be used for long- haul or sky-wave communications at any given time for a given path is called MUF and is a function of electron density:.

$$\mathrm{MUF} = f_{cr} \sec a$$

where f_{cr} = the maximum frequency, in hertz, that will be reflected back at vertical incidence.
sec a = the secant of the angle of incidence between the direction of propagation and the perpendicular to the earth.

Frequencies greater than the MUF will not bend back to the earth. The lowest usable frequency is referred to as LUF and is a function of the transmitted signal strength. Frequencies below the LUF are unusable due to absorption. The most reliable frequency for long distance propagation at a specific time is the frequency of optimum transmission, called FOT. The FOT is 85% of MUF.

2. Fading

Fading is a decrease in HF radio signal strength observed at the receiver. HF signals propagated through the ionosphere may vary in intensity for short periods of time. There are five (5) major reasons for fading:

- Random variations in polarization of the radio wave. This causes changes in the received HF signal to occur because the antenna can not receive polarization changes.
- The HF signal frequency is too close to the MUF and changes in the ionosphere may cause a change in signal strength.
- Absorption of the HF signal energy in the ionosphere. Absorption varies inversely with the square of the frequency. i.e., double the frequency and absorption is reduced by a factor of 4 (1/4 of the original level).
- Skip-distance variations occur where the geometry of a single-hop transmission is such that the signal skips over the receiving station. As the ionosphere varies in intensity and height, the skip-distance may increase and decrease causing changes in the received signal strength.
- Multipath propagation is the major cause of fading.
[Ref. 12:p 6-13]

3. Multipath

Multipath fading results from the successive reinforcement and cancellation of the HF signal when two or more waves having different path-links and different phase-shifts combine at the receiving antenna. The longer the distance and the lower the operating frequency below the MUF, the greater the number of possible paths. The longer paths support more multipaths because there is more opportunity for increasing the number of hops along the path to the receiver. The resulting multipath causes a spreading in time of the received signal. A large spread in the time-delay causes inter-symbol interference (ISI) in the data being transferred. Multipath spread is generally less than 5 milliseconds (ms) and is the primary restriction on the information capacity of a HF system. [Ref. 13: p 42-1]

> Figure 4 shows the various paths a signal can travel between two sites. One signal, the ground wave, may follow the path XYZ. Another signal, refracted from the E layer (XEA), is received at A, but not at Z. Still another path (XFZFA), results from a greater angle of incidence and two refractions from the F layer. At point Z, the received signal is a combination of the ground wave (XYZ) and the sky wave (XFZ). If these two waves are received out of phase, they will produce a weak or fading signal. If they are received in phase, the waves will produce a stronger signal. Small alterations in the transmission path may change the phase relationship of the two signals, causing periodic fading. This same addition of signal components occurs at point A. At this point, the double-hop signal from the F layer may be in or out of phase with the signal arriving from the E layer. [Ref. 12: p. 6-14]

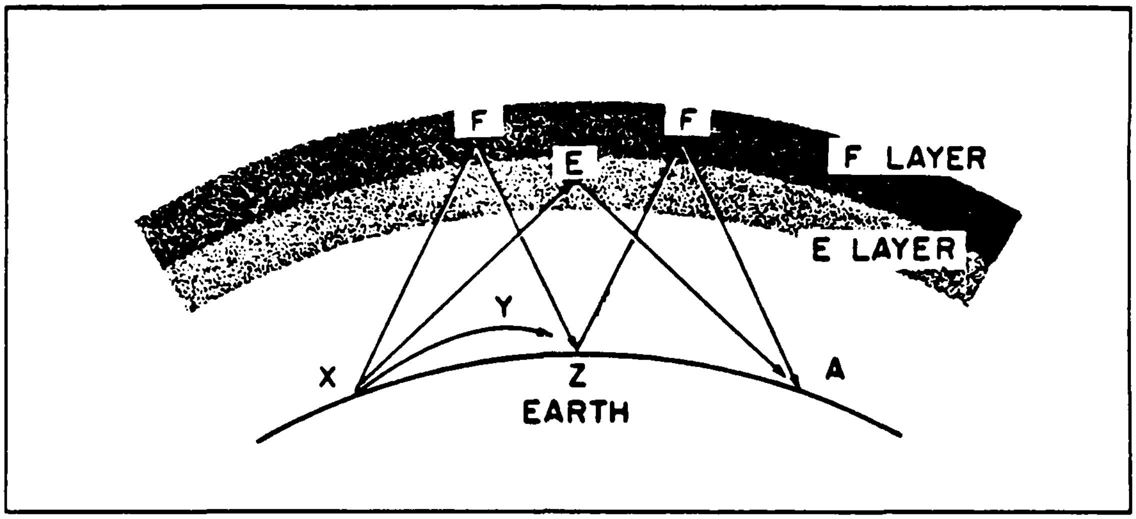

Figure 4. Multipath Propagation [Ref. 12: p. 6-12]

4. Selective Fading

Fading resulting from multipath propagation is variable with frequency since each frequency arrives at the receiving site via a different path. When a wide band of frequencies, such as multichannel single sideband, is transmitted, the frequencies in the sideband will vary in the amount of fading. All frequencies within the envelope of the transmitted signal may not retain their original phase relationship and relative amplitudes. The vector addition of these signals create gaps in the received signal spectrum. This phenomenon is known as frequency selective fading. The degree of fading can vary from a few decibels (db) to 40 db or more. Whenever selective fading occurs, it may cause severe distortion of the signal and limit the total bandwidth which can be transmitted. [Ref. 12: p. 6-14]

5. Noise

A significant factor affecting HF communications is noise. Noise interferes with the desired frequency and can make it totally unusable. Noise is normally classified as either internal or external. Internal noise arises from a variety of components and mechanisms within a receiver or amplifier. External noise arises from all of the sources outside of a communication system and includes atmospheric noise, galactic noise, man-made noise, and interference from other communication systems. Even though the effects of external noise on a communication system can be reduced somewhat, they can not be completely eliminated due to the nature of "external" noise.

a. Atmospheric Noise

Atmospheric noise is primarily due to local and distant thunderstorms. The noise from thunderstorms is propagated to the receiving station by the same ionosphere that allows HF signals to be received. The power spectrum of atmospheric noise varies inversely with frequency such that it becomes insignificant above 25Hz. Diurnal and seasonal variations can be extreme. Atmospheric noise can be severe during tropical rain seasons in equatorial regions, but it decreases towards higher latitudes with less severe weather. [Ref. 14: p. 388]

b. Galactic Noise

Galactic noise originates from the sun, background radiation in space, and many other cosmic sources outside of the earth's atmosphere. The frequency range affected is between 15 Mhz to 500Mhz and its power spectrum varies inversely with frequency. [Ref. 14: p. 388]

c. Man-made Noise

Man-made noise consists of electrical noise generated by man-made systems, i.e., electric power lines, electric motors, neon signs, etc.. The level of man-made noise is significantly higher in urban areas of the world. As a result remote rural areas are usually selected for radio astronomy telescopes and satellite tracking stations. [Ref. 14: p. 388]

d. Other communication interference

Interference from other communication systems produces the same undesirable effects as the noise sources previously mentioned. The large number of electromagnetic transmissions generates background radiation across the entire HF spectrum. The operator must be prepared to deal with interference from other communication systems operating at the same frequency or emitting other electromagnetic signals. These effects are commonly referred to as RFI (radio frequency interference) and EMC (electromagnetic compatibility). [Ref. 14: p. 388]

e. Data rates and Noise performance

When evaluating and comparing different systems, the communication manager can develop a basic understanding of relative performance based on data rate, noise, bandwidth required, and bit error rate/probability of error.

In general,

(1) D = R/l = R/log2 L or R = Dlog2 L

where D = modulation rate, bauds
R = data rate, bps
L = # of different signal elements
l = # of bits per signal element

Rather than use signal to noise ratio (S/N), it is more convenient to use Eb/No (signal energy per bit/ noise energy per hertz) to determine data rates and error rates associated with any given probability of error.

(2) Eb/No = S/NoR

where S = signal power
1/R = Tb, time to send one bit
No = kT
k = Boltzman's constant
= 1.38 x 10^{-23} J/^{o}K
T = temp, ^{o}K

Eb/No can also be related to the bandwidth efficiency. No is the noise power density in watts/hertz. The noise in a signal of bandwidth Bt is:

(3) $N = NoBt.$

substituting, we have

(4) $Eb/No = (S/N)(Bt/R)$

For a given encoding scheme, the bit error rate can be reduced by increasing Eb/No. This can be accomplished by increasing the bandwidth or decreasing the data rate, i.e. reducing bandwidth efficiency in order to gain lower error rates. [Ref. 10: p. 78]

Often Eb/No is referred to in the following decibel notation for convenience of presenting power requirements:

substituting in equation (2)

(5) $Eb/No = S/kTR$

(6) $Eb/No = S - 10\log R + 228.6\ \text{dbW} - 10\log T$

where S = signal power
$228.6 = -10\log k$

As the bit rate R increases, the signal to noise ratio S/N (therefore the signal power) must increase in order to maintain a given Eb/No. [Ref. 10: p. 45]

6. Errors

In HF communication elementary data transmission consists of a sequence of bits (binary digits) which can be either ones (1) or zeros (0). A "bit error" occurs whenever a bit changes value due to some undesired phenomenon during the actual transmission. Errors in HF data transmission can be attributed to variations in the ionosphere, noise, communication equipment, and the mode of operation (data rate, modulation scheme, etc.).

Given the "unpredictable" nature of HF, errors can not be predicted with high accuracy. Therefore the occurrence of errors is presented in the form of a statistical model of probability of occurrence. The Guassian, Raleigh-fading, Rice-fading, and Markov chain models are representative of the most widely accepted models [Ref. 15: p 12]. The performance criterion most often used for evaluating HF systems is the probability of error.

a. Random Errors

Random errors are generally caused by random atmospheric noise spikes, random variations in the propagation path, and random transients generated in the communication equipment. They occur "individually" and each occurrence is statistically independent of any previous error. When the bit error rates in a communication system are low (i.e., 10^{-6}) random errors make up the bulk of total errors in the system. However, when bit error rates are high, random errors account for only a small portion of the total errors. [Ref. 15: p. 13]

b. Burst errors

In line of sight (LOS) and extended line of sight (ELOS) HF communication, burst errors are predominantly caused by other user interference, atmospheric noise, or narrowband jamming. For beyond line of sight (BLOS) HF, the causes of burst errors are frequency selective fading and flat non-selective fading [Ref. 16: p. 3-7]. A typical example is noise due to lightning associated with thunderstorms. This results in errors ranging from 1-5 bits in duration depending upon the burst intensity and duration, and channel baud rate.

c. Error Performance

The ratio of the number of bit errors to the total number of bits transmitted is called the bit error rate (BER). The average bit error rate is useful in comparing randomly distributed "undecoded" or raw bit error coding parameters, but it is a poor indicator of performance of a decoder for a compound channel composed of burst errors superimposed on a background of random errors. The undecoded BER could be dominated by the bursts. Error-free blocks or the cumulative distribution of gaps is a more meaningful description of errors when this occurs. A gap refers to the number of error-free bits between any two consecutive errors. [Ref. 17: p. 2]

IV. TECHNIQUES CURRENTLY USED IN HIGH-SPEED MODEMS

A. INTRODUCTION

In the preceding chapter the characteristics of the HF medium and its effects on transmission data throughput rates was described. Advances in microcircuitry have led to the development of new HF modems that use signal processing techniques to improve data throughput. This chapter provides a review of various coding and processing techniques currently proven and available in NDI high-speed HF modems. A basic understanding of these techniques will enable the communication planner or manager to evaluate competing technologies when upgrading current or future HF systems.

B. CODING TECHNIQUES

Coding techniques may be used to create a more reliable communication system (reduce the probability of error), or to increase the efficiency (throughput) and lower the cost of a system (less power required), or both. Very little knowledge of highly mathematical coding theory is required in order to understand coding in a communication system [Ref. 18: p. 2].

The problem in discussing coding techniques comes in deciding what classification criterion to use, i.e., function, design cost, efficiency, etc., [Ref. 18: p 4]. Figure 5 outlines some of the well known codes whose functions are error detecting and/or error correction.

The amount of improvement achieved when a coding scheme is used is referred to as the "coding gain" for that scheme. The coding gain is determined by plotting the probability

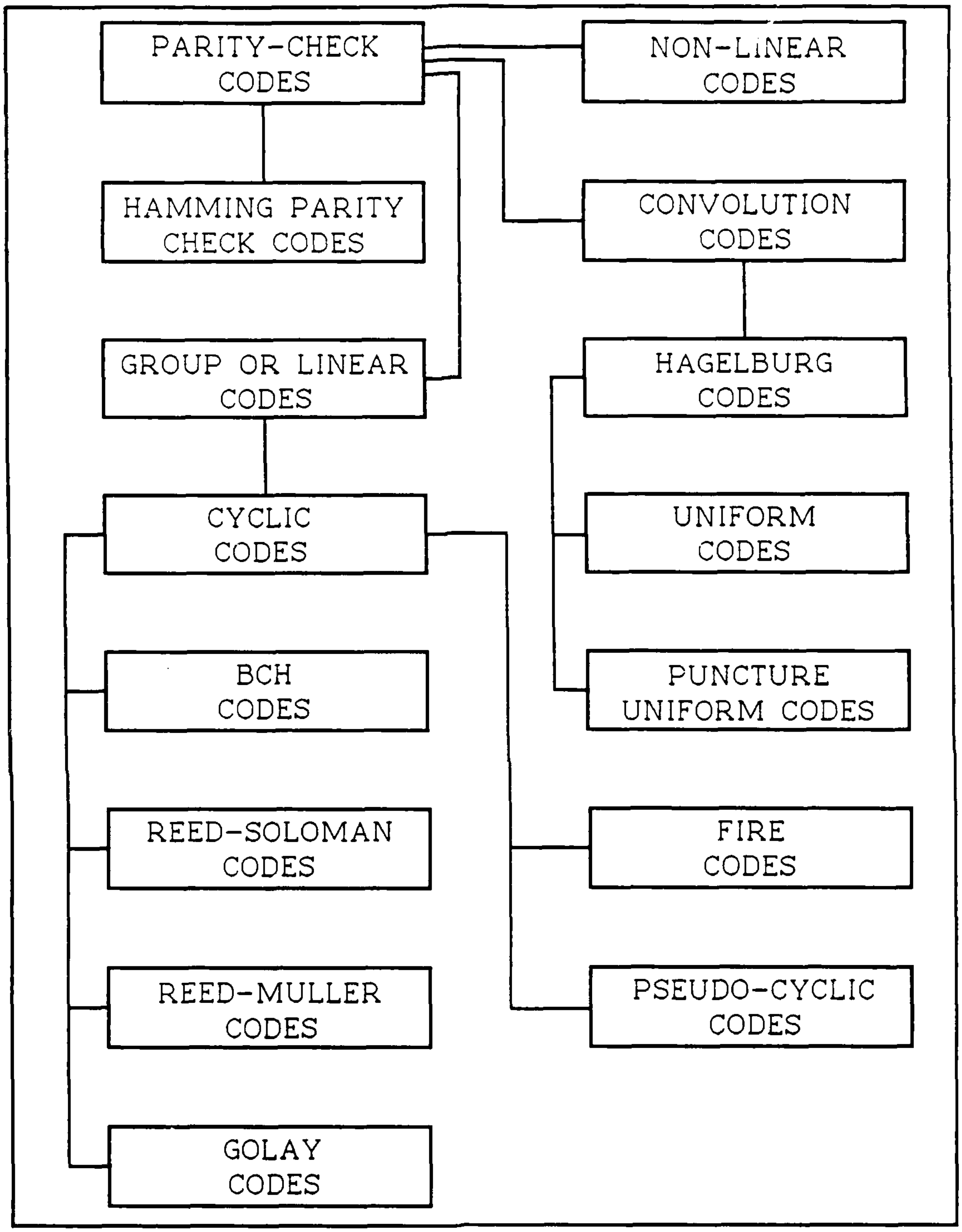

Figure 5. Error Detecting and/or Error Correcting Codes

[Ref. 18: p. 34]

of error versus Eb/No (signal energy per bit/ noise energy per hertz) of both the uncoded and coded transmissions, then measure the difference in Eb/No required to achieve a given error rate . This is demonstrated using the prominent (23,12) Golay code (the only multiple error correcting binary perfect code) in Figure 6. Although the use of coding schemes can produce impressive improvements, it should be noted that at sufficiently low values of Eb/No, (i.e., extreme channel interference or jamming) error-correction coding actually may make the situation worse. This occurrence is common to all coding schemes. Thus under conditions of severe jamming, the use of error correction is not effective. [Ref. 19: p. 25]

The two most common methods utilized in communication systems for error detection/correction (EDAC) are Automatic Repeat Request (ARQ) and Forward Error Correction (FEC). ARQ requires two way communications so that if a received data block contains an error, the receiver system can send a "request for retransmission" for that data block. FEC on the other hand, does not require two way communications, since the data is "encoded" prior to transmission and the receiver system decodes the data correcting the majority of errors which may occur [Ref. 7: p. 6].

1. Automatic Repeat Request (ARQ)

Typically, ARQ systems code data bits into characters or long data blocks for transmission. This coding includes additional "redundant" bits which enables the receiver decoder to detect those blocks which have errors and request retransmission [Ref. 20: p 779]. This technique does not "correct" errors, it detects them. ARQ schemes belong to basically two categories: (1) stop-and-wait schemes, in which the channel is idle from time to time, and (2) continuous schemes, in which data blocks are sent from the transmitter to the receiver without interruptions.

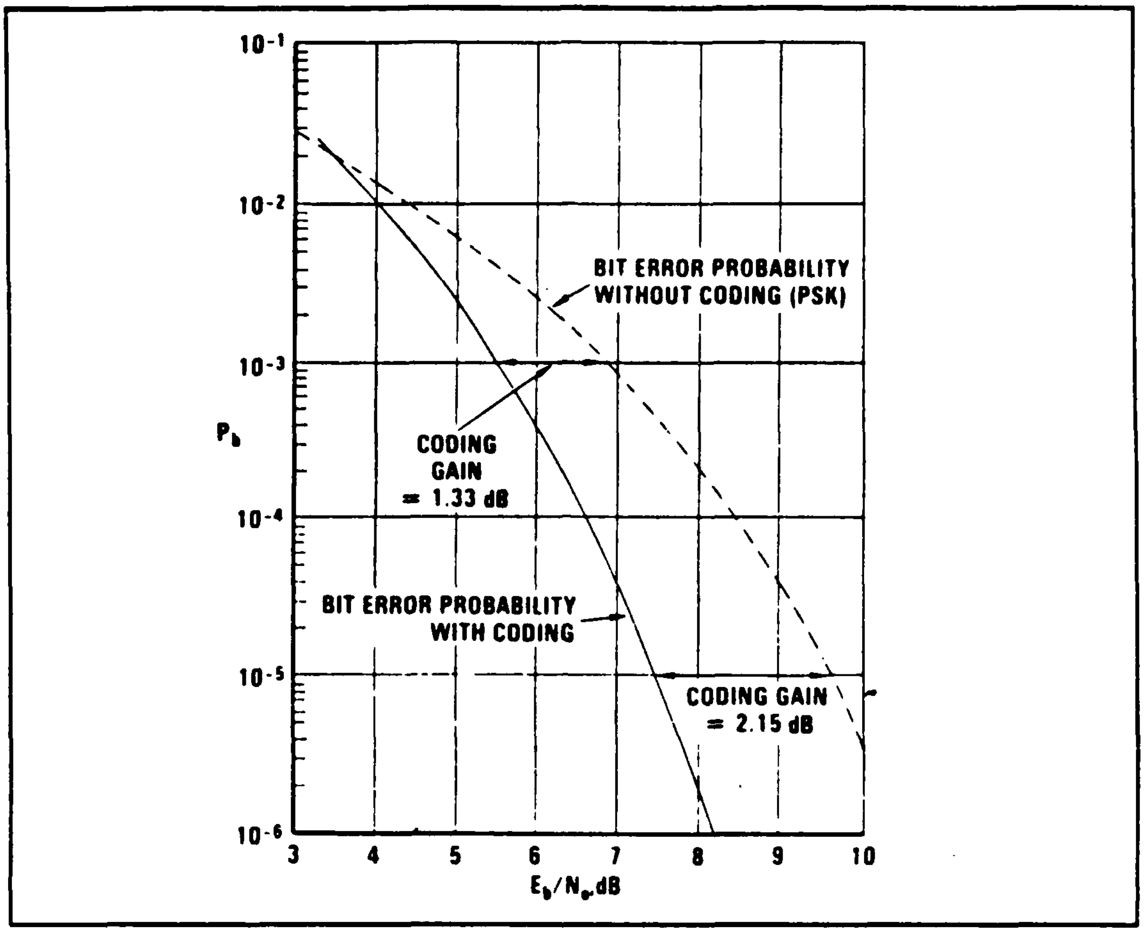

Figure 6. Bit Error Probability versus Eb/No for the (23,12) Golay Code [Ref. 19: p. 36]

Stop-and-wait schemes require the transmitter to transmit a single data block and wait for the receiver's acknowledgment. The principal advantage of stop-and-wait is its simplicity. Its disadvantage is that it is inefficient in HF systems where the propagation time greatly exceeds the transmission time for a data block. [Ref. 10: p. 137]

The most utilized continuous schemes are the go-back-N scheme and the selective repeat scheme. The go-back-N scheme allows the transmitting station to continuously transmit blocks of data and the transmitting station maintains a copy of the most recently transmitted blocks in storage for possible retransmission. The receiving station checks incoming blocks for errors and requests retransmission when an error is detected. The receiving station will disregard all future blocks until the block in error is correctly received. [Ref. 10: p. 137]

The selective repeat scheme is a more sophisticated approach than go-back-N. The receiver system sends out an "acknowledged" message for each block received error free. The only blocks retransmitted are those for which a "not-acknowledged" (NAK) message is sent and received at the transmitter station. While this appears to be more efficient than go-back-N, the receiver requires more memory for storing "acknowledged" blocks and a more complex logic for re-inserting "not-acknowledged" blocks in their correct sequence when received. The transmitter also requires more complex logic in order to transmit blocks out of sequence. [Ref. 10: p. 139]

The throughput efficiency if an ARQ scheme is defined as the ratio of the number of information bits delivered to the total number of bits transmitted. The best throughput efficiency is realized by the selective-repeat scheme. Selective-repeat has the disadvantage of requiring the receiver system to reorder the data blocks. This is not required for the go-back-N scheme. Because of the complexity of selective-repeat schemes, the go-back-N scheme is more commonly used. [Ref. 10: p. 139]

2. Forward Error Correction (FEC)

A forward error correction processor takes a bit stream and processes it through a series of complex algorithms prior to its transmission, adding extra (redundant) bits to the original data. The redundant bits are used by a FEC processor at the receiver system to determine if the data were received correctly and to correct the errors which may have occurred. The most useful forward error correction codes may be categorized into two broad types: linear block codes (of which a subclass are cyclic codes) and convolutional codes. [Ref. 7: p. 6]

a. Linear Block codes

In a linear block code data bits are coded into blocks of length k information bits and additional check bits, equal to r, are added to form a unique "code word" made up of n bits.

(7) $n = k + r$

where n = total number of bits per block
k = number of information bits per block
r = number of check bits per block

Linear block codes are referred to as (n,k) codes. Codes containing k bits yield 2^k possible code words. Additionally it is required that the sum of two code words must also be a code word. [Ref. 21: p. 401; Ref. 7: p. 7]

When comparing block code efficiency it is useful to examine the code rate, R given by the following;

(8) $R = k/n$

the reciprocal, n/k is the ratio by which the channel bandwidth must be increased to allow for the added redundancy of the code. As shown in equations (4) and (6) in the previous chapter, this requires a trade-off between bandwidth and signal power. Additionally, in channels with a limited bandwidth, the maximum capacity for data bit transfer is fixed and increased redundancy reduces the number of information bits. [Ref. 21: p. 401; Ref. 7: p. 7]

A subclass of block codes known as cyclic codes (see Figure 5), have especially attractive properties, such as ease of implementation using simple shift registers, ability to correct a large number of random errors or long burst errors, and maintaining system synchronization. The use of cyclic codes with shift registers results in equipment that is considerably simpler than that required of block codes. [Ref. 7: p. 7]

b. Convolutional Codes

A convolutional code is one in which the information bits are intermixed together with the check bits in a continuous stream. This is accomplished by passing the *k* information bits through L stages of a linear finite-state shift register. For each *k* bit sequence the shift register generates an output of *n* bits. The check bits generated for a particular block of *n* bits are determined not only by the *k* bit sequence, but also by the preceding N-1 blocks of *n* bits (N>0). [Ref. 22: p. 7-8]

A high level of redundancy in a convolutional code (e.g., code rate = 1/2) reduces the complexity of the decoding process. At the other extreme, when less redundancy is utilized and the output is based on a comparison with a high number of previously transmitted bits (N-1), the complexity of both the encoder and decoder is higher [Ref. 23: p. 68].

c. Block Coding vs. Convolutional Coding

A considerable amount of literature exists concerning coding theory and its application to HF communications. Until recent years most comparisons of block versus convolutional code performance were the result of computer simulations. This was primarily due to the complexity and cost of developing a suitable decoder for convolutional codes. Advances in microprocessor technology, coupled with the decrease in cost and significant improvement in decoding algorithms has reduced the disparity in cost between convolutional and block decoders. Communication managers and planners must consider the cost and complexity of competing systems when making final comparisons.

Some characteristics common to both convolutional and block codes are: (1) encoding using simple shift registers, (2) some codes require very little decoding equipment, (3) codes exist which are capable of correcting random and burst errors. Convolutional codes maintain several distinct advantages over block codes: (1) smaller data blocks yield smaller decoding delays, (2) less memory storage required, and (3) loss of synchronization is less serious. [Ref. 22: p. 7-9]

Table 2 and Table 3 provide additional comparison of coding techniques. In Table 2 the probability of error for all techniques was set at 10^{-3} and the resultant channel probability listed is considerably larger, while the required Eb/No is smaller.

TABLE 2. COMPARISON OF CODING TECHNIQUES BY PROBABILITY ERROR, REQUIRED Eb/No, AND COMPLEXITY [Ref. 21: p. 403]

Technique	Required Channel P_e	Required Eb/No		Complexity (# of integrated circuits)
No coding	10^{-3}	11.7		-
$r = 1/2$, conv	0.0266	10.2		10
Golay (24,12)	0.0266	10.2		20
Block (48, 24)	0.029	10.0		60
$r = 1/3$, conv	0.082	10.7	(Viterbi)	80
$r = 1/2$, conv	0.064	9.4	(Sequential)	500

TABLE 3. COMPARISON OF CODING TECHNIQUES BY CODING GAIN AND DATA RATE CAPABILITY [Ref. 19: p. 342]

Technique	Coding Gain 10^{-5}	Coding Gain 10^{-8}	Data rate capability
Concatenated (RS and Viterbi)	6.5-7.5	8.5-9.5	10 Kbps - 1 Mbps
Sequential (soft)	6.0-7.0	8.0-9.0	10 Kbps - 1 Mbps
Concatenated (RS & biorthogonal)	5.0-7.0	7.0-9.0	10 Kbps - 1 Mbps
Block codes (soft)	5.0-6.0	6.5-7.5	10 Kbps - 1 Mbps
Concatenated (RS & short block)	4.5-5.5	6.5-7.5	> 20 Mbps
Viterbi decoding	4.0-5.5	5.0-6.5	1 Mbps - 20 Mbps
Sequential (hard)	4.0-5.0	6.0-7.0	1 Mbps - 20 Mbps
Block codes(hard)	3.0-4.0	4.5-5.5	1 Mbps - 20 Mbps
Block codes (threshold decoding)	2.0-4.0	3.5-5.5	1 Mbps - 20 Mbps
Convolutional (threshold decoding)	1.5-3.0	2.5-4.0	> 20 Mbps
Convolutional	1.0-2.0	1.5-2.5	1 Mbps - 20 Mbps

(Viterbi, Sequential, and Threshold refer to decoding algorithms.)

3. Interleaving

The most effective way to achieve protection against both random and burst errors is by interleaving the code. Interleaving is the technique of spacing data bits farther apart prior to transmission. This makes it easier for the receiving processor to correctly locate bits in error due to burst errors. This is the standard technique for transforming a burst error signal into a random error signal. Coding for random error correction is more easily applied than coding for burst errors. Interleaving is also effective in processing random errors alone. [Ref. 7: p. 9; Ref. 16: p 3-6]

Figure 7 and Figure 8 illustrate interleaving of burst and random error correction. In these arrays, *m* code words of *n* bits are arranged by row. The arrows show the order in which bits are transmitted. If the selected code can correct *t* random errors, the Interleaved code can correct a burst up to *mt* errors. If random errors occur, interleaving is effective as long as there are no more than *t* errors in any single row. [Ref. 7: pp. 9-10; Ref. 24: p. 1298]

Interleaving can be applied with either block or convolutional coding. It requires much more additional memory and processing power than would be required without interleaving [Ref. 23: p. 69]. The interleaver circuits may be internal or external to the modem and they are generally classified as either periodic or pseudorandom. The periodic interleaver is less complex, but the pseudorandom interleaver is much more robust.

4. Soft Decision vs. Hard Decision Decoding

In soft decision decoding a determination is made as to whether a received bit is a "one" or a "zero" as compared to a voltage or phase threshold. Based on how far above or below this threshold a bit is, the decoder assigns a confidence level which is used to provide a weight for each bit. The amount of information provided to the decoder is

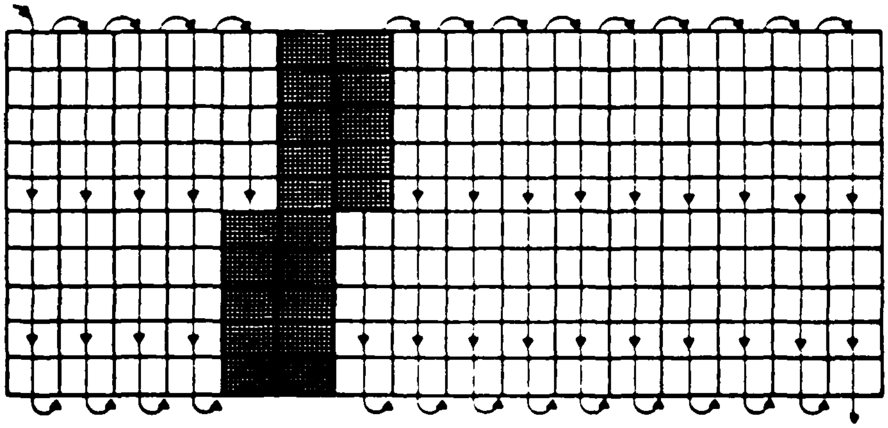

Figure 7. Burst Correction with Interleaved Codes, $n = 16$, $m = 10$, $t = 2$. [Ref. 24: p. 1298]

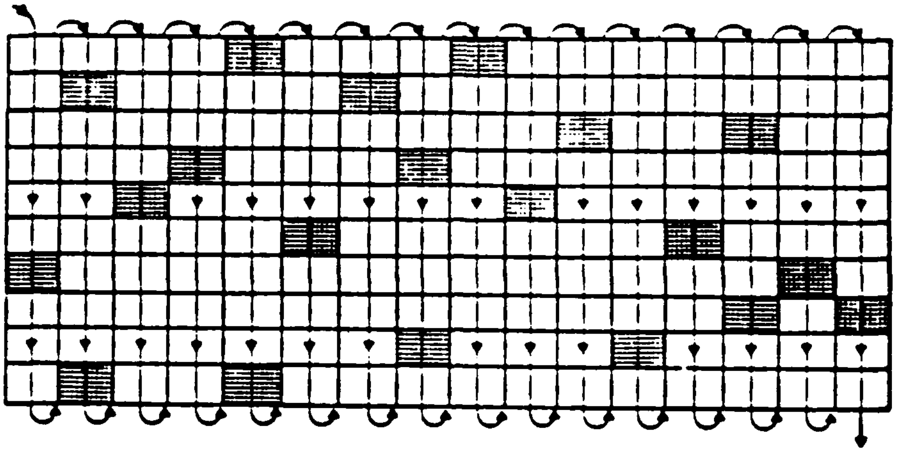

Figure 8. Random-Error Correction with Interleaved Codes, $n = 16, m = 10, t = 2$. [Ref. 24: p. 1298]

increased substantially and yields an additional processing gain of 2 db in most systems. The disadvantage of soft decision decoding is that as the number of confidence intervals assigned increase, the complexity of the decoder increases rapidly. [Ref. 7: p. 8; Ref. 25: p. 12]

A hard decision decoder simply determines whether a received bit is a "one" or a "zero" without regard to how far above or below a threshold a bit is. The decoder assigns equal weight to all bits. The hard decision decoder is less complex to implement and is therefore more common. The algorithm in a decoder is the primary performance factor; soft decision design simply increases that performance when utilized.

C. PARALLEL TONE MODEMS

1. Parallel processing

The parallel tone modem has been the primary method of high speed HF communication in the Navy. The parallel tone modem divides incoming data into parallel data streams (commonly sixteen) and transmits using four-phase differential phase-shift keying (DPSK) on (sixteen) low speed parallel sub-channels or tones. The slower speed creates data symbols of a duration that can overcome inter-symbol interference (ISI) due to multipath propagation.

In the military standard (MIL-STD-188C) sixteen tone modem, sixteen sub-channels are transmitted at 75 baud, with 2 data bits per baud, yielding an overall transmission rate of 2400 bits per sec. The parallel tone technique was developed in the early 1950's and is commonly referred to as Kineplex. All of the current parallel modems use some form of the Kineplex approach. [Ref. 7: p. 11]

2. Advantages

There are few "advantages" to parallel modems, but they are very significant: (1) parallel modem technology is well established, (2) more importantly, it is the military standard, and (3) the technology is a less complex solution to ISI than adaptive equalization used in serial modems.

3. Disadvantages

There are three primary disadvantages to the parallel tone approach: (1) it has large peak to mean variation in its signal, which leads to inefficiency in current peak power limited transmitters, (2) transmitter power is divided between the sub channels resulting in reduced power and performance, and (3) frequency selective fading can completely eliminate some of the sub channels.

Controversy over the performance potential of parallel versus serial modems is extensive and the "proven choice" varies from manufacturer to manufacturer. However, a majority of the most recent literature and test results shows that further performance gains in parallel modems is not likely, while the potential for serial modem improvements is great. [Ref. 26: p. 44-1]

D. SERIAL MODEMS

1. Serial processing

Serial modem techniques were not in widespread use prior to the late 1970's. Also, the literature discussing theoretical or actual performance of this technology is not as extensive as that concerning parallel modem technology. This is apparently due to the proprietary nature of associated research and development as well as the inability of earlier techniques to "track" or follow the variable HF signal. [Ref. 27: p.1617]

The serial tone approach uses phase shift keying and some form of decision feedback equalization. The technique is best described by Toomey and Bole [Ref. 26: p. 44-1].

> A serial tone is phase-shift keyed at a fixed baud rate up to about 2400 symbols per second (consistent with the requirement for transmission in a 3 Khz voice-band channel). The modulating signal is composed of data, usually interspersed with a pseudorandom "training" sequence. Channel-equalization or estimation techniques utilize the training information...to adaptively model the receiver for optimum detection.... The availability of high-speed, signal-processing hardware now permits real-time adaption with sufficient capability to track the fast-changing HF channel.

2. Advantages

Serial transmission has the advantages of: (1) improved frequency diversity, (2) better bandwidth efficiency, (3) improved peak transmitter power utilization (approximately one-half the power requirement for parallel), (4) reduced error rates at transmission speeds above 2400 bps, and (5) greater resistance to frequency selective fading, narrowband frequency shift keying (FSK) or continuous wave (CW) interference. [Ref. 26: p. 44-1; Ref. 28: p 139]

3. Disadvantages

The most significant technical disadvantage to serial processing techniques is adaptive equalization. Serial modems must achieve rapid equalizer adaption in order to adjust to variations in the HF propagation path. An even greater disadvantage facing communication planners is that no industry or military standard has been developed and serial modems of different manufacturers are not compatible.

F. SOFTWARE VS. HARDWARE

There are two prime advantages to implementing HF modem techniques in software vs. hardware: (1) a variety of waveforms can be implemented and tested on one piece of equipment, and (2) system improvements can be easily installed. [Ref. 16: p.1-1]

V. PERFORMANCE CHARACTERISTICS OF NDI MODEMS

A. INTRODUCTION

In the preceding chapter basic coding and processing techniques currently proven and available in NDI high-speed HF modems were described. This chapter presents a sample of currently available representative NDI high-speed HF modems. It is intended to present the techniques and capabilities available, without additional DOD research and development, for use in long haul HF communications. The selection of specific modems included in this thesis was based solely upon the availability of technical data and does not represent an endorsement by the U.S. Navy or DOD.

High-speed HF modems can be divided into four categories: (1) parallel processing modems, (2) serial processing modems, (3) frequency hopping modems, and (4) spread spectrum modems. It is beyond the scope of this thesis to present information concerning frequency hopping and spread spectrum techniques. This chapter will be limited to the presentation of data concerning parallel and serial modems.

B. PARALLEL MODEMS

1. Harris RF-3466

The power and speed of the RF-3466 integrated circuits allow time differential phase shift keying to be combined with forward error correction (FEC) as well as channel and in-band diversity to achieve high, data transfer rates while minimizing errors. The RF-3466 utilizes quaternary phase shift keying to modulate 39 tones between 675 Hz and 2812.5 Hz. A 14,10,2 or 7,3,2 Reed-Solomon code is used to provide FEC. Interleaving is used to minimize burst errors. Dual channel diversity is available at all data rates.

Optional soft decision decoding for improved bit error rates is available. Selected technical data for the RF-3466 is shown in Table 4. [Ref. 29: p. 1-2]

2. Cossor CTM 1080

The CTM 1080 is designed to provide a robust high speed circuit over HF with the advantages of low power, small size, and ease of operation. The modulation format of the CTM 1080 is based on the proven MIL-STD-188C, providing 16 tone differential phase shift keying with a range of data rates form 75 bps to 2400 bps. Forward error correction is provided up to 1200 bps. A liquid element display (LED) provides the operator with signal quality, transmit or receive indications, and frequency offset values. Selected technical data for the CTM 1080 is shown in Table 5. [Ref. 30]

3. Tadiran MD-23

The MD-23 is a programmable modem which utilizes multi-processing techniques for data communications and firmware-implemented digital processing to provide high performance without the need for adjustments or tuning. It features multi-tone differential phase shift keying, out-of-band diversity, error correction coding, in-band diversity, interleaving, and soft decoding. [Ref. 31: p. 433]

The modem can be controlled via: (1) a 16-key pad control panel with an interactive menu-driven display, (2) a remote control computer connected to a standard asynchronous serial interface (RS-232), or (3) optional automatic control of receiving parameters by a transmitting modem. Additionally, audio monitoring of all transmit and receive channels is provided. Selected technical data for the MD-23 is shown in Table 6. [Ref. 32]

TABLE 4. TECHNICAL DATA RF-3466 MODEM

[Ref. 29 : p. 1-2; Ref. 33: p. 24]

Data Rates	75, 150, 300, 600, 1200 and 2400 bps
Tone Libraries	39 tones, 675 to 2812.5 Hz with 56.25 Hz spacing plus one doppler tone at 393.75 Hz
Doppler correction	+/- 75 Hz during preamble; tracking up to 3.5 Hz per second
Bandwith (nominal)	3 KHz
Synchronization	to within +/- 1.2 ms in acquisition; tracking up to 1.2 milliseconds per second
Modulation	Time Differential Phase Shift Keying (TDPSK), 4-phase;
EDAC	(14, 10, 2) Reed-Solomon code at 2400 bps; (7, 3, 1) Reed-Solomon code at lower rates
Diversity	in-band at 600 bps and lower data rates; out-of-band-dual channel at all rates
Manufacturer	Harris Corporation RF Communications Group 1680 University Avenue Rochester, New York 14610

TABLE 5. TECHNICAL DATA CTM 1080 MODEM
[Ref. 33: p. 24; Ref. 30; Ref. 31: p 446]

Data Rates	75, 150, 300, 600, 1200 and 2400 bps
Tone Libraries	16 tones, MIL-STD-188C modem
Doppler correction	+/- 75 Hz, displays actual offset
Bandwith (nominal)	3 KHz
Synchronization	(information unavailable)
Modulation	Differential Phase Shift Keying (DPSK)
EDAC	FEC up to 1200 bps
Diversity	in-band and out-of-band interleaving
Manufacturer	Cossor Electronics Limited The Pinnacles Harlow Essex, England CM195BB

TABLE 6. TECHNICAL DATA TADIRAN MD-23 MODEM
[Ref. 32; Ref. 31: p 433]

Data Rates	75, 150, 300, 600, 1200 and 2400 bps
Tone Libraries	multi-tone,
Doppler correction	+/- 100 Hz immediately during preamble; continuous at 3.5 Hz per second
Bandwith (nominal)	3 KHz
Synchronization	fast (preamble) and slow (continuous)
Modulation	Differential Coherent Phase Shift Keying (DCPSK), 2-phase, 4-phase
EDAC	up to 1200 bps
Diversity	in-band up to 1200 bps
Manufacturer	Tadiran Ltd. 11 Ben-Gurion Street, Givat Shmuel P. O. Box 648 Tel Aviv, Israel 61006

4. Rockwell Collins TE-233P

The TE-233P is a firmware implemented synchronous HF modem designed to provide both half and full-duplex operation over long haul HF channels. It utilizes two, four, or eight-phase differentially coherent phase shift keying with out-of-band or space diversity, varying degrees of in-band diversity, forward error correction, interleaving, and soft decision decoding. The programmable micropocessors allow flexibility for updating the modem as future improvements in processing techniques become available. Selected technical data for the TE-233P is shown in Table 7. [Ref. 31: p. 499]

5. GTE-Sylvania AN/USQ-83

The AN/USQ-83 is a HF programmable digital modem which provides multi-mode, microprocessor-implemented data communications. The modular programs contained in the programmable read only memory (PROM) firmware can be easily modified for future modem applications. The AN/USQ-83 currently provides four co-resident digital operational modes:

- Tactical Data Link (Tadil A) - for Link-11.
- Voice Frequency Carrier Telegraphy (VFCT) - for 16 channel Fleet Broadcast.
- Data A - high speed modem compatible with ANDVT.
- MIL-STD-188C - for 16 tone phase shift keying, high speed modem compatible with MD-1051 modem.

All operational modes (except VFCT) provide varying degrees of EDAC. An operator display control panel provides for interactive control of various modem modes and operating parameters. The modem contains a comprehensive built-in-test feature that automatically identifies malfunctions which are displayed on the control panel.

TABLE 7. TECHNICAL DATA TE-233P MODEM
[Ref. 33: p. 49; Ref. 31: p. 499]

Data Rates	75 to 2400 bps
Tone Libraries	16 data tones, 935-2585 Hz with 110 Hz spacing plus one doppler tone at 605 Hz. IAW MIL-STD-188C.
Doppler correction	+/- 75 Hz
Bandwith (nominal)	3 KHz
Synchronization	fast and slow
Modulation	Differentially Coherent Phase Shift Keying (DCPSK), with 2-phase, 4-phase, 8-phase modulation depending upon the data rate and EDAC
EDAC	2400 bps: 2/3 rate code 75 to 1200 bps: 1/2 rate code
Diversity	in-band 75 to 1200 bps
Manufacturer	Rockwell International Electronic Systems Group Data Products Marketing Newport Beach, California 92660

Additionally, the AN/USQ-83 contains a non-volatile memory circuit which provides for immediate restoration of the last operating mode in the event of power source interrupt or failure. [Ref. 31: p. 477; Ref. 34]

The AN/USQ-83 was developed under a $10.4 million contract from the U.S. Navy Space and Naval Warfare Systems Command. It is designed to fully meet military specifications for shipboard applications and is about one-half the size and cost of present fleet HF modems (UCC-1 and MD-1051). The AN/USQ-83 is scheduled for operational evaluation of only the Tadil A and VFCT modes in 1988 and production delivery in 1990. Selected technical data for the AN/USQ-83 is shown in Table 8. [Ref. 35: p. 942]

C. SERIAL MODEMS

1. Harris Model 5254B

The Model 5254B is a high performance serial modem capable of operating at transmission speeds up to 3600 bps providing coded information rates up to 2400 bps. The Model 5254B utilizes single phase modulated frequency which out performs standard parallel modems in HF multipath and fading environments. A convolutional code of either 1/2 rate or 2/3 rate is used to provide FEC. Interleaving is used for all data rates to minimize burst errors. Reprogramable microprocessors provide flexibility for future updates. Selected technical data for the Model 5254B is shown in Table 9. [Ref. 36]

2. Plantronics-Frederick Electronics HSM-1A

The HSM-1A is a high-speed serial modem designed to minimize the detrimental effects of multipath HF propagation. It utilizes adaptive equalization, phase shift keying, 2/3 rate convolutional coding and Viterbi decoding to provide low error rate transmission.

TABLE 8. TECHNICAL DATA AN/USQ-83 MODEM
[Ref. 33: p. 14; Ref. 31: p. 477; Ref. 34]

Data Rates	75, 150, 300, 600, 1200, 2400 BPS
Tone Libraries	16 tones, 935 to 2585 Hz with 110 Hz spacing plus one doppler tone at 605 Hz
Doppler correction	605 Hz tone
Bandwith (nominal)	3 KHz
Synchronization	slot
Modulation	Differential Phase Shift Keying (DPSK), 4-phase
EDAC	Golay (24,12) hard decision
Diversity	2(SB) (2400 BPS); 2(SB), 2 (in-band) (others)
Manufacturer	GTE Sylvania ESE Eastern Division 77 A Street Needham Heights, Massachusetts 02194

TABLE 9. TECHNICAL DATA MD-5254B MODEM
[Ref. 33: p. 24; Ref. 36]

Data Rates	75, 150, 300, 600, 1200 and 2400 bps
Tone Libraries	single tone
Doppler correction	(information unavailable)
Bandwith (nominal)	3 KHz
Synchronization	(information unavailable)
Modulation	Phase Shift Keying (PSK), 8-phase
EDAC	convolutional code, constraint length 7 Rate 2/3 at 2400 bps Rate 1/2 at 75 to 1200 bps
Diversity	interleaving - long (10 sec) or short (1.25 sec)
Manufacturer	Harris Corporation RF Communications Group 1680 University Avenue Rochester, New York 14610

Data rates and coding levels operator selectable via a front display panel which provides real time data quality display. The HSM-1A is adaptable to frequency hopping and its modular construction allows conversion to a 16 tone parallel modem. Selected technical data for the HSM-1A is shown in Table 10. [Ref. 31: p 447; Ref. 33: p 11; Ref. 37]

3. Echotel

The Echotel utilizes adaptive equalization and phase shift keying to provide low error rate transmissions up to 2400 bps. It is also capable of higher data rates via intermittent transmissions and buffers which maintain continuous data processing at the receiving end. Selectable sampling rates allow the Echotel to utilize low frequency (LF) and very low frequency (VLF) with any additional modification. Signal quality is continuously displayed on the front control panel. Selected technical data for the Echotel is shown in Table 11. [Ref. 31: p. 427; Ref. 38]

TABLE 10. TECHNICAL DATA HSM-1A MODEM
[Ref. 31: p 447; Ref. 33: p. 11; Ref. 39]

Data Rates	300, 600, 1200 and 2400 bps
Tone Libraries	single tone, convertible to 16-tone PSK
Doppler correction	(information unavailable)
Bandwith (nominal)	2000 Hz centered at 1600 Hz
Synchronization	synchronous, asynchronous
Modulation	8-ary Phase Shift Keying (PSK)
EDAC	adaptive equalization 2/3 rate convolutional code, Viterbi decoding
Diversity	(information unavailable)
Manufacturer	Frederick Electronics Corporation Hayward Road P. O. Box 502 Frederick, Maryland 21701

TABLE 11. TECHNICAL DATA ECHOTEL MODEM
[Ref. 31: p. 427]

Data Rates	50, 75, 150, 300, 600, 1200 and 2400 bps
Tone Libraries	single tone
Doppler correction	+/- 75 Hz initial; tracking up to 3.5 Hz per second
Bandwith (nominal)	3 KHz
Synchronization	(information unavailable)
Modulation	Quaternary Phase Shift Keying (QPSK), 4-phase;
EDAC	coherent, Decision Feedback Equalizer, continuously adapted to HF-channel
Diversity	(information unavailable)
Manufacturer	Aeg-Telefunken Postfach 1730 7900 Ulm (Donau) Federal Republic of Germany

C. Modem Test Results

It is beyond the scope of this thesis to present a comprehensive listing of test results. The test results presented in this section are representative of the performance observed or expected for HF serial or parallel modems. It should be noted that these test results were selected from available unclassified literature. The fact that Harris, GTE-Sylvania, and Rockwell-Collins dominate the results presented on the following pages, simply reflects what was available in the unclassified literature, but it remains representative of current technology.

1. Rome Air Development Center (RADC)- HF Modem Test, 1981.

Under the control of RADC, Signatron Inc. in 1981 conducted computer simulated testing of a newly developed serial modem. The simulation compared a new, less complex decision feed-back equalizer (DFE) with the performance of a Harris Corporation serial modem and previous test results of parallel modems. The new DFE serial modem out performed the parallel modems and was comparable with the Harris serial modem (5254A). The Harris serial modem and the new DFE modem both demonstrated a 6 to 10 db gain over the parallel modems. [Ref. 40: p. 6-2]

2. (RADC)- HF Modem On-the-Air Test, 1982.

During 1981 and 1982, RADC conducted on-the-air long haul HF perfomance tests with a Harris serial modem, a GTE-Sylvania serial wide band HF modem with ARQ, and the current parallel modem, AN/USC-12A. The Eastern Space and Missile Center had identified a requirement for a 4800 bps modem to replace the aging 2400 bps AN/USC-12A. The test indicated that serial tone modems would provide increased data throughput by a factor of 2 with equal or better BER when compared to the AN/USC-12A. [Ref. 41: p. 31]

3. Rockwell-Collins Adaptive Serial Modem Test, 1983.

In 1983, Rockwell-Collins conducted simulated and on-the-air testing of a new adaptive serial modem in comparison with a Kineplex 16 tone parallel modem. The serial modem consistently out performed the Kineplex modem achieving a 10:1 reduction in error rate during on-the-air testing . The simulator performance results and the on-the-air results are shown in Figure 9 and Figure 10 respectively. [Ref. 42: 120]

4. U.S. Army CECOM HF Modem Test, 1984

Harris Corporation and the U. S. Army conducted long haul HF test of a Harris serial tone modem, an AN/USC-12A parallel modem, a Rockwell-Collins serial modem (TE-233S), and a Rockwell-Collins parallel modem (TE-233P). This test was conducted in 1984 and verified previous tests of the AN/USC-12A in that the Harris serial modem provided double the data transfer rate with equal or better bit error rate. Neither Rockwell-Collins modem performed as well as the Harris modem. The performance results are shown in Figure 11. [Ref 43: p. 157]

5. Honolulu-Canberra HF Modem Test March 1987

In March 1987, the Advanced Engineering Laboratory of Australia with the cooperation of the Defense Communication Agency, Pacific and NAVCAMS EASTPAC, conducted extensive testing over a 8300 km transequatorial HF radio circuit. The test results should be released to DCA-PAC/P406, Wheeler AFB, Hawaii 96854-5000, in April 1988. This test has the potential to be the most competitive, unbiased comparison of state-of-the-art commercial modems. The modems tested are shown in Table 12. [Ref 44]

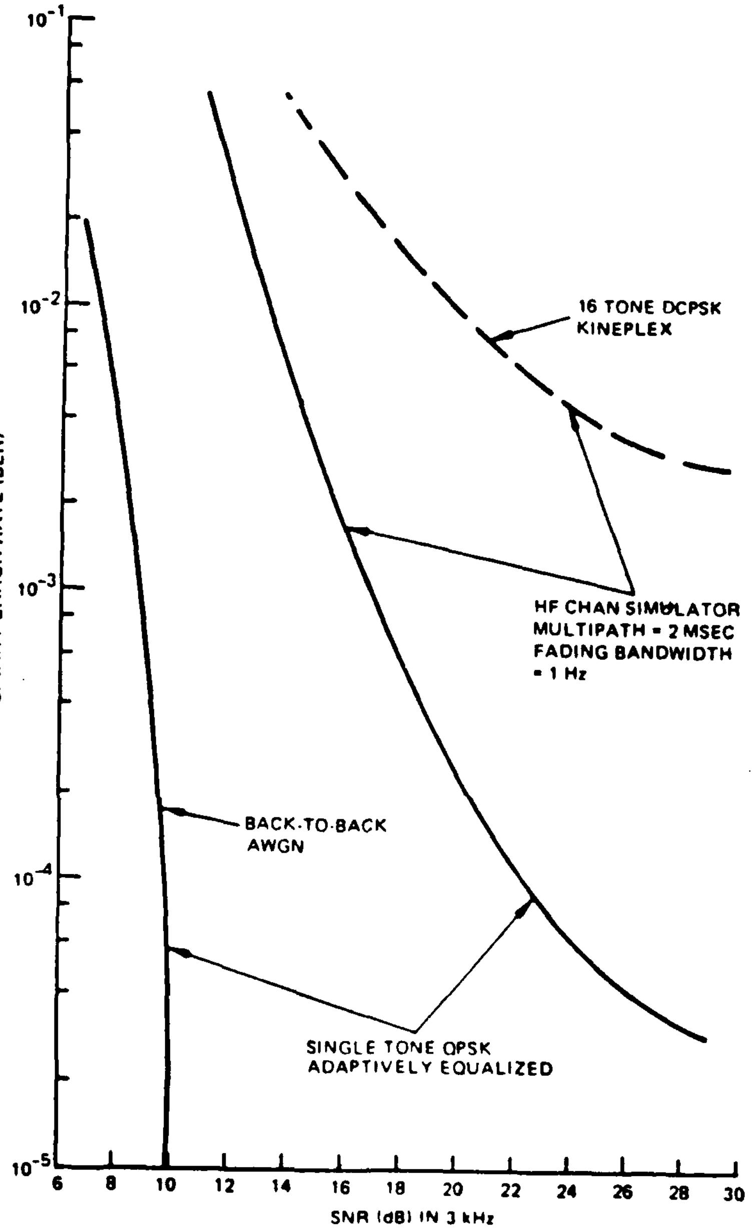

Figure 9. HF Simulator Performance Results for Single Tone and 16 Tone QPSK Modems [Ref 42: p. 120]

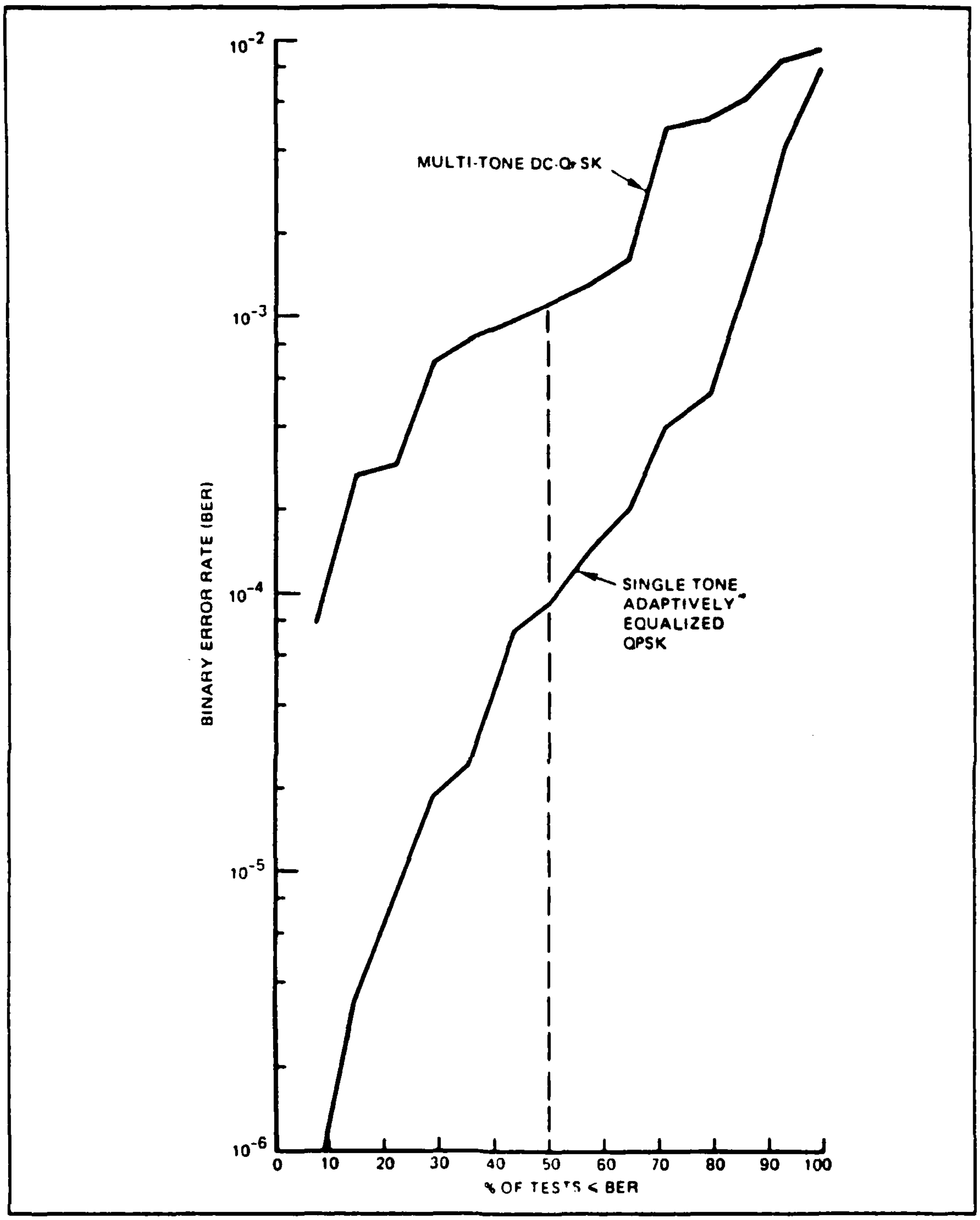

Figure 10. On-the-Air Test Results for Single Tone and 16 Tone QPSK Modems [Ref 42: p. 120]

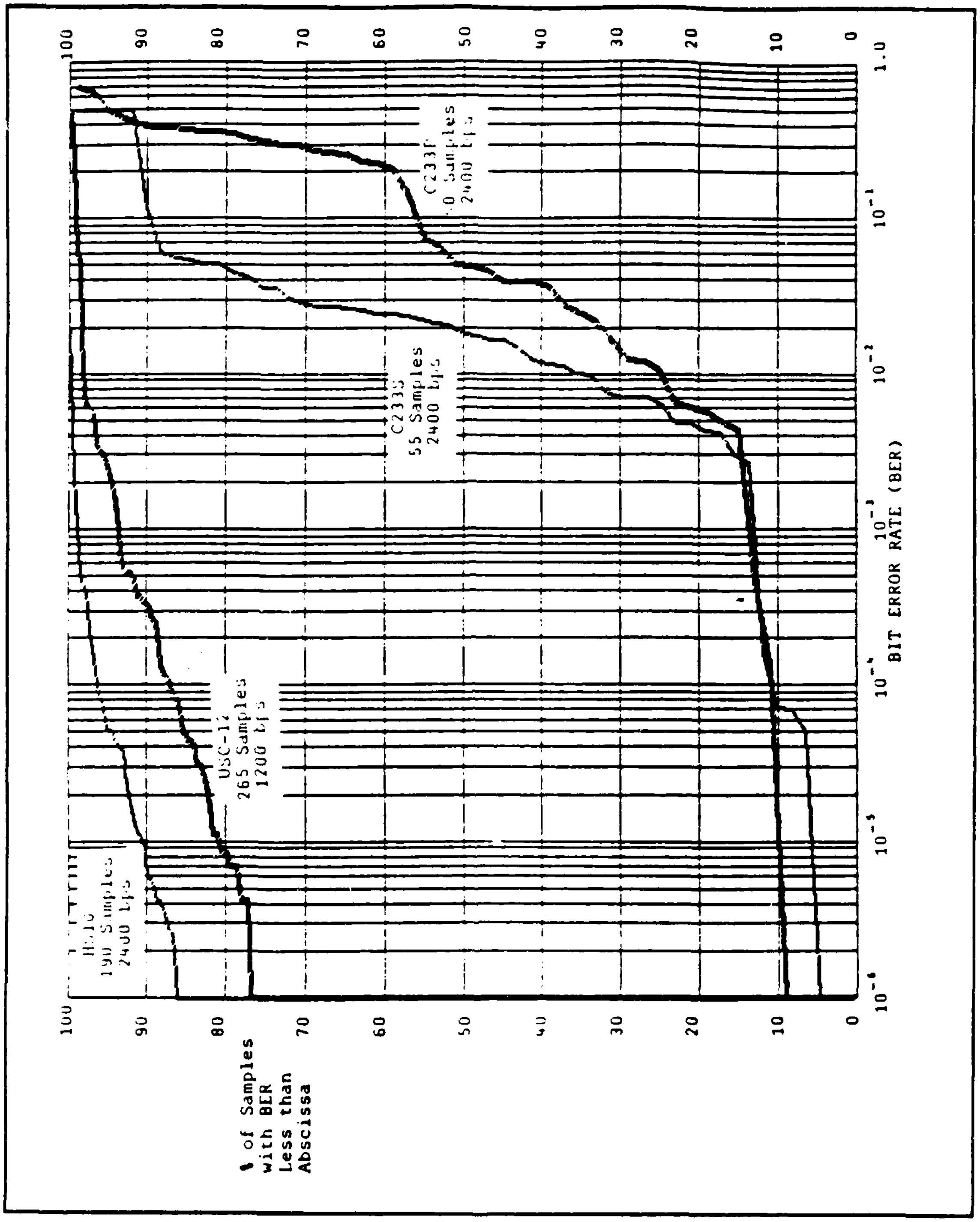

Figure 11. Probability of Achieving Specified Error Rate for Full Power Runs [Ref 43: p. 159]

TABLE 12. NDI MODEMS TESTED ON HONOLULU-CANBERRA LINK 1987 [Ref 44]

Parallel Modems	Serial Modems
Magnavox MX513B	Planatronics-Frederick HSM-1
Rockwell-Collins TE-233P	Echotel
Tadarin MD-23	Rockwell-Collins
Harris RF-3466	
Cossor CTM 1080	

VI. CONCLUSIONS/RECOMMENDATIONS

In long haul HF communications certain channel characteristics are fixed; i.e.,

- transmitter output power.
- channel bandwidth (3 Khz).
- noise power of the HF channel.

Additionally, the HF planner and manager is constrained by the complexity and cost of communication systems. As a result, a compromise between encoding scheme (thus cost) and desired probability of error for a given system must be decided. The question becomes: "Do we need the best performance and is it cost effective?" or "What is the minimum performance required and is it more cost effective?"

From the technical point of view, the areas requiring further investigation include:

- Modification of existing NDI modems to meet realistic military specifications.
- Design of interfaces for high speed teleprinters in order to utilize high-speed HF manually and interfaces for current automated message processing systems (.i.e., NAVMACS).
- Selection of a standard NDI high speed teleprinter.
- Problems unique to HF long haul network development.
- Design of efficient real-time channel evaluation (RTCE) systems.
- Design of adaptive signal generation and processing equipment.
- Design of more realistic HF simulation facilities, particularly in respect to co-channel interference models and the effects of radio frequency (RF) equipment interference in the shipboard environment.

The parallel tone modem has been the primary method of high speed HF communications in the Navy. Test results and simulations indicate that serial modem techniques exceed the performance of parallel modems. The simulations of adaptive serial techniques now in development show even greater promise when compared to parallel modems. [Ref. 13: p. 42-1]

It is recommended that adaptive equalization, forward error correction, and interleaving signal processing techniques be incorporated into the upcoming DOD high speed HF modem standard. Additionally, it is recommended that future modem modifications include operator display and audio indication of channel and modem performance

The Honolulu-Canberra test appears to be a competitive, unbiased comparison of state-of-the-art commercial modems. This is the best way for DOD agencies to initially determine the performance characteristics of NDI modem technology. Regardless of the results of this test, additional competitive performance evaluations should be conducted in a similar manner instead of relying on manufacturer supported testing programs.

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APPENDIX : GLOSSARY OF TERMS

Algorithm - A procedure for solving a mathematical problem (code) in a finite number of steps and repetition.

ARQ: automatic repeat request - A communications procedure where a unit of data is retransmitted until it is successfully received error free.

ATTENUATION - Decrease in power of a signal over a communications channel.

BANDWIDTH - Difference between highest and lowest frequency that can be transmitted over a communications channel.

BAUD - Unit of signalling or modulation corresponding to a rate of 1 signal element per second.

BER: Bit error rate - Digital measure of errors introduced by the transmission medium in a communications channel (HF). Related to signal to noise ratio (S/N).

bps: Bits Per Second - number of bits transmitted over communication channel per second, refers to the data rate of the modem.

CARRIER: continuous frequency capable of modulation by information-bearing signal.

CHANNEL: circuit or means of transmission between 2 identifiable physical locations.

CODEC: Coder-decoder - A codec provides error coding data in a transmission channel and forward error corrects data in a receiving channel.

dB: decibel - unit for measuring relative strength of signal.

DIVERSITY: signal derived from a combination of or selection from, a number of transmission channels or paths.

DOD: Department of Defense.

DPSK: DIFFERENTIAL PHASE-SHIFT KEYING.

DUPLEX: A communication system where two separate frequencies are used simultaneously or in both directions.

DCPSK: DIFFENENTIALLY COHERENT PHASE SHIFT KEYING, DCPSK is the modulation technique used in conventional multitone modems.

EDAC: ERROR DETECTION AND CORRECTION, EDAC is the algorithms used to improve modem performance by detecting and correcting modem received bit errors.

ELF: EXTREMELY LOW FREQUENCY

FEC: FORWARD ERROR CORRECTION

FFT: FAST FOURIER TRANSFORM, an FFT is used to determine frequency and amplitude characteristics of the received signal for the FSK data modes.

FLTBCST: FLEET BROADCAST

FSK: FREQUENCY SHIFT KEYING, FSK is the modulation in which different frequencies are used to represent binary 1 and 0 value of modulating wave, technique used in the 300, 150 and 75 BPS data rates.

GROUND WAVE: RADIO WAVE,characteristics of which are affected by proximity.to the ground and travel smaller distances.

HALF DUPLEX: transmission in both directions, but not simultaneously.

Kbps: thousand bits per second

Khz: kilohertz

Mhz: megahertz.

MODEM: derived from the terms modulation and demodulation. The conversion of digital output from data transmission terminal to voice frequency signals for transmission over analogue speech network and back again into digital form for acceptance by data terminal at reception end.

ms: millisecond.

MULTIPLEXING: use of common channel to make 2 or more channels either by dividing frequency band of common channel into narrower bands ,FDM, or by allotting it in turn to different intermittent channels ,TDM.

NAVMACS: Naval Modular Automated Communications System.

ODC: OPERATOR DISPLAY CONTROL -The ODC is the control and indicator module mounted on the front of the modem that houses the control push buttons and the monitor display.

PSK: phase shift keying.

QPSK: quadrature phase shift keying -utilizes 2 bi-phase subchannels to generate the final 4 phase modulation.

SIGNAL-TO-NOISE RATIO: ratio of the magnitude of a signal to that of noise.

VFCT: voice frequency carrier telegraphy.

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