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LINK-11 COMMUNICATIONS

by

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Distinctive Link-11 communication features are discussed. These features consist of Phase Shift Keying (PSK), signal generation, signal structure, and binary coding. The protocol, consisting of the frame structure, control codes, and net operation, which operates the net automatically is introduced. A review of radio equipment and its management concludes the thesis.

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Link-11 Communications

by

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of the requirements for the degree of

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ABSTRACT

This thesis provides the reader with an overview of the Link-11 system and what telecommunication assets are needed to operate the system. Fundamental aspects of High Frequency (HF), Ultra High Frequency (UHF), and communication configurations are reviewed. An examination of the Link-11 equipment operations is presented. This includes a description of the Tactical Data Set (TDS) computer and encryption device. The thesis also contains an in-depth review of the Data Terminal Set (DTS). The specific operations of the DTS that are studied are Error Detection and Correction (EDAC), audio signal generation, link protocol control, NTDS computer interface, and digital/analog conversion.

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TABLE OF CONTENTS

I. INTRODUCTION

As the world has grown both technologically and socially, the importance of protected sea lanes has steadily increased. Since man first set sail, the seas have proven to be the primary source of transporting supplies. The United States is separated from the majority of the developed nations by vast oceans, so secure sea lanes have been of utmost importance to the nation's survival.

The projection of sea power by battle group commanders has been the essence of the United States Navy. Initially, naval forces were limited to attacking and defending forces that were within the visual horizon. But the introduction of over-the-horizon weapons and surveillance techniques has brought sweeping changes in naval operations.

Today, commanders need to be able to detect hostile activities as far from their own unit as possible. Link-11 technology enables units of a battle group to exchange real-time tactical information that has been detected by their own sensors. By sharing this tactical information, commanders are essentially extending their own detection capabilities.

A. PURPOSE

The communications over the Link-11 circuit plays a vital and integral part of battle group operations. This study is intended to provide communicators with a overview of the Link-11 system. A review of the telecommunication assets needed to operate the system is presented, and some perspectives of how communicators can manage the Link-11 network is provided.

This study's purpose is not to determine if new telecommunications technology is necessary, nor will it attempt to develop new technology. It will, however, simply review the present assets available to achieve efficient Link-11 communications in support of the battle group.

B. ORGANIZATION AND SCOPE

The Link-11 system is an intricate and complicated computer-to-computer communications exchange network. The best way for communicators to manage a system is to understand all the aspects of that system. To provide this managerial perspective of Link-11, the entire system is presented in the following chapters.

Chapter II covers the basic fundamentals of communications to prepare the reader for an in-depth study of Link-11. It is comprised of a review of communication terminals, switching equipment, transmission media, and radio frequencies.

Chapter III is a general description of Link-11. This chapter presents a description of the different Tactical Digital Information Link (TADIL) networks and some data link terms. It develops an understanding of the system operation and the equipment used to exchange the digital information.

Chapter IV is a detailed presentation of the Link-11 signal generation that includes phase shift keying, signal structure, and binary encoding. This chapter also discusses the particulars of the Link-11 network protocol.

Chapter V provides a discussion of some managerial aspects of the system; chapter VI touches on possible net alternatives and summarizes the thesis.

II. COMMUNICATION FUNDAMENTALS

A telecommunication circuit can contain a seemingly limitless amount of equipment to enable two or more stations to transfer information between them. "Three essential elements comprise any communications system: terminals, switches, and transmission." [Ref. 1:p. 2-1] These are the basic elements needed to construct a circuit as illustrated in Figure 1. Many more devices are typically added to the circuit to produce the type of communications desired.

A. TERMINALS

"Of all the communications equipment, terminals are probably the most familiar to the user." [Ref. 1:p. 2-1] Terminals can consist of any number of items depending on the type of information to be transmitted and the type of transmission media used. A telephone is a terminal that is common to most people. Other types of terminals include: radio, video, facsimile, and teleprinters.

B. SWITCHING

"Switching is the means by which user traffic is routed through a communications system." [Ref. 1:p. 2-2] These switches may be manually operated, like the old telephone operator switchboard, or they may be automatic. These

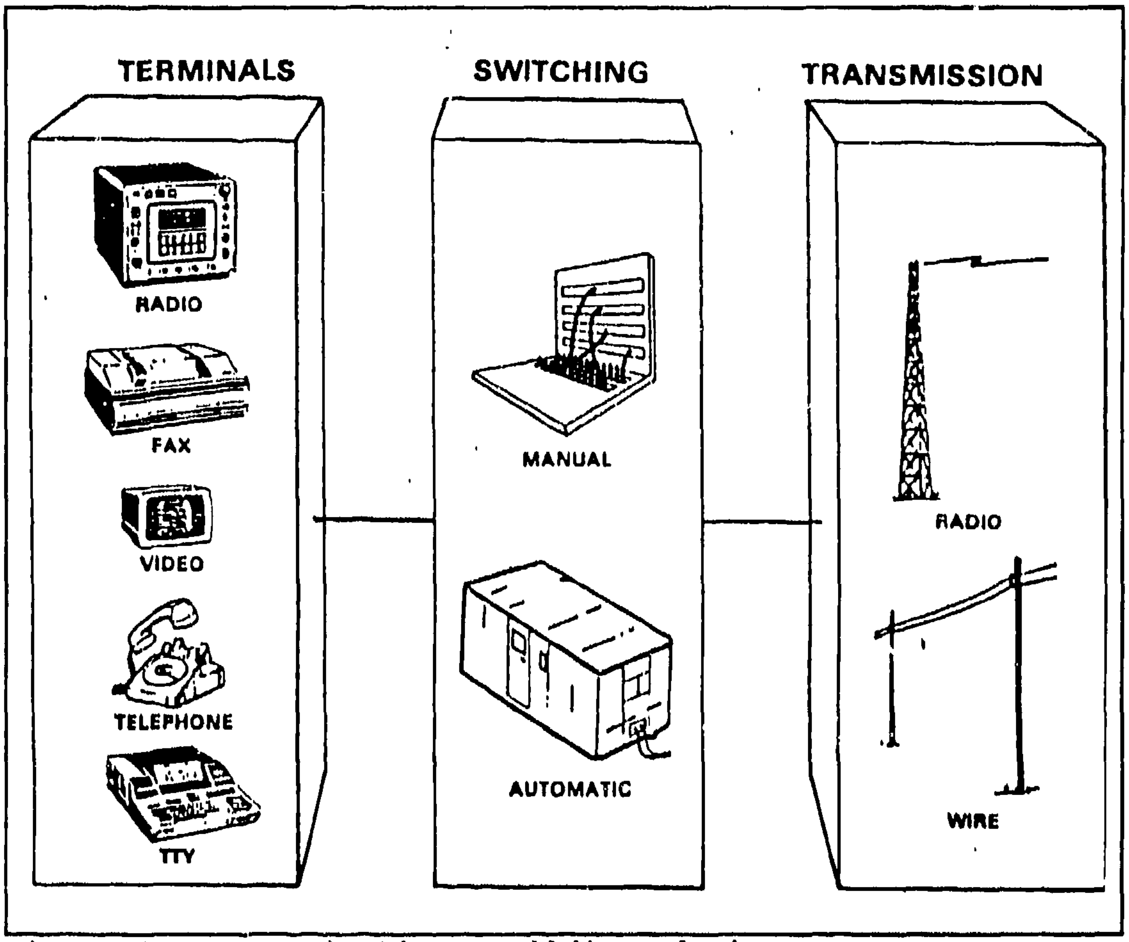

Figure 1. Communications Building Blocks

switches my be local and support only local users, or they may operate networks that cover entire nations.

There are two types of switches, circuit and message switches. Circuit switches are generally used to transmit voice transmission, but they can be used to transmit message data. Message switches are more suited to the transfer of electronic data. Message switches can be further broken down into store-and-forward or packet types. Store-and-forward switches have intelligence in them that allow them to store parts of a message in memory and then forward the message when the entire message has been received. Packet switches are more adapted to handling data, since the information to be transferred may be broken down into small packets that may travel several different paths to arrive at the destination. [Ref. 1:p. 2-2]

C. TRANSMISSION

"Traffic exchanged between users travels between points over radio waves, wire or cable landlines or a combination of the two." [Ref. 1:p. 2-3] These transmissions are directed by switches which operate as an interface between terminals and the transmission media. Transmission media consist of twisted pair wire, coaxial cable, fiber optics, and radio waves. The transmission of Link-11 from user to user is generally accomplished with radio waves, while on-board transmission is accomplished through "patch panels" with twisted pair wires.

D. RADIO FREQUENCY (RF)

"The usable radio frequency spectrum extends from 30 Hertz (Hz) to 300 Giga (billion) Hertz (GHz)." [Ref. 1:p. 2-15] Being a part of the electromagnetic spectrum, radio waves travel at 186,000 miles per second (the speed of light). Radio frequencies cover just a small portion of the electromagnetic spectrum, and Link-11 is used only in the High Frequency (HF) and Ultra High Frequency (UHF) ranges.

1. High Frequency

The HF portion of the frequency spectrum is from 2 to 30 MegaHertz (MHz). HF has traditionally been used for long haul communications for surface ships. The ground wave can deliver ranges of up to 300 miles. HF also has a sky wave component associated with it that allows communications of up to one thousand miles, and sometimes several thousand miles, depending on the atmospheric conditions.

2. Ultra High Frequency

The Navy's UHF equipment operate in the 225-400 MHz range. UHF is typically a line-of-sight (LOS) frequency band and is used only for short range communications. Depending on the height of the transmitting and receiving antennas, propagation ranges of 20-30 miles may be expected for ship-to-ship transmissions. For surface-to-aircraft communications, ranges vary depending on the altitude of the aircraft.

III. GENERAL DESCRIPTION

The introduction of over-the-horizon weapons triggered a new era of battle management for the force commander. The Department of Defense has expended an extensive portion of the nation's research and development funds to exploit this capability and to produce an adequate defense against it. The development of several Tactical Digital Information Link (TADIL) has given force commanders an additional and essential capability to effectively fight in an over-the-horizon environment.

A TADIL net enables units to exchange tactical information that has been acquired by their sensors. By obtaining the tactical situation of a unit outside the range of his/her own unit's sensors, the commander has effectively extended the detection capabilities of his/her unit.

A. DATA LINK DESCRIPTION

Units exchange tactical data information on a computer-to-computer communications link known as TADIL. Like any other telecommunications network, messages transferred over the tactical data links must convey the same meaning to both the transmitting and receiving stations. To accomplish this, message standards and protocols have been established for intraservice use by each of the four branches of the military, for interservice use, and for use between U.S. and military allies. JCS exercises control over U.S. standards, while the CNO maintains standardization of data links for the Navy. [Ref. 2:p. II-1]

Link-1 is a NATO digital data link between land-based units. It is a two-way, full-duplex, secure, point-to-point link. Link-4A is the NATO designation of TADIL C. It is a one- or two-way non-secure UHF data link that controls interceptor aircraft through surface-to-air, air-to-air, and air-to-surface computer interface. Link-1 and Link-4A have unique message standards and protocols and do not communicate between each other or directly interface with Link-11/TADIL A. Link-14 is the NATO designation of a one-way teletype broadcast that is designed to provide information obtained in the Link-11 environment to non-NTDS ships. [Ref. 2:p. II-1]

> Link-11 is the NATO designation of TADIL A. The Navy has adopted the term Link-11 in order to maintain commonality within the NATO arena. Link-11 is a tactical data information link employing netted communication techniques and standard message format for the exchange of digital information. Link-11 is a half-duplex netted, normally secure, digital data link that normally operates in a roll call mode under control of a Net Control Station (NCS). Link-11 provides for the mutual exchange of information among net participants via HF or UHF radio. Tactical data processing equipments, located at each station, are linked together via a common transmission medium into a netted configuration. [Ref. 2:p. II-1]

TADIL B is a full-duplex, two-way, point-to-point digital data link. It provides a telecommunications link for the transfer of data between units of the Army, Air Force, Marine Corps and Special Information Systems (SIS). Although the message standards are the same as Link-11, the equipment, protocols and data rate are different; therefore, TADIL B cannot be directly interfaced with Link-11. [Ref. 2:p. II-2]

Link-16 is the NATO designator for the developmental link known as TADIL J. Link-16 merges elements of Link-11 and Link-4A into one common system that will expand the force commander's capabilities. Link-16 is being designed to enable it to operate with existing Link-11 hardware or the Joint Tactical Information Distribution System (JTIDS) terminal. TADIL J refers solely to the message standard and protocol, whereas JTIDS refers to the multipurpose communications equipment that may be employed to operate Link-16. [Ref. 2:p. II-2]

The Navy Tactical Data System (NTDS) makes use of the TADIL system to support the battle group commander at sea. NTDS is presently supported by several TADIL components. NTDS is composed of the Link-4A, Link-11, and Link-14 components of TADIL.

B. DATA LINK TERMS

The following terms and definitions are provided from the Link-11 Operating Procedures (OPNAVINST C3120.39B) for the reader as a basis in understanding the NTDS dialect.

1. Link-11 Unit

A Link-11 unit is a platform capable of exchanging Link-11 information. These units include: ships, submarines, aircraft, shore facilities, interservice forces, and allied forces (NATO).

2. Tactical Data System (TDS)

TDS's are the computers that supply tactical digital information to the net participants. They retrieve and process incoming digital tactical information received from other net participants.

3. Participating Unit (PU)

A PU is Tactical Data System (TDS) unit that is operating in a Link-11 net in any mode of operation.

4. Forwarding Participating Unit (FPU)

A FPU is a Link-11 unit capable of exchanging data on TADIL B. It has been designated to forward data between TADIL A and TADIL B, thereby actuating a TADIL A/TADIL B configuration. Combinations of this type are often used for Joint Tactical Air Operations (JTAO).

5. Gridlock

Gridlock is a procedure for eliminating induced track position errors caused by navigational errors, radar alignment errors and data transformation errors between two TDS units. Force gridlock is the process of adjusting the local tactical grid of each unit to that of a designated gridlock reference unit, thereby simultaneously gridlocking all units.

6. Net Coordinator

The net coordinator is responsible for the technical operation of the Link-11 net.

7. Unit System Coordinator

The unit system coordinator is responsible for monitoring and analysis of Link-11 performance on board his own unit. The unit system coordinator communicates with the net coordinator concerning Link-11 performance.

8. Unit Net Coordinator

The unit net coordinator is responsible for evaluation of Link-11 performance on board his own unit and for the operation of Link-11 data terminal equipment. The unit net coordinator communicates with the net coordinator on the Data System Admin circuit. The functions of unit system coordinator and unit net coordinator may be combined on board some units, depending on equipment configuration.

C. SYSTEM DESCRIPTION

Link-11 functions as a computer-to-computer communications link to exchange information between shipboard, airborne and land based tactical data systems of the U.S. Navy. Figure 2 is a diagram of the various configurations from which the Link-11 system can be interfaced. [Ref. 2:p. II-4]

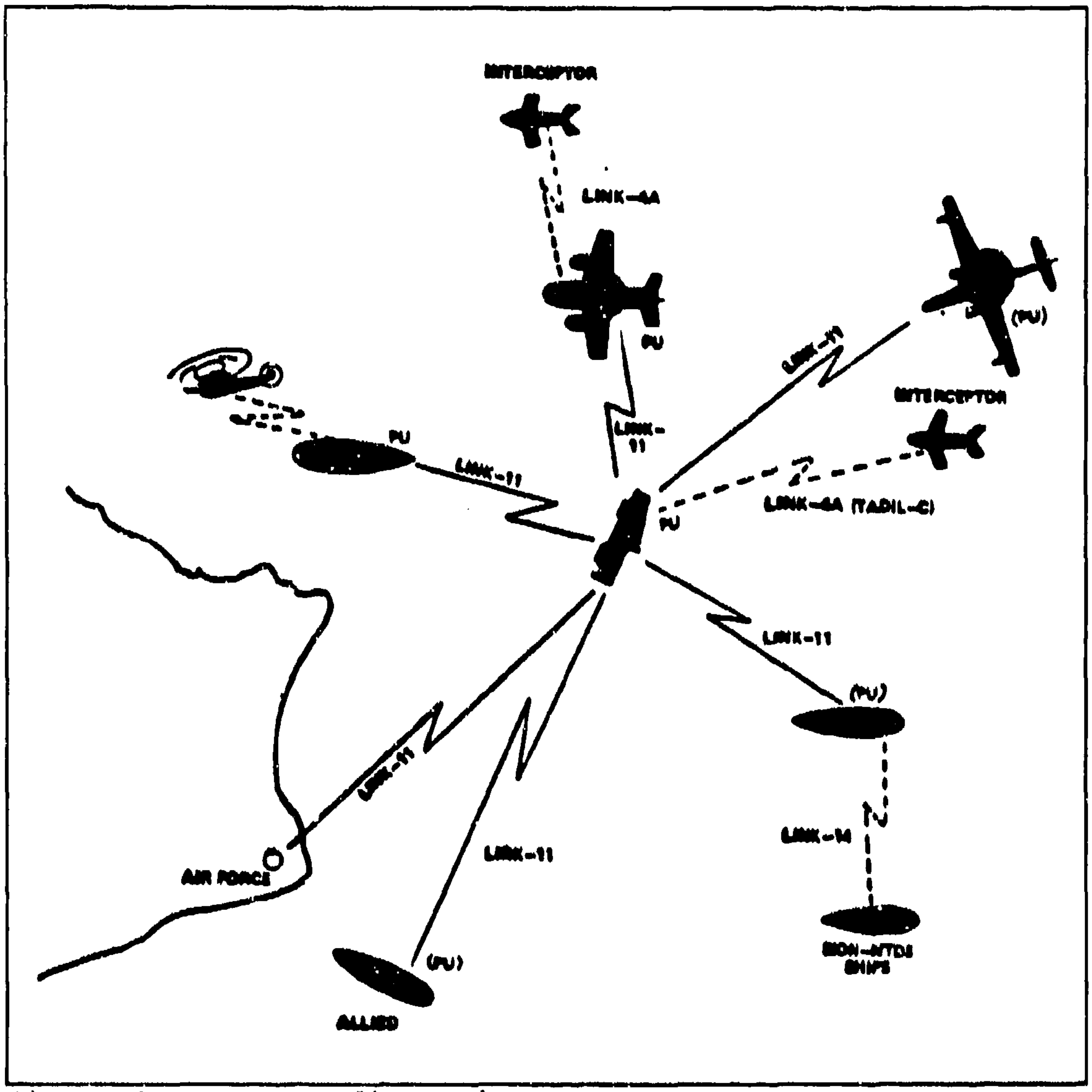

Figure 2. NTDS Configuration

"Link-11 employs netted communications techniques and standard message formats for the exchange of digital information." [Ref. 3: p.1-2] Data processing equipment located at each unit, henceforth referred to as the TDS computer, is linked to the other units via HF or UHF radio. The Link-11 data terminal set acts as a control interface between the data processing equipment and the Link-11 radio equipment. The terminal converts digital information into an analog signal for transmission. It also performs the protocol functions of address and control code recognition. Once initiated, the data terminal set controls operation of the Link-11 net. A detailed description of the NTDS equipment is discussed below.

D. HARDWARE

A typical Link-11 system is illustrated in Figure 3 and contains the essential NTDS components: a computer system, an encryption device, a data terminal set (DTS), and a radio set. TDS computers generate digital messages to report contact information obtained from the units sensors. The binary message data is transferred to an encryption device, then sent on to the data terminal set.

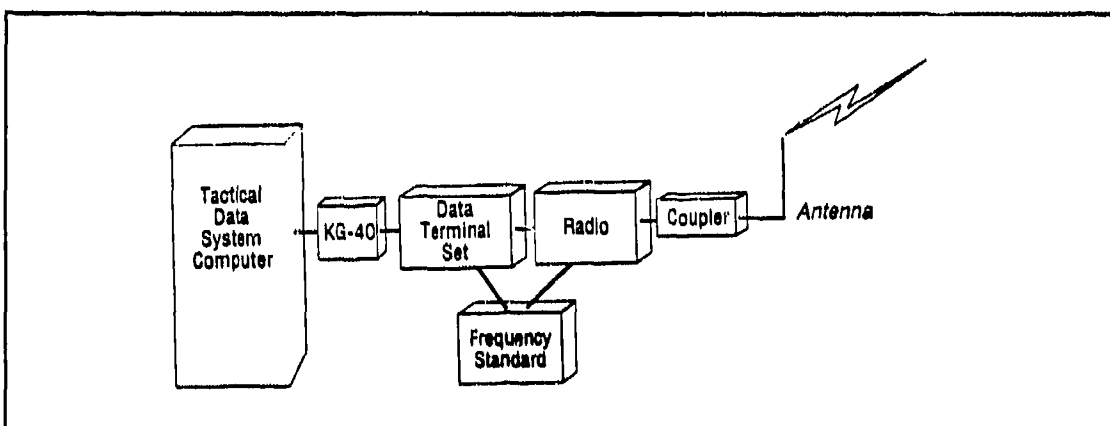

Figure 3. NTDS Equipment

"The terminal provides error detection and correction code information (Hamming codes) and control code information for use by the other terminals." [Ref. 2:p. II-8] Hamming codes serves as a coding system that is added to a message enabling the receiving station to make corrections to digital information if the message has minimal errors. A further explanation of Hamming codes is discussed later in this chapter.

Like modems for home computers, the data terminal set changes the binary information into audio tones used to modulate the radio frequency carrier. The flow of data through the NTDS equipment is shown in Figure 4 for transmitting and in Figure 5 for receiving.

1. The Tactical Data System (TDS)

"The TDS receives data from sensors, such as radar, navigation systems, and operators." [Ref. 3:p. 1-4] The TDS computer collects this information in digital data bases. The information is arranged into standardized message formats so it can be exchanged with other TDS units. The TDS computer has a memory buffer that stores incoming and outgoing messages. This buffer holds the outgoing messages until the data terminal set is signaled to transmit over the Link-11 net. When receiving information over the net, bursts of messages are stored in the buffer until the TDS computer processes them.

The TDS equipments that are specific to the Navy are often referred to as NTDS computers. Although there are different

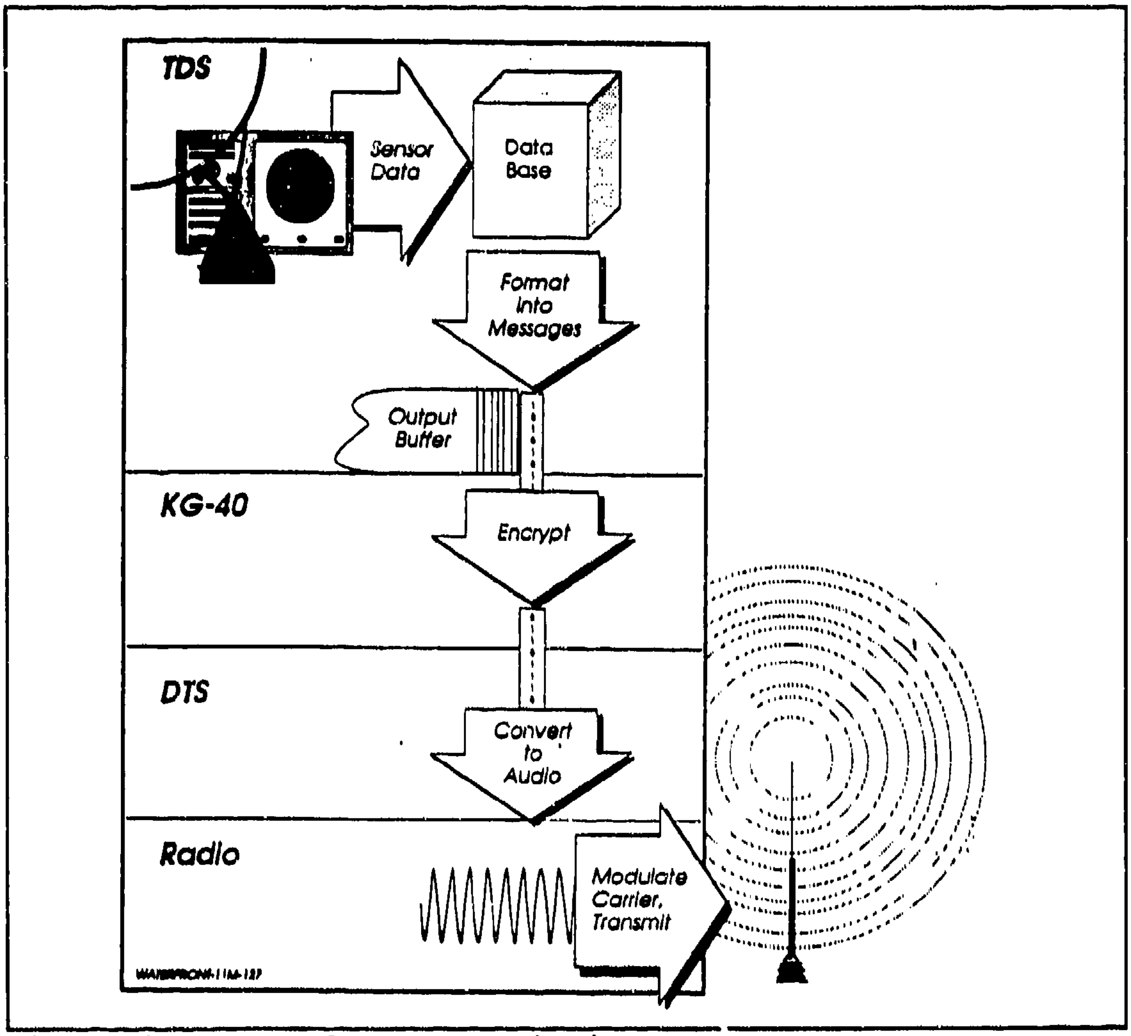

Figure 4. Data Flow (Transmission)

NTDS models, they all perform the following basic functions:

-"Supplying tactical digital information to net participants.

-Retrieving and processing incoming tactical digital information received from net participants." [Ref. 3:p. 1-8]

In addition to sustaining the tactical data base, the NTDS computer manages the display functions for the operator, performs track updates on contacts, and replies to operator inquiries.

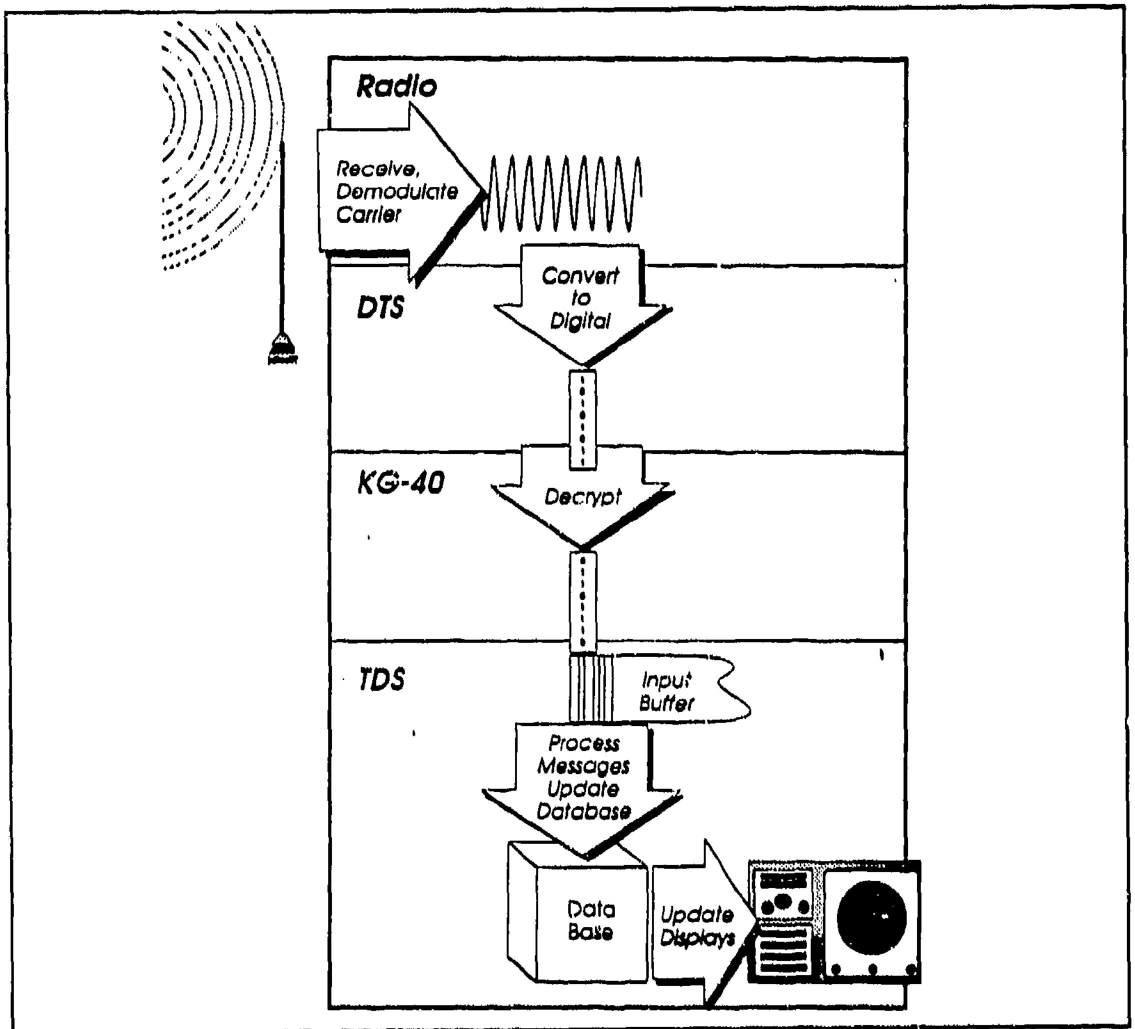

Figure 5. Data Flow (Receiving)

2. Encryption Device

All NTDS units are equipped with the KG-40 encryption device to ensure encryption of all data transmitted over the net. The encryption of the information passed over the Link-11 net is required for maintaining an advantage over opposing forces. Opposing forces will react differently if they know whether they have been detected or not, or they don't know if they have been detected. Proper operation of the crypto device is crucial to the exchange of tactical information.

3. The Data Terminal Set

The Data Terminal Set (DTS) is the heart and soul of the Link-11 net. As the primary element of the Link-11 net, the DTS controls the operation of all the NTDS equipment on board the ship. "The DTS is designed as a Modular/Demodulator (MODEM)." [Ref. 3:p. 1-17] Its normal mode of operation is in the half-duplex mode, when it can either transmit or receive. The exception is when it is in test mode when it can transmit and receive at the same time. There are five other functions that the DTS controls on a continuous basis.

a. Error Detection and Correction

The receiving DTS is capable of making corrections to the received message if there are minimal errors in the data word. It accomplishes this with the aid of the Hamming code system. Each data word is made up of twenty-four bits. Six control bits are added to the data word to check the parity of the bit pattern. In checking the parity of the bit pattern, if one bit is in error, the control bits can determine which bit is in error and correct it. "A selection on the DTS determines whether a detected error is to be labeled or corrected." [Ref. 3:p. 1-20]

There are many different versions of Tactical Data System software, (i.e., NTDS, ATDS for strickly air operations, and the other TADIL nets). Some allow messages with errors to be corrected or discarded. But, "all NTDS systems discard the message containing the error, whether corrected or not." [Ref. 3:p. 1-13] Since units are continuously updating each other every few seconds, a single discarded message will not significantly degrade the net.

b. Audio Signal Generation

"The newly formed 30-bit word is used to phase-modulate internally generated audio tones. The phase-modulated audio tones, together with Doppler correction tone, are then combined into a composite audio signal that is applied to either the HF of UHF radio equipment for transmission." [Ref. 3:p. 1-20] The Doppler correction tone is used to ensure that all the units in the Link-11 net are in synchronization with each other. (Phase-modulation will be covered in the next chapter.)

c. Link Protocol Control

The protocol control is what enables the system to operate automatically once it has been initiated. "The DTS generates and recognizes protocol data that controls the type and number of transmission." [Ref. 3:p. 1-20] Each message that is transmitted over the Link-11 net has a start and stop code that mark the beginning and end of each ship's transmission. There are codes in the message that identify which station is transmitting the current message and which station will transmit next. With precise timing and these protocol codes, all the units are able to continuously update each other on contact information in seconds.

d. *NTDS Interface Control*

The interface between the NTDS computer and the Data Terminal Set is controlled by the DTS. Although the crypto equipment operates between the NTDS computer and the DTS, it simply encrypts the data and transfers it. The KG-40 operation appears transparent to the NTDS computer and the DTS.

The DTS signals the NTDS computer when it wants data for transmission over the Link-11 net and when it has data for the NTDS computer to process and display on the operator monitors. "The NTDS computer supplies and receives digital information only after being notified to do so by the DTS." [Ref. 3:p. 1-21]

e. *Digital/Analog Conversion*

The fifth operation of the DTS is merely the conversion of data signals from digital to analog during transmission, and from analog to digital when receiving.

E. DTS MODES OF OPERATION

Although the Link-11 system is designed to operate automatically, there are some special modes of operation in addition to the normal set-up. The four basic modes of operation are Roll Call, Net Sync, Net Test, and Radio Silent.

1. Roll Call Mode

"This is the normal mode of Link-11 operation for full utilization of force area surveillance and tracking capabilities." [Ref. 2:p. II-8] In the roll call mode, one unit is designated as the Net Control Station (NCS) while the other units operate in the picket mode. The NCS data terminal controls the sequence of stations transmitting over the Link-11 net by calling on itself and each picket station in turn. Picket stations assume control of the net only temporarily for transmission of own unit data when called on by the NCS. This net roll call cycle is automatic once initiated.

The time it takes for all the units to transmit their information is called the Net Cycle Time (NCT). The NCT is variable, and depends on the number of units in the net, the amount of data each transmits, and the net timing rate specified (fast or slow). The assignment of the NCS only determines which unit's DTS will perform the NCS function and is no way related to the command or authority to control the operation of the link or force units.

2. Net Sync Mode

The net sync mode is a special purpose mode that permits the terminal of each picket station to synchronize its internal timing to that used by the NCS terminal. [Ref. 2:p. II-9]

3. Net Test Mode

The net test mode is used to test terminal operations. Specified test data is transmitted by the NCS. An automatic comparison and analysis is accomplished by each unit so that the operators will be able to verify normal equipment operation. [Ref. 2:p. II-9]

4. Radio Silent Mode

This mode permits a unit to receive Link-11 data from the net but does allow any transmission from the unit if called on by the NCS. A unit often enables this mode just prior to joining an active net in order to sync its TDS with the NCS, thus preventing a disruption of the active net. [Ref. 2:p. II-9]

IV. NTDS COMMUNICATIONS

NTDS computers communicate with each other over radio frequencies that carry digital information. The Data Terminal Set (DTS) accomplishes this conversion by generating a sinusoidal signal, then encodes digital data onto the signal using quadrature phase shift keying modulation (QPSK). The digital information is encoded into the signal in thirty-bit words called frames.

A. SIGNAL GENERATION

The Link-11 signal is produced in the Data Terminal Set (DTS). Within each DTS is a modulator/demodulator (modem) and a sine-cosine generator. The sine-cosine generator and the modulator produce sixteen individual frequency tones that are combined together to form the data signal. Each of its sixteen tones are capable of carrying digital information.

The Link-11 system uses QPSK to encode digital data onto each of the tones. The individual sixteen tones are shown in Figure 6, along with a two tone composite preamble signal and a data signal with all sixteen tones. [Ref. 3:p. 2-8]

1. Phase Shift Keying (PSK)

Digital information may be represented on an analog signal by shifting the phase of the signal. "The process of

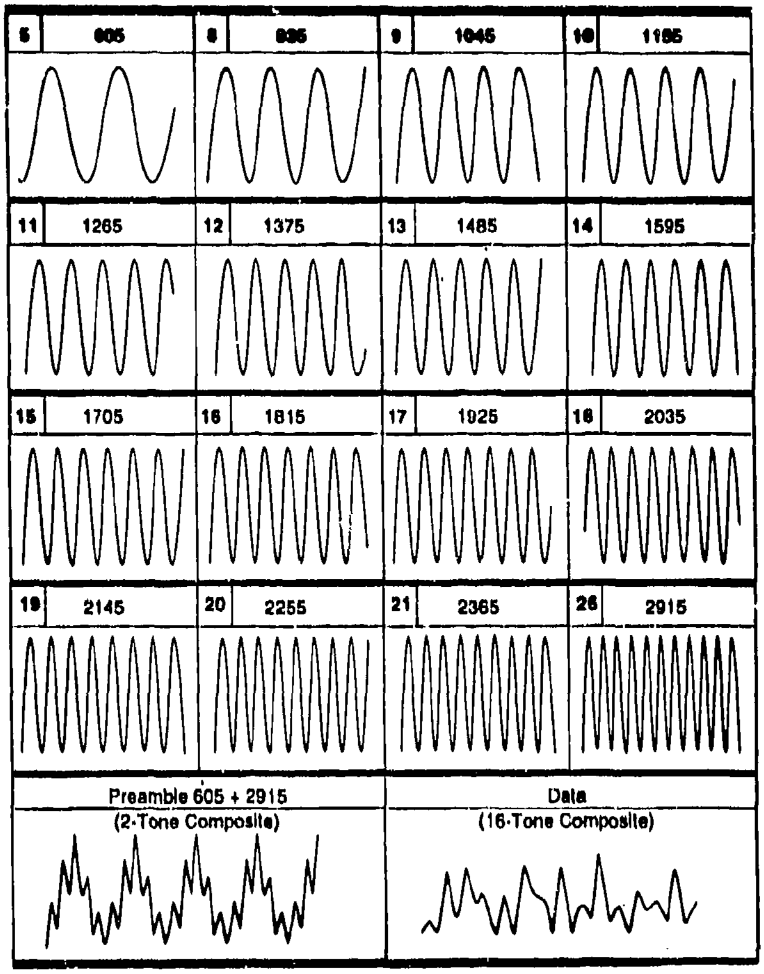

Figure 6. Tones and Their Composite Signal

phase-shift keying (PSK) utilizes a fixed-frequency sinusoid whose relative phase shift can be changed in abrupt steps." [Ref. 5:p. 325] The simplest form of PSK is to shift the phase of the signal by 180 degrees, thus representing a binary one or zero. This type of PSK is illustrated in Figure 7 [Ref. 5:p. 324].

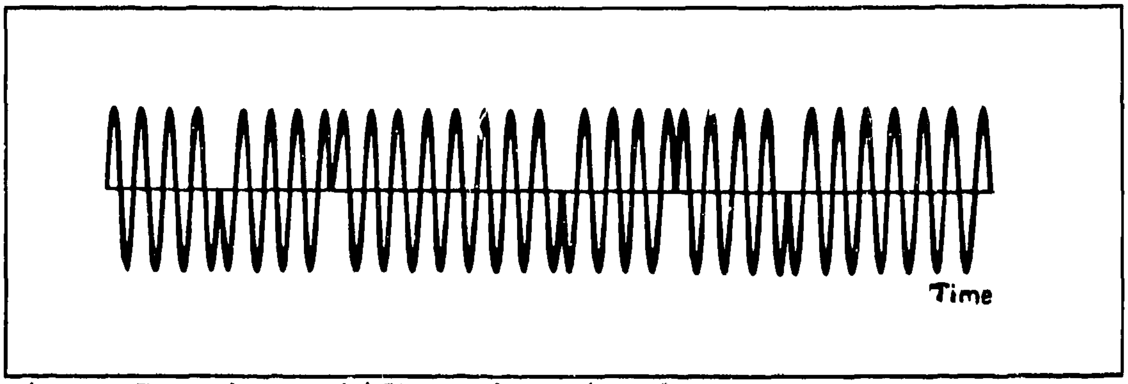

Figure 7. Phase Shift Keying Signal

The Link-11 system employs Quadrature Phase Shift Keying (QPSK). QPSK shifts the angle of the existing signal (referenced in time by the last frame) by -45, -135, -225, or -315 degrees. Since the angle can be shifted into one of four positions, each position can represent one of four binary combinations. An example of how the phase of an analog signal is shifted for QPSK is presented in the bottom half of Figure 8 [Ref. 4:p. 3-42]. The four shift possibilities and their binary values are presented in the top of Figure 8.

For the receiving DTS to recognize the phase shift, the shift can fall anywhere within the quadrant that the shift is supposed to be in. For example, if the shift is supposed to be a -45 degrees the DTS will pick up the shift if it is anywhere between -1 and -89 degrees. An error greater than that will cause the phase to fall into an adjacent quadrant. [Ref. 3:p. 2-10]

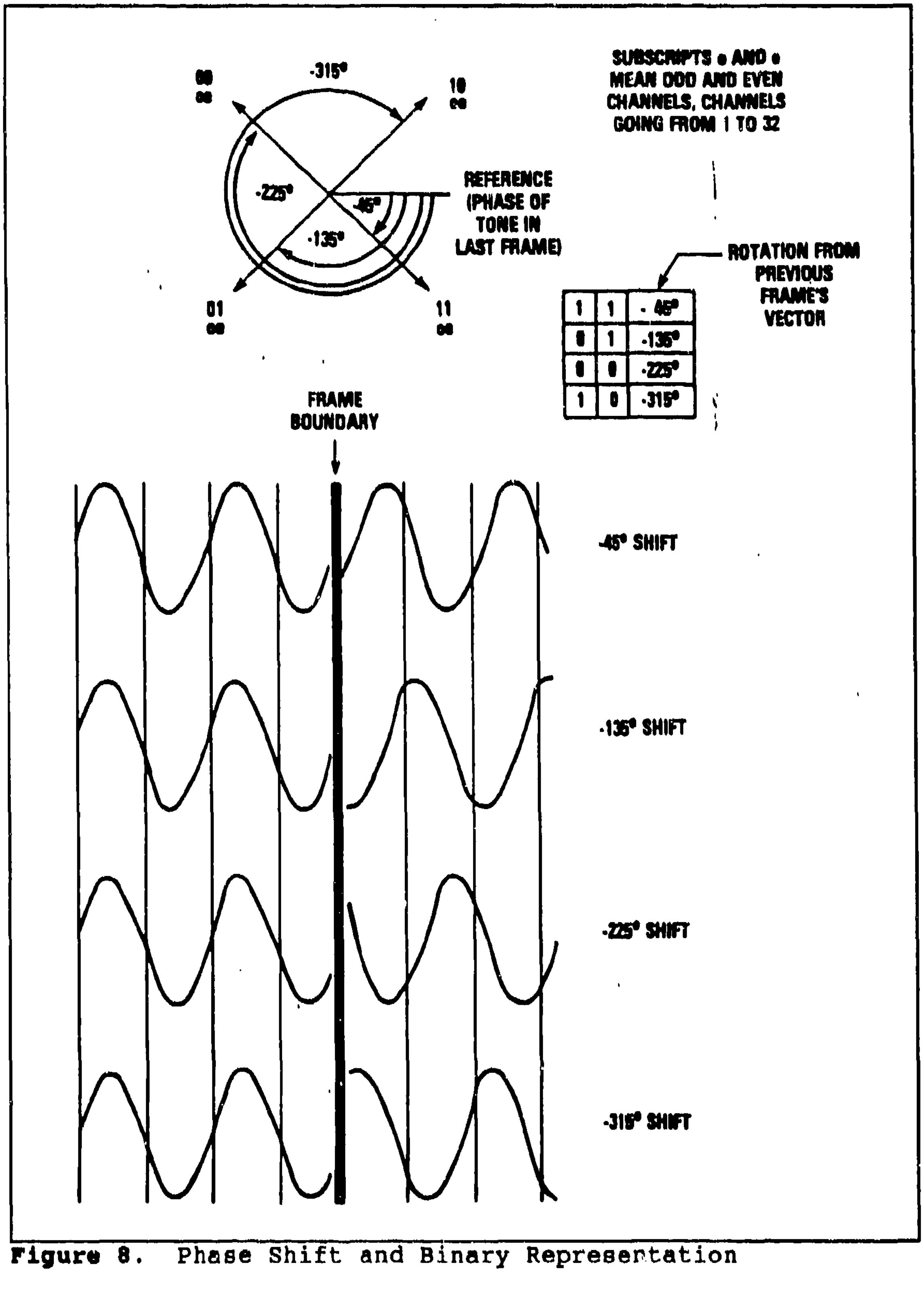

Figure 8. Phase Shift and Binary Representation

2. Signal Structure

Figure 9 is a spectral representation of the sixteen tones that are generated by the DTS [Ref. 3:p. 2-9]. To obtain the frequency of the individual tones, use the formula: (2n+1) X 55 Hertz. Using this formula the first tone is determined to be:

$$[(2 \times 5) + 1] \times 55 \text{ Hertz} = 605 \text{ Hertz}$$

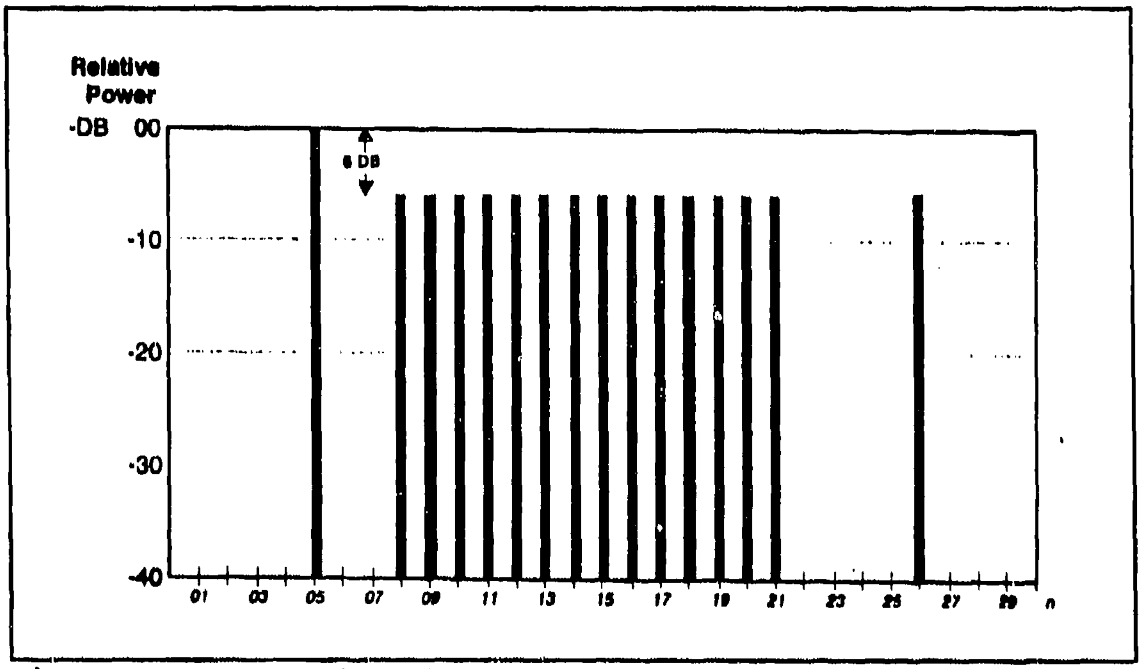

Figure 9. Tones (2n+1) X 55 Hertz

The first tone, at 605 Hertz (Hz), is known as the doppler correction tone, and is used to correct for units moving in different directions. "The (doppler) effect on the demodulated audio signal is identical to the effect of a carrier that is off frequency." [Ref. 3:p. 3-14] The DTS analyzes the 605 Hz tone of the received signal and if necessary compensates for any error. The 605 Hz tone is also phase continuous (it does not shift phases). Since it remains phase continuous it does not carry any digital data. This tone is always 6 dB higher than the other tones.

The last tone, 2915 Hz, is used for two purposes. First, it is trigonometrically added to the 605 Hz tone to create the preamble signal. Only the first and last tones are transmitted during the preamble signal as illustrated in Figure 10 [Ref. 3:p. 2-7]. To generate the preamble signal the angle of the 605 tone is held constant and the angle of the 2915 tone is shifted 180 degrees at the boundary of the five preamble frames. The 2915 Hz tone is also used to encode digital data using quadrature phase shift keying (QPSK).

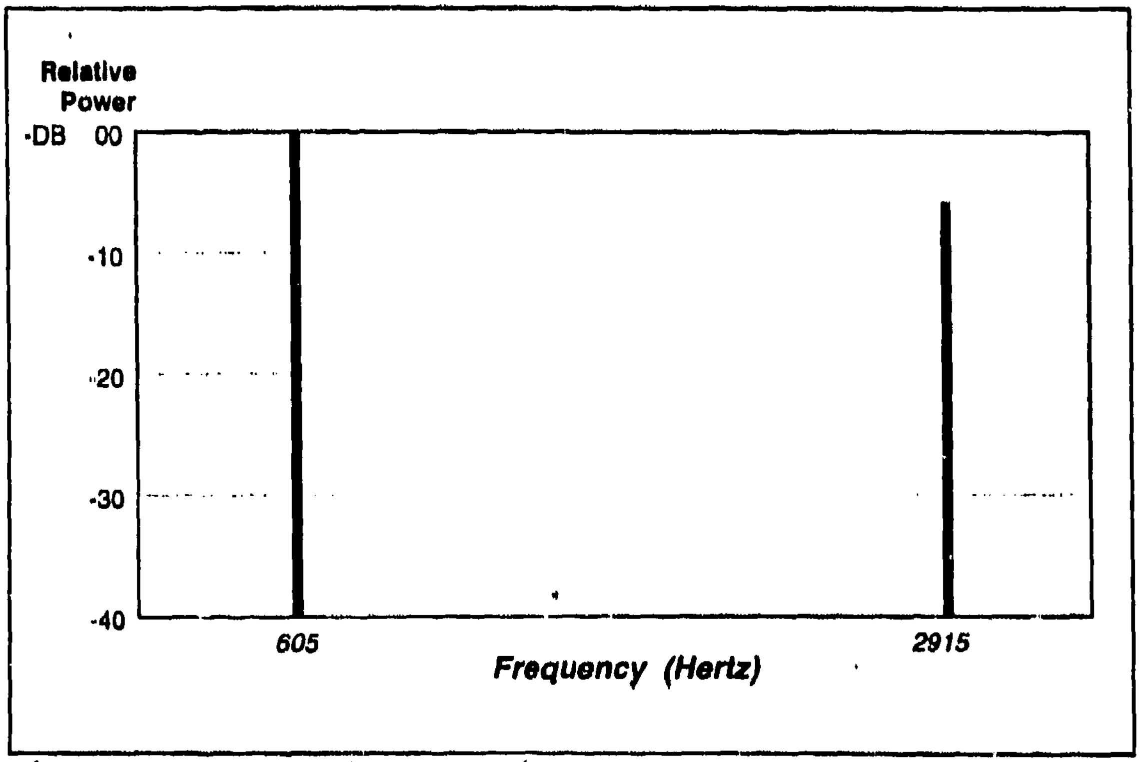

Figure 10. Preamble: The First and Last Tones

In summary the first tone is used as a reference to determine any doppler shift and generate the preamble signal. Tones two through fifteen are used exclusively to encode digital data with QPSK. Tone sixteen is used to generate the preamble signal and to encode digital data with QPSK.

3. Binary Encoding

The two-digit binary representation of the phase shift of each of the fifteen data tones allows for the representation of a thirty-bit binary word. An example of the thirty-bit binary word and its corresponding tones is shown in Figure 11 [Ref. 3:p. 2-11]. The thirty-bit word represents digital information that the DTS decodes and uses, or passes through the crypto device to the NTDS computer. Whether the DTS uses the information for net operation or passes the information depends on what types of frames they are.

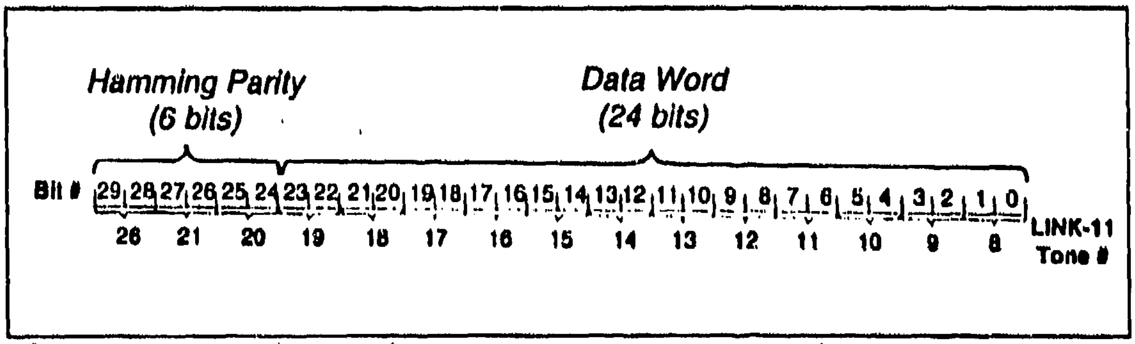

Figure 11. Thirty-bit Data Frame construction

B. LINK-11 PROTOCOL

All information exchanged over the Link-11 net is encoded into frames. The Link-11 net can operate at two different data rates. These data rates are determined by two frame times that support the Link-11 net. The fast data rate operates at 75 frames per second or 2250 bits per second (bps). The slow data rate operates at 45.45 frames per second or approximately 1364 bps. [Ref. 3:p. 2-2]

The data frames contain the tactical information that NTDS computers are exchanging. The other frames, presented in Figure 12, manage the operation of the net and allow the net to operate automatically once initiated. The frames that are not data frames are not encrypted and are generated within the DTS. These frames are composed of preamble frames, a phase reference frame and control codes as illustrated in Figure 12 [Ref. 4:p. 3-3].

Bringing together the previous sections of this chapter, the formation of the Link-11 information signal can be understood. Figure 12 illustrates the composition of the signal in time, whereas Figures 6 and 9 illustrate the spectral representations. So, at each frame boundary in time their is a change in data that is represented by a phase change of tones two through sixteen. Using QPSK, the fifteen tones make up thirty-bit words that change with the beginning of every frame.

1. Link-11 Frames

At the beginning of each transmission are five preamble frames. The preamble frames are sent to alert

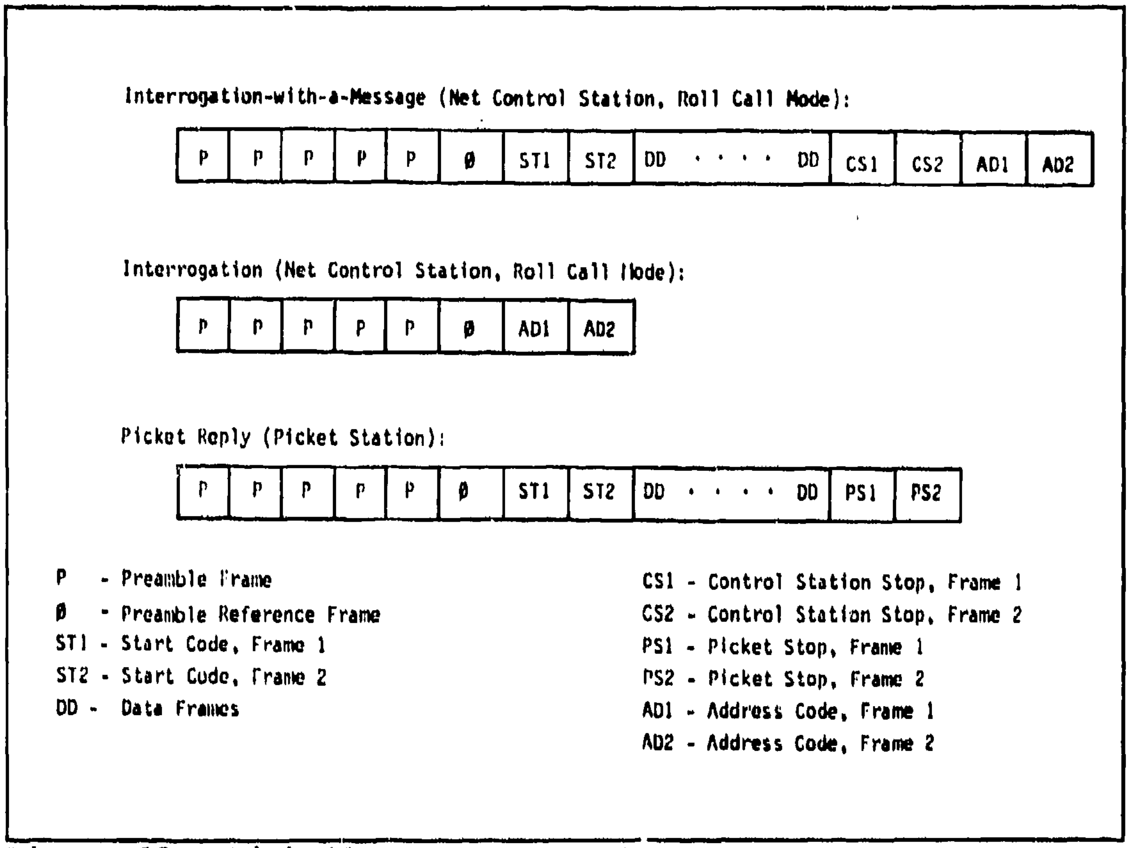

Figure 12. Link-11 Message Formats

receiving stations that a new transmission is being sent. The five preamble frames only have the first and last tones so the DTS knows that these frames are used for net operation.

The next frame is always the phase reference frame. The phase reference frame is comprised of the sixteen tones all in the same phase. There is only one phase reference frame and it provides a phase reference for each of the data tones of the following frame. [Ref. 3:p. 2-13]

As shown in Figure 12, the three different types of transmissions are interrogation-with-a-message, interrogation, and picket reply. (Within the Link-11 community, the terms

Picket Station and Participating Unit (PU) are often used interchangeably.) The first type of transmission, shown in Figure 12, is when the Network Control Station (NCS) has information to transmit to the other net participants. To save time the NCS directly follows the data message with a call-up or interrogation to the next unit in the link. The second transmission in Figure 12 is simply a call-up to a unit in the net to transmits its data. The third is the data transmission from the called or interrogated participating unit.

2. Control Codes

"The Link-11 control codes are the start code, the picket stop code, the control stop code, and the PU address codes." [Ref. 3:p. 2-13] The types of control codes that are used will depend on the type of message that is being transmitted. The control codes are transmitted with all sixteen tones using QPSK to encode data onto tones two through sixteen.

The start code is used whenever data is to be transmitted and immediately follows the preamble reference frame. The start code signals the DTS that message data is following. The DTS then prepares to pass the message data to the NTDS computer. The start code consist of two frames of thirty-bit words.

The PU address code is used by the NCS to identify which unit in the link will be next to transmit its message data. As soon as a picket station receives its address code, the picket station switches from receive to transmit and sends its message data.

The control stop code is used only by the NCS and it indicates the end of the data transmission. The control stop code immediately follows the data transmission of the NCS. Whenever a PU receives message data, it checks to see what type of stop code is used. If the stop code is from the NCS, then the PU checks to see if its address code follows. If the address code is not the code of that PU, then the PU remains in the receive mode and waits for next transmission.

The picket stop code is used only by PU's to indicate the end of its message data. When other PU's receive this stop code, they prepare to receive another transmission. Whenever NCS receives this code, it initiates an interrogation message or an interrogation-with-a-message transmission.

3. Net Operation

If start code frames follow the phase reference frame, then the DTS knows to pass the frames following them to the NTDS computer and watch for stop code frames. The start code frames and the two different types of stop code frames are always made up of the same thirty-bit binary words. These thirty bits are encoded into an octal representation of

000 = 0	
001 = 1	
010 = 2	
011 = 3	
100 = 4	
101 = 5	
110 = 6	
111 = 7	

Figure 13. Octal Representation of Binary Digits

information as illustrated in Figure 13. Since the control codes have the same thirty-bit words, then they also have the same octal representations. Their octal representations are illustrated in Figure 14.

If the frames that followed the phase reference frame were not the start code, then the DTS knows they are address codes. The DTS will compare the address code frames with its own address code to determine if its unit is next to transmit information. Note that the frames used for net operation do no contain Error Detection and Correction (EDAC) bits (Hamming Codes). EDAC bits are only used with binary words that are being passed to the NTDS computer.

77777 77777 77777 77777

Picket Stop Code

00000 00000 00000 00000

Control Stop Code

74506 04077 54673 22342

Start Code

Figure 14. Octal Representation of Control Codes

After the start code frames are received, the DTS knows that the message data frames are next. When these are received, the DTS will decode the digital data from the analog signal using the six EDAC bits to check for errors. The other twenty-four bits represents the digital information that the NTDS computers are exchanging.

These twenty-four bits are passed through the crypto equipment to the NTDS computer. The twenty-four bits represent eight octal digits. The NTDS computers use these octal digits to denote the tactical data that is transferred between the NTDS computers.

4. Net Cycle Time (NCT)

The NCT depends primarily on how many units are in the net and in what order they are interrogated. The net cycle is entirely at the discretion of and determined by the NCS. When initializing the net, operators on board the NCS enter the sequential order of the net into their DTS. The operator can enter the participating units in any order desired. The operator also can enter units into the cycle twice. This allows technologically advanced or "high value" units to be polled more often. The drawback of this is that it increases the NCT, and the other picket units that may have vital information are not polled as often. To ensure an efficient net the NCS needs to weigh these factors when determining the order of the net.

C. RADIO EQUIPMENT

Link-11 communications equipment provides a point-to-point exchange of tactical digital information among Link-11 users. This equipment may be a transmitter/receiver configuration with the equipment conducting independent operations; or, a radio may function interdependently containing both the transmission and receiving functions. These interdependent radios are called transceivers. [Ref. 3:p. 1-28]

Radios used for Link-11 must meet requirements that are different from radios designed for voice-only operations. Link-11 radios must have a quick transmit-to-receive switching time. The transmitter must be keyed before the data arrives. To do this transceivers must be able to key up for transmission within milliseconds. "Because of the speed at which the link operates, all link communication equipment must be able to keep up with the repetitive cycles of transmission and reception." [Ref. 3:p. 1-30]

1. HF Communications

"HF radios use a modulation technique called Amplitude Modulation (AM) in which the Link-11 (baseband) audio signal is used to modulate, or vary, the amplitude of the carrier."

These radios may operate in several different modes. For HF Link-11 operations, the Independent Side Band Suppressed Carrier (ISBSC) and the Single Side Band Suppressed Carrier (SSBSC) mode is available. In the ISBSC mode the carrier frequency is suppressed and the tactical data information is supplied to the Upper Side Band (USB) and the Lower Side Band (LSB) for transmission as illustrated in Figure 15. [Ref. 3:p. 1-31]

As shown in Figure 15, each side band carries the same information consisting of all sixteen tones. When operating in the ISBSC mode the exact same information is applied to both side bands. Using ISBSC the receiving stations has a better capability of receiving an accurate signal. When operating in the dual side band mode, "the receiving unit can automatically select the best data from the upper side band, the lower side band, or the diversity." [Ref. 3:p.1-32]

Link-11 HF operations are normally conducted in the dual side band setting, with the data terminal operating in the diversity mode. Communications can be accomplished using the single side band (SSBSC) mode but this is not attempted often since there is no redundancy of the signal. Single side band operation is only available in the upper side band mode. [Ref. 2:p. III-4]

2. UHF Communications

The Navy's UHF radios use a modulation technique called Frequency Modulation (FM). An example of AM and FM is illustrated in Figure 16 [Ref. 3:p. 1-34]. "This technique of modulation is more resistant to interference than the technique of amplitude modulation." [Ref. 3:p. 1-33] Since FM

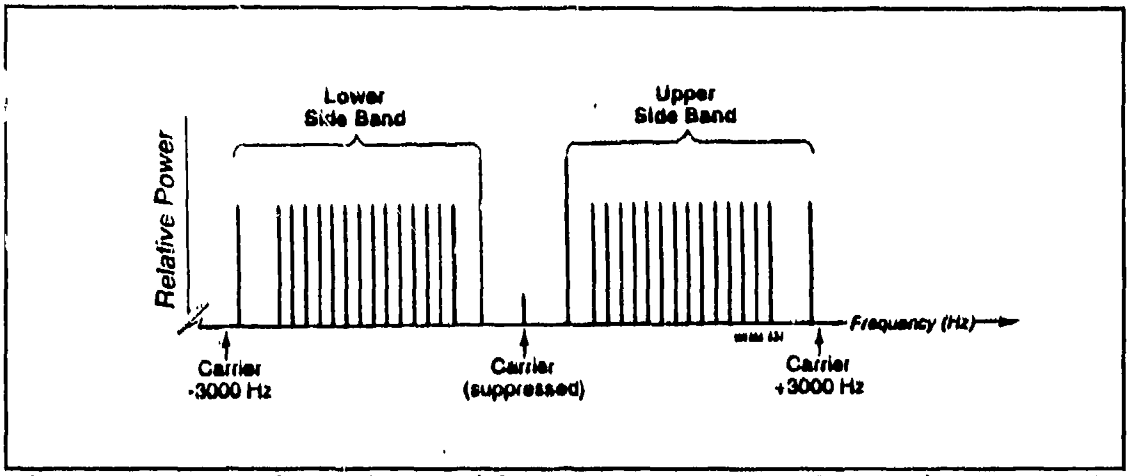

Figure 15. Independent Side Band Suppressed Carrier (ISBSC)

is more resistant to interference, the Navy's UHF radios produce clearer signals. And since UHF is line-of-sight, a measure of protection from signal exploitation can be obtained when operating Link-11 in UHF. [Ref. 2:p. III-5]

The primary disadvantage of UHF is that it is limited in range to line-of-sight. Unfortunately, UHF communications can only be employed when force size and separation permit. Transmissions from surface units under normal propagation conditions are limited to line-of-sight ranges on the order of 20 to 30 miles. The actual transmission ranges will vary depending on the height of the transmitting and receiving antennas and the existing propagation conditions.

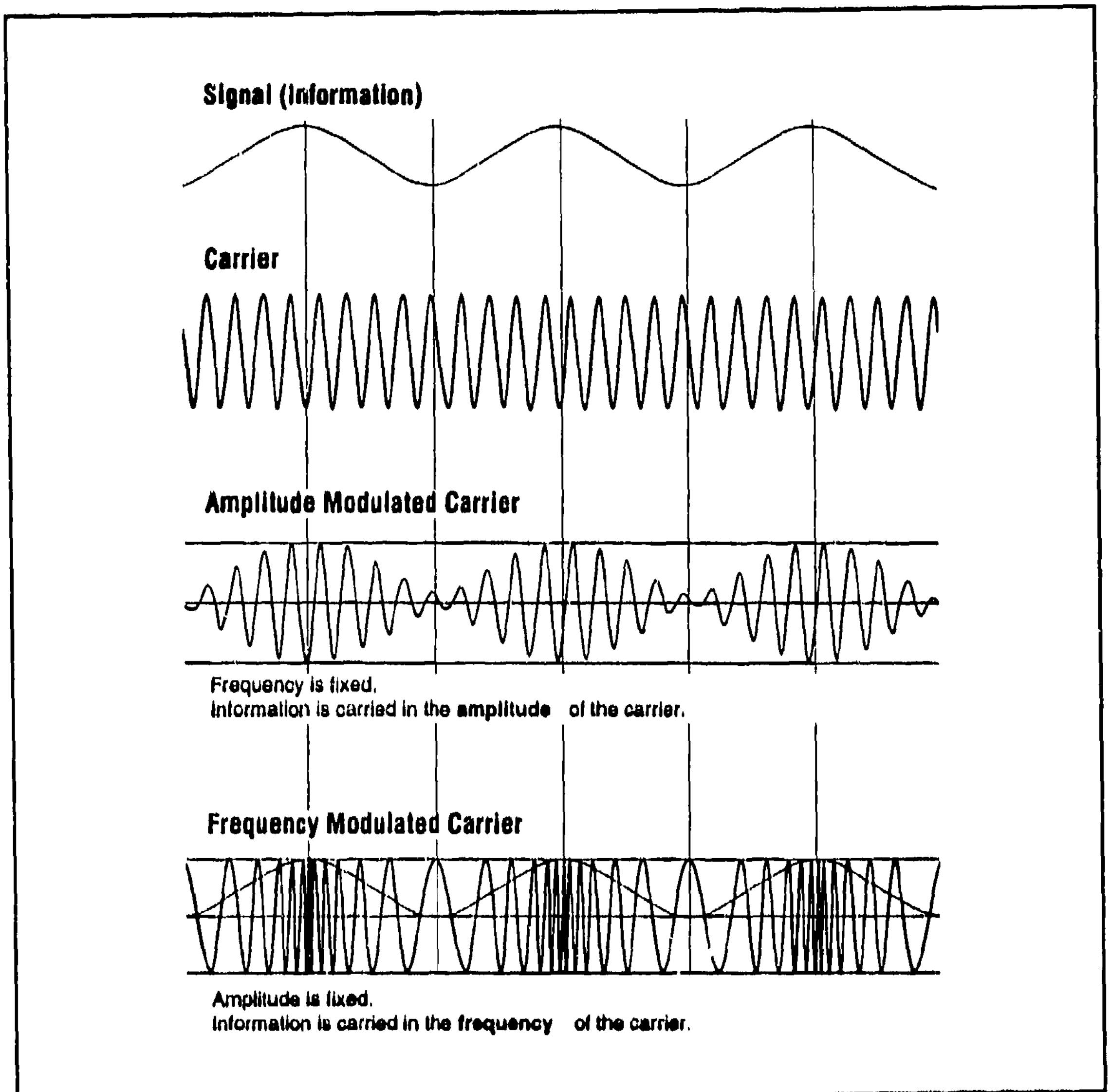

Figure 16. Amplitude and Frequency Modulation

V. SYSTEM MANAGEMENT

"Net management is the activity of planning, monitoring, and adjusting assignments, functions, parameters, and participation within the net." Some of the things that need to be considered in managing the Link-11 net are which unit should be the Net Control Station (NCS), what frequency to use and when, and how to analyze the efficiency of the net. [Ref. 3:p. 5-1]

The selection of the NCS can have an effect on the entire Link-11 net. The position of the NCS should be in the ideal location to assure communications with every other Link-11 unit. If the NCS is in a position where one or more units are not in communication with it, then those units will not receive the signal for them to transmit. If this occurs then the other units in the net will not receive the tactical data of the units that were left out.

The equipment capabilities of the NCS also can have a significant effect on the usefulness of the Link-11 net. If the NCS has a degraded receiver, the NCS Data Terminal Set (DTS) may not realize another station is transmitting its data. Consequently the NCS will neutralize the tactical data from those participation units (PU) and degrade the entire net. [Ref. 3:p. 5-4]

A. FREQUENCY MANAGEMENT

There are several factors that determine the optimum frequency for a given situation. The first and foremost is distance. The short UHF line-of-sight range does not allow its use among surface units in a dispersed force. An exception to this is when an airborne Link-11 unit is used as the NCS. The airborne unit may be employed to provide a tactical picture to surface units over a large area. "During surface EMCON the surface force can operate in the radio silent mode (receive only) utilizing the tactical picture provided by the airborne TDS units." [Ref. 2:p. III-5]

Although HF can be used for greater distances than UHF, there are many factors that influence the propagation of the HF signal. One variable is the ground wave range of different HF frequencies. "For example, a 1000-watt transmitter at 2 MHz will have a (ground wave) range of 350 miles. The same transmitter at 30 MHz will have a (ground wave) range of 90 miles." [Ref. 3:p. 5-7]

Another factor that affects HF propagation is the ionosphere. The ionosphere makes up a portion of the atmosphere that is between 50 and 200 miles above the earth. "This region contains ions and electrons in numbers large enough to affect the direction of radio wave travel." [Ref. 3:p. 3-16] The density of the ions and electrons in the ionosphere make a significant impact on the sky wave component of a HF signal. Since the beginning of the ionosphere starts at an altitude of 50 miles, it has a lesser effect on the ground wave component of a HF signal.

Ultraviolet radiation from the sun increases the amount of ionization in the atmosphere. During the day the ionosphere is composed of the D, E, F1, and F2 layers as shown in Figure 17 [Ref. 3:p. 3-17]. At night the D and E layers disappear, and the F1 and F2 layers combine into the F layer. The ionosphere has more layers and is denser during daylight hours. When the ionosphere is denser it has a greater tendency to refract HF radio waves. When the ionosphere is dense it also has a tendency to absorb radio waves, thus reducing communication ranges.

The ionosphere affects each frequency differently. As Figure 17 shows, different frequencies are refracted at different heights. The degree of refraction will depend on the density of the layers and the frequency of the radio wave. Layer density varies with the time of day. At noon when the sun is directly overhead, all four layers are at their densest. At sunrise and sunset the layer density is difficult to establish. The D and E layers are barely discernable and the F layer is in transition. The density of the ionosphere is at its least at night when only the F layer exists.

The higher the frequency the lessor the ionosphere affects it. During daylight hours the D layer acts as a "sponge" absorbing lower frequencies that try to pass through it. This phenomenon virtually eliminates the sky wave component of

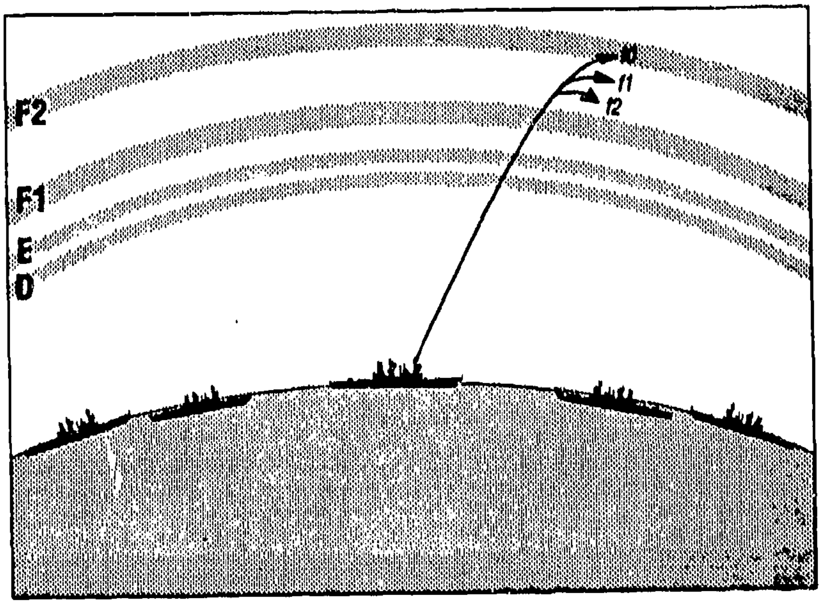

Figure 17. Ionosphere Layers During Daylight Hours

lower frequency signals. At night, when the ionosphere is thinner, higher frequencies are not refracted enough to return to earth and pass through the ionosphere. Again the sky wave component is essentially nullified. Figure 18 illustrates the usable frequencies in relation to the time of day. [Ref. 3:p. 5-9]

"Changing the Link-11 frequency is at times unavoidable because of weather, atmospherics, and/or interference." When conditions require a change, it must be made as swiftly as possible to secure a smooth change of frequencies. Other units may advise the net coordinator of the quality of its

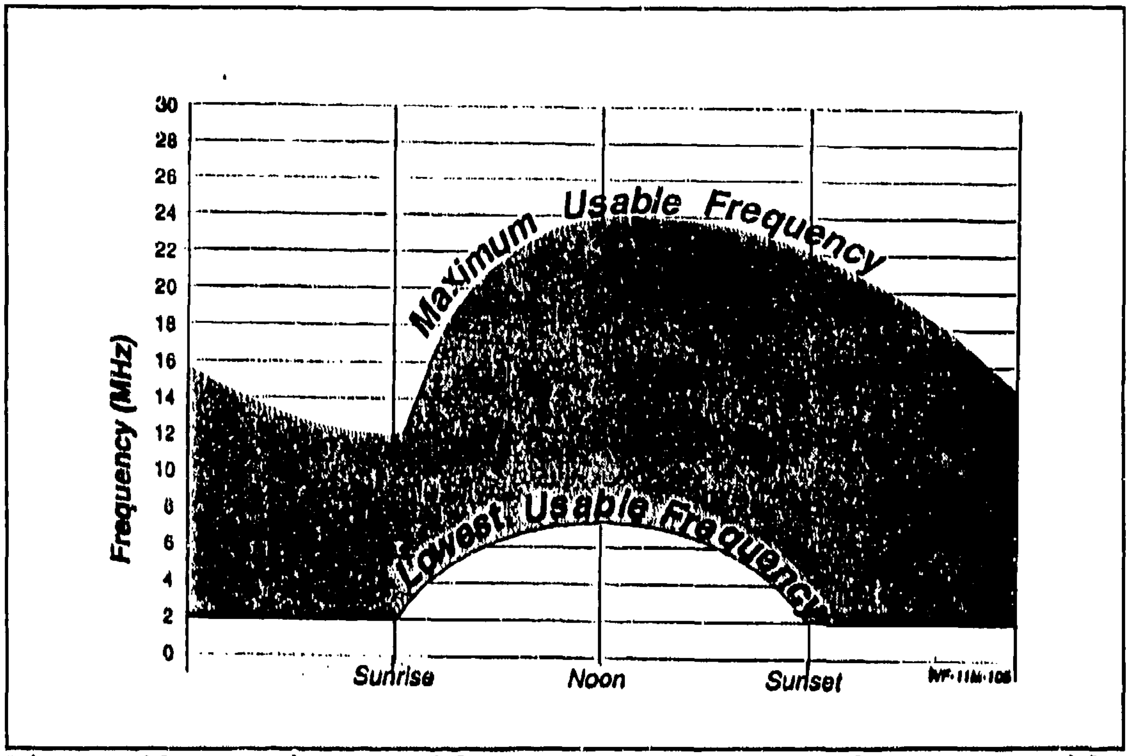

Figure 18. Maximum Usable Frequency (MUF) and Lowest Usable Frequency (LUF)

communications, but the net coordinator is responsible for the overall Link-11 performance.

B. SIGNAL EXPLOITATION/JAMMING

"A Link-11 net operating in the HF spectrum is significantly more vulnerable to signal exploitation by hostile forces operation beyond the local horizon than a Link-11 net operating in the UHF spectrum." Although the HF ground wave can be detected out to about 300 miles, the potential sky wave range of over one thousand miles makes HF extremely vulnerable to intercept and Direction Finding (DF). Limited

Range Intercept (LRI) techniques should be considered when practical. [Ref. 2:p. III-5]

"HF is probably the frequency band most susceptible to jamming. Jammers located far from the receiver are known to be able to jam/disrupt HF reception, particularly when operating via sky wave propagation." [Ref. 1:p. 2-20] Nuclear blackouts present another potential liability to HF sky waves. They are most vulnerable to nuclear blackout resulting from high altitude nuclear burst. It is expected that HF sky wave communications could be lost for several hours or even days in a nuclear environment. Although the effects of nuclear blasts have a significant effect on HF sky waves, the groundwave portions of HF communications are not affected and normal propagation ranges can be expected. [Ref. 1:p. 2-20]

UHF is less susceptible to jamming since the jamming station must be within line-of-sight (LOS) of the receiving station. UHF is also less vulnerable to nuclear blackouts, with a loss of communication expected to last only a few seconds.

C. RECEPTION QUALITY

"Reception Quality, or (RQ), is a numeric value measuring the ability of every ship to receive every other ship." [Ref. 3:p. 4-29] The RQ values are used by net operators to monitor the Link-11 net. RQ values vary from one to seven with seven representing the highest degree of communications quality. Figure 19 shows the breakdown of RQ values. [Ref. 3:p. 4-29]

[illegible]	[illegible]	[illegible]	
7	None	93	- 100%
6	None	79	- 92%
5	None	65	- 78%
4	None	50	- 64%
3	None	36	- 49%
2	None	22	- 35%
1	None	7	- 21%

Figure 19. Reception Quality (RQ) Values

A RQ value of seven indicates that all data frames transmitted by that PU have been received with minimal detected errors. The net coordinator should closely monitor any unit with a RQ value less than five. If a unit consistently has a RQ value less than five then the net operators know the net is degrading and an analysis and/or a change may be necessary.

RQ values are calculated for every different communications path. Figure 20 indicates the RQ values between the four ships in the net [Ref. 3:p. 4-32]. Note that ship 56 has problems with the reception of the other ships in the link. This probably indicates a receiver problem with ship 56. Figure 20 also indicates that the communications between ships 30 and 43 is degraded. The problem between ships 30 and 43 may be because of distance, since the communications with other ships in the net is adequate.

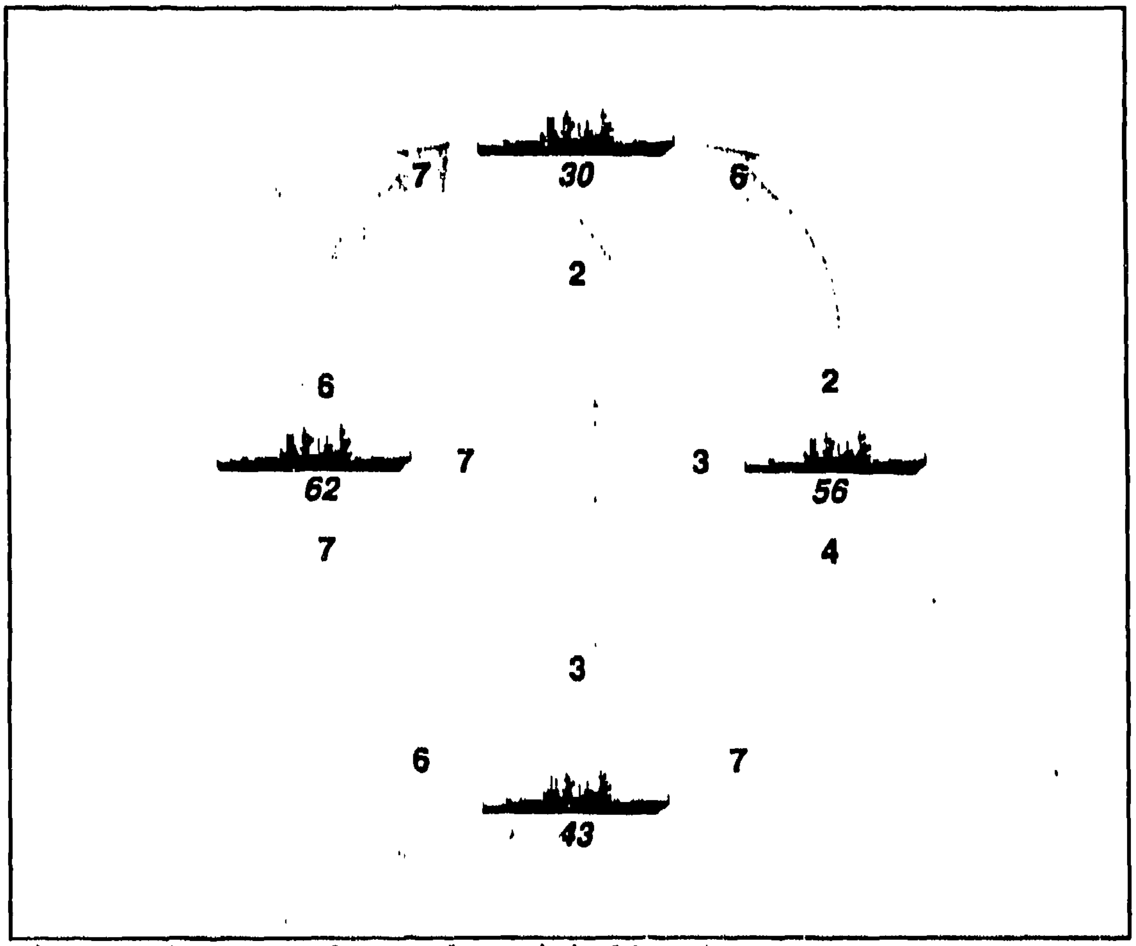

Figure 20. RQ Values of a Link-11 Net

By nature, communication circuits are difficult to analyze without complicated equipment and a technical knowledge of electronics. For communicators to adequately support Link-11, they need to be familiar with all aspects of net operations. They need to know all the equipment that is used for the net and that this equipment is being properly maintained. Although some of this Link-11 equipment is not under their control, communicators should periodically check to ensure that the entire circuit is in excellent condition.

VI. CONCLUSION

In the 1960's and 1970's, the over-the-horizon threat was limited to a few hundred miles. Link-11 was developed to counter this threat. "When operating in the HF band, Link-11 provides gapless omni-directional coverage of up to 300 nautical miles from the transmitting site." [Ref. 3:p. 1-2] But today weapons systems are faster and have a range of several hundred miles. With a data rate that is low (2250 bps) compared to today's standards, the Link-11 system is struggling to keep pace with new technology.

Some existing telecommunications technologies were reviewed to see if any of them could possibly be used for redundancy and/or alternate path communications. These systems include Officer-in-Tactical-Command Information Exchange System (OTCIXS), satellite communications, and Demand Assigned Multiple Access (DAMA).

A. OTCIXS

OTCIXS is a two-way UHF satellite communications network. It is designed to support the Officer-in-Tactical-Command (OTC) of a battle group. This system is used to reduce message traffic over the satellite broadcast. It provides the OTC with a satellite network that is exclusive to the battle group. "The network will support ship-to-ship high speed teletypewriter and tactical record (communications) ... including event-by-event track updates and ... narrative traffic." [Ref. 1:p. 5-38]

Although OTCIXS is a data exchange network and is actually capable of transferring data at a significantly higher rate, the Link-11 system needs a dedicated circuit to operate on. Without this dedicated circuit, Link-11 will not be able to provide accurate up-to-date contact information to net participants. There is also a satellite interface problem that is described below.

B. DAMA

DAMA is a Time Division Multiplexed (TDM) signal that is used in satellite transmissions. TDM is a method of time-integrating samples of several signals onto one radio frequency carrier, each assigned to unique time slots. The DAMA configuration of TDM then uses digital burst transmissions to get a cycle of information into a smaller time slot. Figure 21 shows an example of TDM time slots.

Theoretically, Link-11 can operate on DAMA just like other communication circuits are capable of doing. But there are specific net operating functions that prevent Link-11 from operating with any satellite signal. This unique problem occurs during routine operation of the Link-11 net.

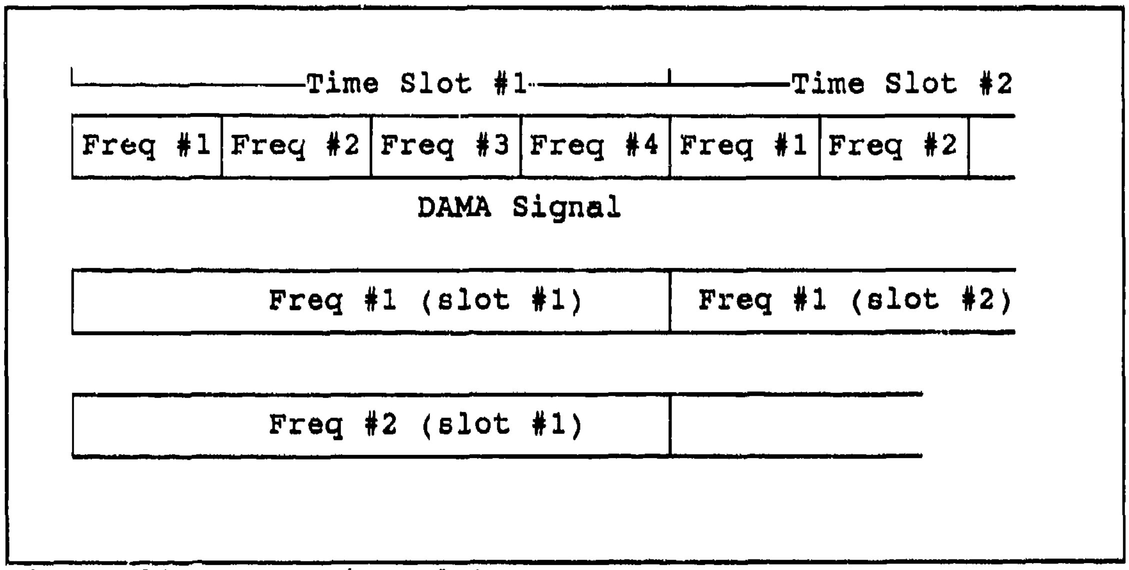

Figure 21. DAMA Time Slots

The Net Control Station (NCS) interrogates other ships to query them for messages. After sending an interrogation message, the NCS waits fifteen frames for a response. If a response is not received within the fifteen frames, then the NCS continues with the operation of the net. Since the Link-11 net is operated around a 300 miles radius, ships have plenty of time to respond to the interrogation from the NCS. But if Link-11 was operated through a satellite, the NCS would not receive a response within the fifteen frames. So, for Link-11 to operate on any satellite communications system, there would have to be equipment modifications to all the Link-11 ships.

C. SUMMARY

Link-11 was designed to provide battle group commanders with real time tactical information from and to all their ships and aircraft within 300 nautical miles. Each ship and aircraft has its sensors continuously feeding contact information to its NTDS computer. Thus, the system enables each platform in the net to exchange tactical information over communication circuits using computer automation. Once initiated the Link-11 net operates automatically without manual intervention.

A specific protocol is used for the operation of Link-11. Within this protocol, certain codes are used to inform each individual platform when to transmit and when to receive tactical data. The system uses Quadrature Phase Shift Keying to encode the tactical data onto the radio frequency carrier.

Link-11 is the best close-in tactical information exchange system the Navy has. With the present equipment configurations, Link-11 is not compatible for operations with or on any satellite networks. However, satellite networks (i.e., OTCIXS) do complement Link-11 in providing long range tactical information.

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