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**FREQUENCY AGILE OFDM SYSTEM FOR RADIO COMMUNICATION  
IN HIGH FREQUENCY BANDS**

by

Erin E. Hill  
B.S. May 2013, Old Dominion University

A Thesis Submitted to the Faculty of  
Old Dominion University in Partial Fulfillment of the  
Requirements for the Degree of

MASTER OF SCIENCE ENGINEERING

ELECTRICAL AND COMPUTER ENGINEERING

OLD DOMINION UNIVERSITY  
May 2022

Approved by:

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## **ABSTRACT**

### **FREQUENCY AGILE OFDM SYSTEM FOR RADIO COMMUNICATION IN HIGH FREQUENCY BANDS**

Erin E. Hill  
Old Dominion University, 2022  
Director: Dr. Dimitrie C. Popescu

High Frequency (HF) radio communication existed as the primary source of over-the-horizon communication for decades prior to the wide implementation of satellite and cellular networks. Even today, should satellite communication become unavailable, the robust backup of HF vitally supports long distance data transmission without the need of a cellular infrastructure. This capability is of particular importance to naval applications while at sea. Frequency choice, however, becomes critical in supporting reliable HF communication as too high of a frequency will not return to earth and too low of a frequency will result in high absorption rates within the atmosphere. A potential solution to explore is to use Software Defined Radio to implement dynamic frequency assignment at regular intervals based on predictive modeling software. Once the optimal frequency is selected and available bandwidth determined, additional parameters can then be optimized to support high data rate reliable transmissions. To overcome the turbulent atmospheric conditions within the atmosphere as bandwidth is increased, we study implementation of Orthogonal Frequency Division Multiplexing (OFDM) to enable a multichannel approach to support the available bandwidth. The concept of applying cognitive radio as sensors become available is also introduced for future implementation.

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This thesis is dedicated to my husband Rich – this work is only completed due to his drive for non-stop encouragement and motivation.

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## CHAPTER 1: INTRODUCTION

Guglielmo Marconi's telegraphic signal sent in 1901 from more than 3000 kilometers away proved the concept of wireless long-haul communication and consumer demand since that date has triggered more than a century of optimization and improvement in long distance wireless communication [1]. The value of long-haul communication further cemented in history when it was utilized to signal distress in the sinking of both passenger ships *Republic* and *Titanic* in 1909 and 1912 respectively. Through the process of meeting consumer demand, scientists and engineers discovered and then began the process of fully exploring the intricacies of ionospheric propagation, or sky waves, which could travel beyond the line-of-sight wireless transmissions. Additionally, since data rate and antenna length are inversely proportional to frequency, optimization demanded the highest frequency ranges within ionospheric propagation possibility. Thus, the emergence of High Frequency (HF) radio systems in the 3-30 MHz range became a staple of wireless communication throughout much of the twentieth century. The dawn of satellite communication and cellular networks in the latter half of the century further established global wireless communication as an essential element in today's consumer need. Today, the over reliance of satellites and scarcity of resources have brought high-bandwidth HF communication to the forefront of relevancy as a backup when satellites become unavailable.

The demand for wireless connections with high data rate capability continues at an unprecedented rate of expansion. Thus, study into an HF system to either serve as a backup to established satellite links or serve as an independent, infrastructure free long-haul radio should support a data rate useful to the user in various applications. The Radio Frequency (RF) spectrum consists of a limited capacity of frequencies, or channels, that create a resource scarcity and the necessity for spectrum management while preserving data rate. This problem is

particularly problematic in the HF range due to the lower number of available frequencies and existence of unusable channels due to fading. Data rate and symbol period are inversely proportional and thus truncating the symbol period increases the efficiency and data rate of the transmission [2]. Having small symbol sizes transmitted simultaneously over multiple frequencies provides a way to transmit large amounts of data in small chunks with high efficiency. Since spectrum management is of high importance, it is desirable to have these channels be as close to each other as practical. If these small chunks are close together in frequency, inter-carrier interference can be avoided by utilizing the orthogonal nature of one to another. This method is termed Orthogonal Frequency Division Multiplexing (OFDM) and presents a potential solution for high bandwidth HF radio networks.

With the implementation of digital and soft radio in the twenty-first century, adaptable communication is possible. Additionally, ionospheric propagation has been extensively measured and studied to provide predictable software models based on location, HF system parameters, sunspot activity, and channel type. Software defined radio can then use these existing models to vary the frequency as the conditions change within the ionosphere to preserve channel integrity and protect data rate and usability. Thus, an HF radio system that uses both OFDM and dynamic frequency assignment can provide an optimal solution to high data rate long-haul communications without any existing networks and infrastructure.

A system described above can be beneficial in many environments when an existing network does not exist, and satellite communication is not possible or available. One potential scenario is military communication between ships at sea in a communication denied environment (i.e., satellite use is denied or restricted). Since ships travel well beyond line of sight from each other or land bases, HF over-the-horizon (OTH) high band width communication channels

provide a solution that does not rely on either satellites or base stations to transmit data across long distances. This application is particularly useful for ships at sea that currently rely on crowded satellite constellations for high bandwidth communication. For naval applications, HF communication antennas and receivers are already utilized and installed, providing an opportunity to increase capability of an existing system without requiring massive hardware changes which would require many years of research and development. While HF communications is currently in service as a redundancy for interrupted satellite service, tumultuous ionospheric conditions and lack of high data rate transmission render this method frequently unpredictable. There is an opportunity, however, to utilize OFDM techniques along with adaptive software defined radio to implement more reliable, higher data rate applications within the HF band.

### **1.1 MILITARY AND HF – A CAPABILITY GAP REALIZED**

To fully appreciate the need for reliable, high throughput over-the-horizon communication, a brief discussion of the importance and applicability of HF communication for military applications is included. In the Second World War, HF communications were the primary means for ship-to-shore and ground-to-air communications. With the launch of Sputnik and the Space Race during the cold war, much of the research and head-way into long distance communication via the ionosphere faded into the background even as satellite systems became crowded and ever still costly to deploy. Additionally, military communication satellites remain vulnerable targets for military opposition and if eradicated, pose a threat to interrupting long distance communications between NATO and other allied forces. Thus, HF provides a useful and versatile tool that is deployable in highly adaptable scenarios. The ability to adjust antenna size and angle provides additional versatility not available in other communication systems.

Since ionospheric conditions constantly vary, and the angle of incidence is critical in understanding how the channel parameters are optimized, the radio operator must be either highly skilled or the system must continually adapt to determine the best parameters for use. With the implementation of software defined radio, algorithms and prediction models would aid NATO forces both on land and at sea to optimize HF radio communications and provide a reliable data link outside of satellite communications that is free of large infrastructure requirements. In recognizing the need for experienced operators of current available handheld HF radio, the US Army has created a lab to fine-tune operator skills in 2019 and continues to train operators today [3]. Thus, a capability gap is recognized that assists operators for a more automated HF radio system that optimized with predicted ionospheric patterns and expands on capable bandwidth is recognized. This paper attempts to provide a proof of concept of one solution to the problem of a high bandwidth, reliable, infrastructure free HF Radio system.

## **1.2 THESIS OUTLINE AND PROBLEM STATEMENT**

Now that the topic has been introduced and needed capability realized, the rest of the paper is dedicated to a proposed solution to close the technology gap to gain this capability. This paper seeks to find a solution to the problem statement of modeling a high bandwidth HF radio system resistant to turbulent ionosphere conditions for multipath and flat fading scenarios. In Chapter 2, background information and study for topics relevant for HF Radio, ionospheric propagation, modeling and prediction software, and OFDM are discussed. Chapter 3 explores parameter optimization for the models to include channel estimation, number of channels, modulation techniques, and signal to noise ratio (SNR) considerations. Chapter 4 outlines the simulation setup and discusses the dynamic frequency assignment proof of concept, narrowband simulation architecture, and OFDM simulation architecture. Simulation assumptions are also

mentioned. Chapter 5 is dedicated to results, conclusions, and future work and applications.

Appendices include all code developed to allow continued development of this model.

## CHAPTER 2: BACKGROUND

### 2.1 IONOSPHERIC PROPOGATION

The HF communication band (3-30 MHz) provides a unique phenomenon that allows for OTH communication through reflections off the ionosphere. The ionosphere is an atmospheric region approximately 40 km above the earth's surface and extends out to several earth radii and consists of several different regions and layers corresponding to altitude and density. Within the ionosphere, solar and cosmic radiation ionizes previously neutral particles and creates high amounts of positively charged particles along with free electrons [4]. This presence of free electrons, otherwise known as electron density, gives the possibility of this propagation over long distances. Yet, the ionosphere remains a complex environment that varies with season, hour of day, sunspot activity, and geographic location [4]. These factors cause variable absorption, polarization mismatch, and scattering that reduce energy density within the signal and thus degrade signal reliance and quality [1]. Due to the existence of both ground and sky waves, and the potential for multiple bounces along different portions of the ionosphere, multiple propagation paths exist, further exasperating signal degradation. The modeling and mathematical derivations of these ionospheric propagation models are complex and outside the scope of this paper. It is necessary, however, to state that the electron density ( $N$ ) is directly proportional to Maximum Usable Frequency (MUF) for HF Communications [4]. Any frequencies utilized above the MUF will propagate beyond the ionosphere and will be considered lost due to no reflection. This MUF also depends on specific information regarding the communication system such as antenna gains, transmit power, and SNR limitations [4]. In general, the MUF is related to the critical frequency ( $f_c$ ) and the angle of incidence ( $\theta$ ).



$$f_c = 9\sqrt{N} \quad (1)$$

$$MUF = \frac{f_c}{\cos \theta} \quad (2)$$

Using existing software and atmospheric predictions regarding the electron density throughout the day, general estimates may be made for the MUF based on radio link parameters, time of day, and geographic locations. These estimates can then be applied to the design of an OFDM system that adapts to changing conditions based on electron density.

One of the draw backs of ionospheric radio propagation is the presence of Doppler shift without added motion of the receiving or transmitting antenna due to the redistributions of electrons within the ionosphere [5] [6]. This will be addressed in chapter 4 for channel simulation. The Doppler shift, which can be referenced by  $\Delta f_d$  is derived and discussed in full in references [5] and [6], but is summarized here for background. The change in frequency ( $\Delta f_d$ ) is as follows:

$$\Delta f_d = \frac{e^2}{4\pi^2 \epsilon_0 m c f} \int_0^h \frac{1}{n} \frac{\partial N}{\partial t} dh \quad (3)$$

Where  $e$  represents the charge of an electron,  $\epsilon_0$  is the permittivity in free space,  $m$  is the mass of an electron,  $c$  is the speed of light,  $n$  is the refractive index and  $N$  is the electron density. The change in  $h$  refers to the altitude. Thus, the shift in frequency is dependent on the refractive index (which is also dependent on electron density), electron density, and frequency of transmission.

Even small shifts in frequency can cause impacts to the quality of transmitted signals and result in

inter-symbol interference if shifts exceed a given threshold. Thus, parameters should be optimized to account for shifts in this nature in addition to traditional fading and multipath.

Additional oddities and specific challenges to be addressed in HF implementation, whether in a narrowband or multichannel application, are skip distance and selective fading [4]. Skip distance refers to a minimum distance between the receiver and the transmitter that acts as a sort of shadow zone. Multipath channels arise due to refraction among two different layers within the ionosphere and the creation of both the ordinary and extraordinary waves [7]. Depending on the frequency utilized and transmitter power, the receiver has the potential to be within the skip distance of the transmitter and not be in receipt of the transmission. Another additional consideration is selective fading, which refers to specific distortion where some sidebands fade while others are enhanced. In the context of OFDM, this represents a potential point of interference among adjacent channels.

Several ionospheric prediction systems exist to aid in determining parameters for various HF communication projects. The prediction software utilized for this research paper is the Advanced Refractive Effects Prediction System 3.0 (AREPS 3.0), Naval Information Warfare Center (NIWC), previously named Space and Naval Warfare Center (SPAWAR). The modeling software makes predictions of Signal-to-Noise (SNR) based on user input of transmitter location, receiver location, angle of incidence, and transmit power. Examples of this prediction software are discussed later in this report. Additionally, how ionospheric data can be exported to MATLAB for use in simulations is also discussed. This modeling and prediction software allows for input into a Software defined radio system to dynamically change the center frequency and calculate the available bandwidth for the required radio link.

In reference [8], the author utilized the Provision of High-Frequency Raytracing Laboratory for Propagation Studies (PHaRLAP) to model HF propagation through the ionosphere. This program was developed by the Australian Defense Science and Technology Organization coded via FORTRAN 2008 and can output to a MATLAB toolbox [9] [8]. Both AERPS and PHaRLAP utilize the International Reference Ionosphere (IRI) model [10] [9] [11]. The IRI model was developed by an international team and sponsored by both the Committee on Space Research (COSPAR) and the International Union of Radio Science (URSI). Developed in the 1960's, the IRI model is updated yearly via a working group. The IRI model utilizes the electron density, electron temperature, ion temperature, ion composition (concentration of oxygen, hydrogen, helium, and nitrilooxonium cations), ion drift, ionospheric electron content (TEC), F1, and spread-F probability. These data for these parameters are through the worldwide network of ionosondes, incoherent scatter radars Jicamarca, Arecibo, Millstone Hill, Malvern, St. Santin, topside sounders, and in situ instruments on satellites and rockets [11]. The F-layer within the ionosphere is the region where long distance propagation occurs and is often split into an F1 region and an F2 region. Although both AERPS and PHaRLAP models utilize IRI and would most likely produce similar results, full integration utilizing the PHaRLAP program would be useful and an option for future work as MATLAB was used extensively in this work.

An additional ionosphere prediction model is the Voice of America Coverage Analysis Program (VOACAP). Similar to VOACAP but includes modeling for the polar region is the Ionospheric Communication Enhanced Profile Analysis and Circuit (ICEPAC). All models discussed utilize statistical methods and median values and are therefore prone to error or not predictable during magnetic storms. While the sunspot schedule and other periodic atmospheric conditions are accounted for, random electromagnetic inferences are not included in the

algorithm. Depending on the model, the data is updated on a periodic basis and is not real-time. Both IRI and VOACAP model distributes data on a monthly basis from its various input sensors [12] [11]. Thus, the concept of cognitive radio is introduced in the future work portion of this work to propose real-time sensor networks and channel modeling to predict optimum frequency assignment for established communication link.

## **2.1 OFDM PRINCIPLES**

Channel fading and multipath propagation delays are obstacles that must be overcome in HF communication systems. The delay spread varies depending on multiple environmental factors including terrain and suburban environments. These delays can cause signal fading that make the receiving signal fall beneath the noise floor and become undetectable. Often, this fading effect is frequency dependent (frequency-selective) and can exist on one frequency but is not present in other frequencies. Impulse noise from natural phenomena such as lightning is another instance that can degrade signals. Thus, as discussed in the last section, the ionosphere is a noisy, bandlimited channel, which creates distortion of the original signal. For instance, in a receiver expecting pulses at certain intervals, the channel distorts the original signal as a delayed pulse reserved for an adjacent signal. Some types of distortions include linear distortion, phase shifts, frequency offsets, impulse noise, and thermal noise. This is particularly true within the ionosphere as it is a time dispersive channel, where the number of paths and associated delays are time-variant, and difficult to predict and thus compensate for [13]. The end result is inter-symbol interference. The effect of this time dispersive channel can be minimized when the time variation within the channel is small compared to the symbol transmission rate. Thus, having multiple narrowband channels vice one broadband channel, can reduce the overall effect. Additionally, to overcome the struggles of wireless propagation through the ionosphere, signal diversity can be

achieved through the utilization of multiple narrowband channels vice one broadband channel. For example, if multiple frequencies are used with a multichannel approach, then in a flat fading scenario for one particular frequency, only a portion of the information is lost.

In order to achieve these multichannel approaches to mitigate inter-symbol interference, a cost-effective way to compute the frequency components of the multi-channel components is necessary. This was achieved with the development of the fast Fourier Transform (FFT) algorithm as it has drastically reduced the complexity of computing the spectrum of these signals and thus reduced the computation time of communication systems utilizing the Discrete Fourier Transform (DFT). This reduction in complexity has allowed for low cost, widespread implementation of digital communication methods utilizing the FFT and inverse FFT (IFFT). The FFT and IFFT algorithm makes multichannel communication achievable with the ability to quickly calculate up to thousands of frequency components [14].

In a multi-carrier system, the overall bandwidth  $B$  is divided into multiple channels with a sub-spacing of each channel is denoted as  $\Delta f$ . The total number of subchannels  $N$ , is the total bandwidth  $B$  divided by  $\Delta f$ . Individual channel width is selected to minimize the variance of the energy spectral energy vs the power spectral density of the noise. The closer to a constant value that can be achieved, the closer an ideal channel can be observed. Additionally, the power of the transmitter can be optimized to increase the SNR to increase the channel capacity across all sub-carriers and subsequently increasing the overall bit transmission rate. In a broadband signal, the channel capacity would be limited to the SNR of the subset of frequencies with higher noise power spectral densities. If a signal is associated by the sinusoidal in equation (4), where  $k$  represents each subchannel and  $N$  represents the number of subchannels [13].

$$s_k(t) = \cos(2\pi f_k t), k = 0, 1, \dots, N - 1 \quad (4)$$

To mitigate for interference among these adjacent frequencies, they are deliberately made orthogonal to each other by ensuring that the following condition exists:

$$\int_0^T \cos(2\pi n f_k t + \varphi_k) \cos(2\pi m f_k t + \varphi_k) dt = 0, n \neq m \quad (5)$$

$T$  is one symbol period and  $f_k$  is the middle frequency of the  $k$ th subchannel. Optimally, the period is the reciprocal of the channel width  $\Delta f$  [15]. This symbol period is inversely proportional to the data rate. Thus, the shorter duration of the subchannel transmission for each symbol, the higher the data rate. The amount of data able to be transmitted for each symbol is directly related to the number of carriers utilized, which is maximized with minimum frequency spacing ( $\Delta f$ ) and is relative to the available bandwidth of the signal.

The composite signal can be represented by equation (6). Where amplitude  $A_k$  and phase  $\varphi_k$  are dependent on modulation scheme chosen [14]. Of note, this equation has been generalized and would be modified depending on the modulation scheme. Figure (2) is an overview of a simplified OFDM system with a block diagram representing the transmitter, channel, and receiver.

$$f(t) = \sum_{k=0}^{N-1} A_k \cos(k\omega_0 t + \varphi_k), \text{ for } 0 \leq t \leq T \quad (6)$$

In equation (6),  $\omega_0$  is  $2\pi k\Delta f$ . If a time sampled digital signal is considered where  $t = nT_s$  where  $T_s$  is the sample interval length and the orthogonality of the signals demands that  $\Delta f = 1/(NT_s)$ , the digital signal can re-arranged to read:

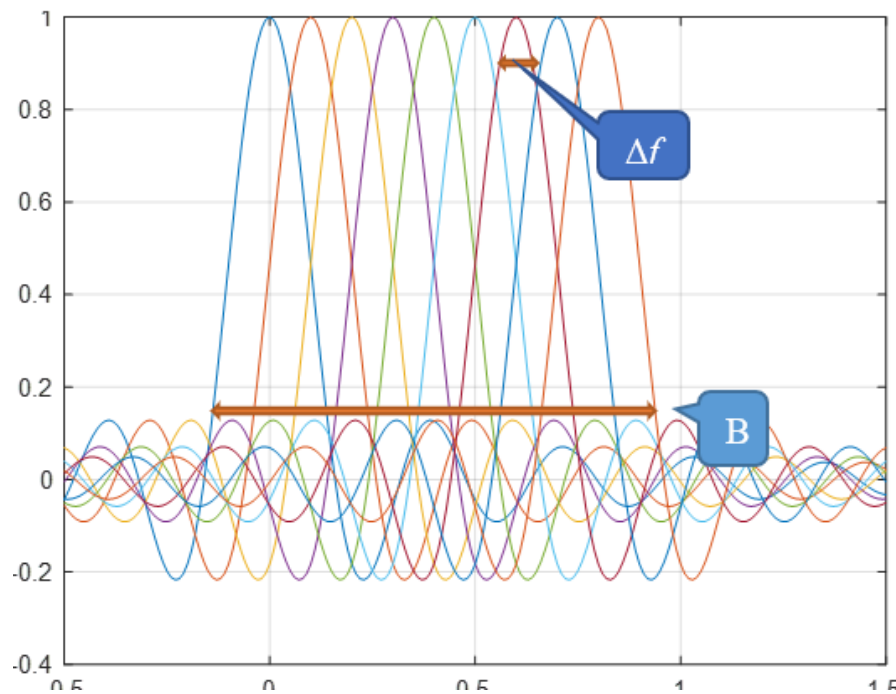
$$\sum_{k=0}^{N-1} A_k e^{j2\pi knT_s/N} \quad (7)$$

Where equation (7) represents an N-point inverse DFT [16]. As discussed previously, the application of the FFT has allowed large data subsets of N to implemented efficiently and with lower cost. Thus the set of data can be represented as a vector,  $v_k$  representing N-1 values of equation (7) or

$$v_k = [v_{k0} \ v_{k1} \ \dots \ v_{k(N-1)}] \quad (8)$$

Where each element of the vector identifies a different subcarrier. The transmitter takes the now serial time domain signal after the IFFT operation is conducted in equation (7) and sends the signal to a digital to analog converter where it passes through the channel and is corrupted by noise. Then, the received signal is taken from the output of an analog to digital converter to a matrix of received sample signals. These received sample signals are then multiplied by the complex conjugate of equation (8) or  $v_k^*$ . This process is also performed efficiently with the FFT algorithm. The signal can then be demodulated and then added together to reconstruct the sent data and sent as an output to the receiver. Typically, OFDM systems employ the addition of a cyclic prefix, where a certain number of samples are added at the beginning of each transmitted and then removed at the receiver. This cyclic prefix avoids inter-symbol interference due to multipath delay.

Therefore, the OFDM approach can be defined as these minimized orthogonal subchannels to mitigate inter-symbol interference and maximize channel capacity at an individual subset of frequencies in order to compensate time variant channel characteristics. Figure (1) gives a time-domain representation of frequency shifted rectangular pulses as time-shifted sinc functions. To mitigate processing delays at the receiver, a guard interval is implemented to mitigate any overlap between the receiver demodulating OFDM signals. This is known as a cyclic extension or a guard interval [2]. Figure (2) shows a functional block diagram of an OFDM system.



*Figure 1: Visual Demonstration of OFDM Signal*



Modulation schemes are summarized in the next section, but another way to maximize channel capacity and reduce bit error rate is to adaptively choose the modulation scheme for each subchannel. When SNR is low, only a lower order modulation scheme can be used due to the high associated bit error rate. When SNR is higher, a high order modulation scheme can be leveraged since channel capacity is increased as SNR is increased. The SNR of each subchannel can be summarized in the following equation:

$$SNR_k = \frac{TP_k|C_k|^2}{\sigma_{nk}^2} \quad (9)$$

Where  $k$  denotes the subchannel,  $T$  represents the symbol period,  $P_k$  is the power of subchannel, and  $|C_k|^2$  represents the squared magnitude of the frequency response of the  $k$ th subchannel (channel factor). The denominator represents the noise power spectral density of  $k$ th subchannel [13]. Thus, test signals and software defined radio provides an opportunity to optimize bit transmission rate by matching channel capacity where possible by compensating for noise power and the frequency response of the channel characteristics with an increasing allotted power per subchannel to increase SNR and potentially increase the order of modulation for that subchannel.

In cellular and wireless internet communication methods, utilization of OFDM has proven to be robust and effective. Thus, OFDM is now frequently utilized throughout consumer and business enterprises. For example, OFDM is implemented in the IEEE 802.11 a/g/n standard for wireless local area network communication.

In summary, in effective wireless communication, both data rate and bit error rate must support transmission requirements for the applications. Broadband HF communication presents the problem of high rates of interference or noise, forcing current HF standards to rely on

narrowband transmissions to prevent high distortion of information. OFDM presents a solution to implement a proven technology to lower bit error rate while increasing data rate by spreading the data over multiple adjacent frequencies with multiple narrowband channels within signals propagated through the ionosphere. Thus, if a single frequency is affected by ionospheric flat fading or other high distortion factor, the other channel containing the majority of information remains unaffected. OFDM also provides a solution to mitigate frequency-selective fading as the information is spread among multiple frequencies. Thus, only a small portion of the information is lost in the event of frequency-selective fading [17]. Additionally, OFDM provides a potential solution for frequency-selective fading by utilizing channel estimation techniques to understand these fading notches and selectively choosing lower order modulation schemes for those identified [18]. Modulation within OFDM signals is discussed in the next section.

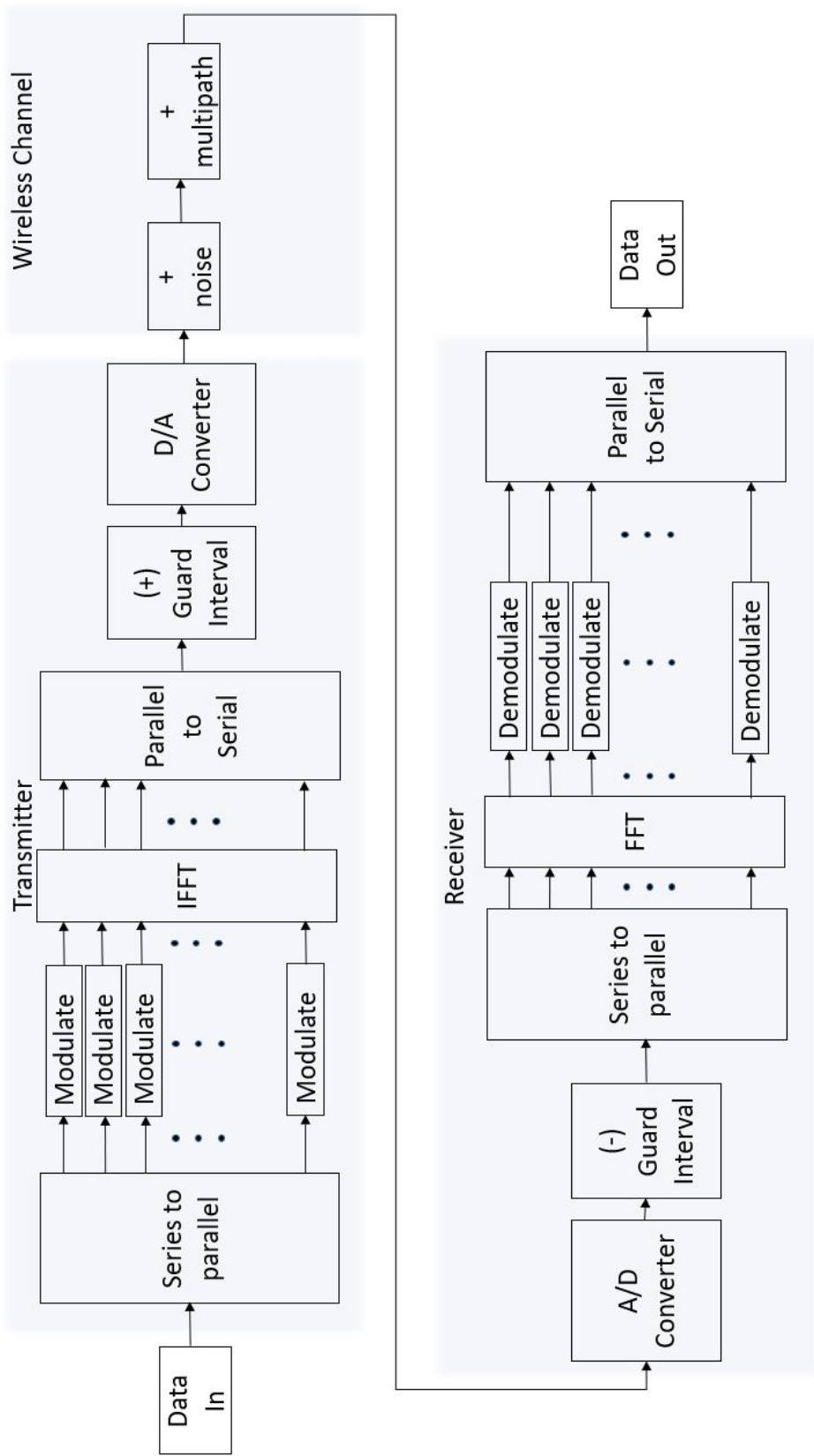
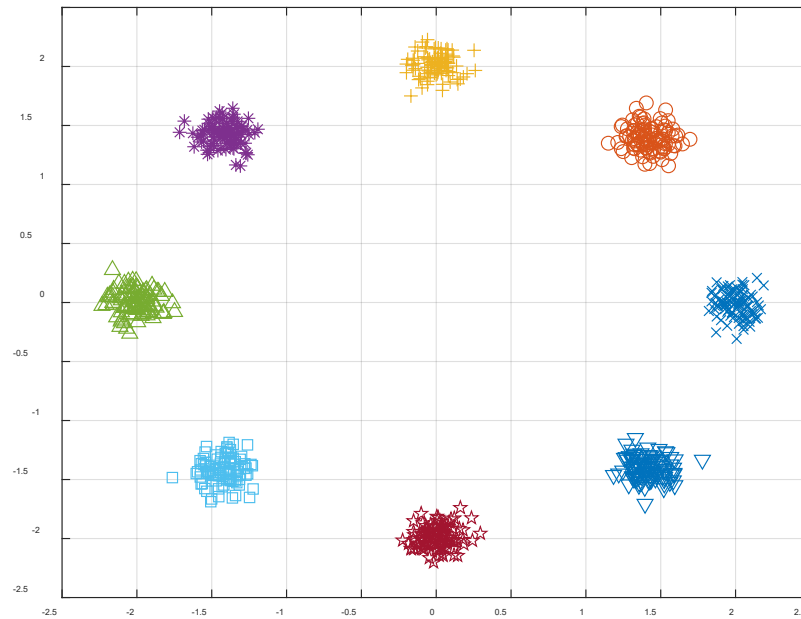


Figure 2: OFDM Functional Block Diagram

## 2.3 MODULATION TECHNIQUES BACKGROUND

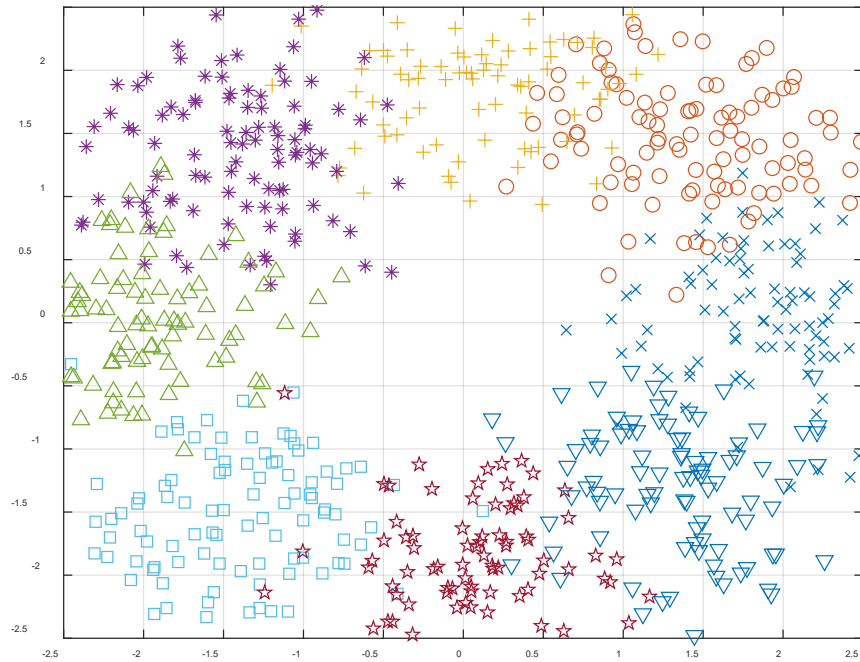
From interpreting the equation for data rate, it can be mathematically shown that maximizing the number of signals within a constellation optimizes the data information rate (bps) sent per OFDM or narrowband signal. As the number of signals increases, however, the bit error rate suffers and thus the number of signals and modulated method should be chosen that produces the greatest information transmitted per symbol with the lowest probability of error due to noise and other channel interference.

The two general modulation methods investigated are Quadrature Amplitude Modulation (QAM) and Phase Shift Keying (M-PSK). QAM builds signal constellations based on differing amplitudes and phases along the in-phase and quadrature axes while PSK builds constellations by altering only the phase between the in-phase and quadrature axes. For both methods, as noise or interference alters the signal slightly, the assigned points within the constellation alter from noise or interference. During demodulation, the bit is interpreted based on the distance between adjacent points within the constellation. If a bit is closer to a different point than originally assigned, then then it demodulates as the incorrect symbol, resulting in bit error. Thus, the more signal points in a constellation, the higher probability that the signal can be interpreted incorrectly and the bit error rate (BER) increases. While QAM modulation techniques can increase the spectral efficiency more than PSK techniques, it is more sensitive to noise and tradeoffs would be necessary to increase the signal to noise ratio (SNR) to mitigate the increased sensitivity [14]. Scenarios were conducted in MATLAB to demonstrate the trade-offs between modulation techniques and how noise variance impacts the position in the constellation a bit was assigned to. An example of the trade-off between constellation size can be seen below.



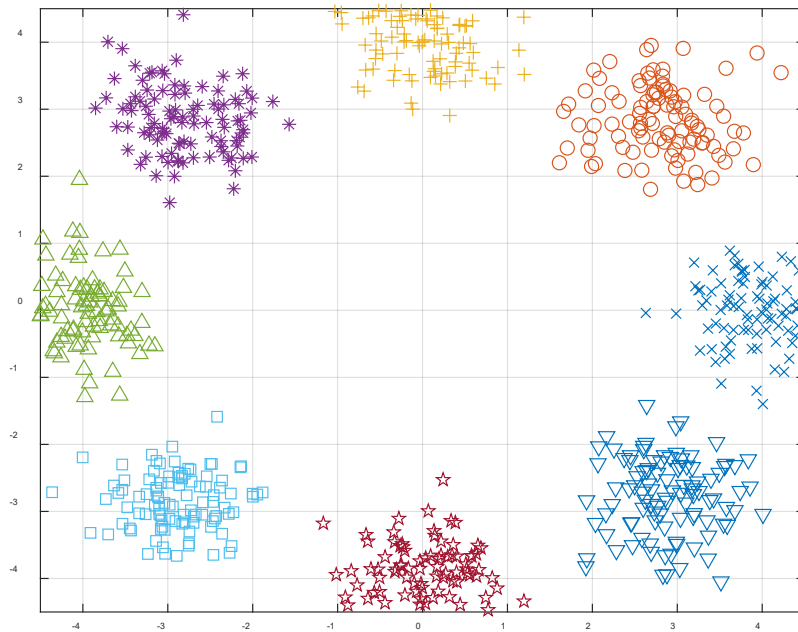
*Figure 3: 8-PSK signal with Amplitude of 2 and Noise Variance of 0.1*

When noise variance is low, 8-PSK provides relatively few errors (figure above). When the variance is increased by a significant factor, however, bit errors occur and the signal becomes degraded.



*Figure 4: 8-PSK Signal Distorted with Amplitude of 2 and Noise Variance of 0.25*

The same noise variance, however, can be overcome by doubling the assigned Signal to Noise Ratio (SNR) with little to no errors.



*Figure 5: 8-PSK Signal Distorted with Amplitude of 4 and Noise Variance of 0.25*

## CHAPTER 3: OPTIMIZATION OF OFDM SYSTEM PARAMETERS

Since HF propagation is highly variant and subject to flat fading, interference, and Doppler spread, optimizing channel parameters in the radio link can dramatically improve performance. In this chapter, the number of channels along with frequency spacing, data rate, modulation techniques, and available SNR are discussed. Not discussed in the paper, but yet applicable, are filters to overcome channel disturbances. For example, iterative algorithms to overcome phase shifts (autofocus methods) are not discussed but present solutions to some observed effects.

The number of channels is intrinsically linked to both data rate capability (see next section for calculations) and bandwidth availability. After the number of frequencies are determined possible for transmission, the bandwidth of each channel can be estimated (i.e. frequency spacing allotted in a given bandwidth of frequencies). To limit effects of high Peak to Average Power Ratio effects, low potential SNR values due to long distance communication, and antenna limitations with transmitted power, the number of channels in most scenarios is limited to 32 [7].

### 3.1 DATA RATE

In the design of any communication system, system trade-offs must be made with a goal of maximizing transmission bit rate ( $R_b$ ), minimizing the probability of error, and thus optimize the required bit energy per noise power. Thus, it is necessary to optimize data rate while minimizing bit error. Data rate ( $R_b$ ) can be determined by the following expression:



$$R_b = \frac{r_c \sum_{k=0}^{N-1} \log_2(m_k)}{T} \text{ (bps)} \quad (10)$$

$N$  is the channel number,  $m_k$  is the number of signals within the modulation constellation and  $r_c$  denotes the information bit per encoded bit (this value would be 1 if an uncoded approach is taken) [19]. From interpreting equation (10), it can be shown that minimizing  $T$  and maximizing both  $m_k$  and  $k$  is desirable.

To maximize  $k$  (the number of channels), the maximum bandwidth and smallest frequency spacing must be obtained as shown in the following expression:

$$B = k\Delta f \text{ (hz)} \quad (11)$$

For spectrum management purposes, the ideal scenario is to minimize bandwidth to create the maximum spectral efficiency ( $\eta$ ), which is denoted by the following expression.

$$\eta = \frac{R_b}{B} = \frac{R_b}{k\Delta f} \left( \frac{\text{bps}}{\text{Hz}} \right) \quad (12)$$

Thus, minimum frequency spacing without interference allows for the highest bandwidth efficiency.

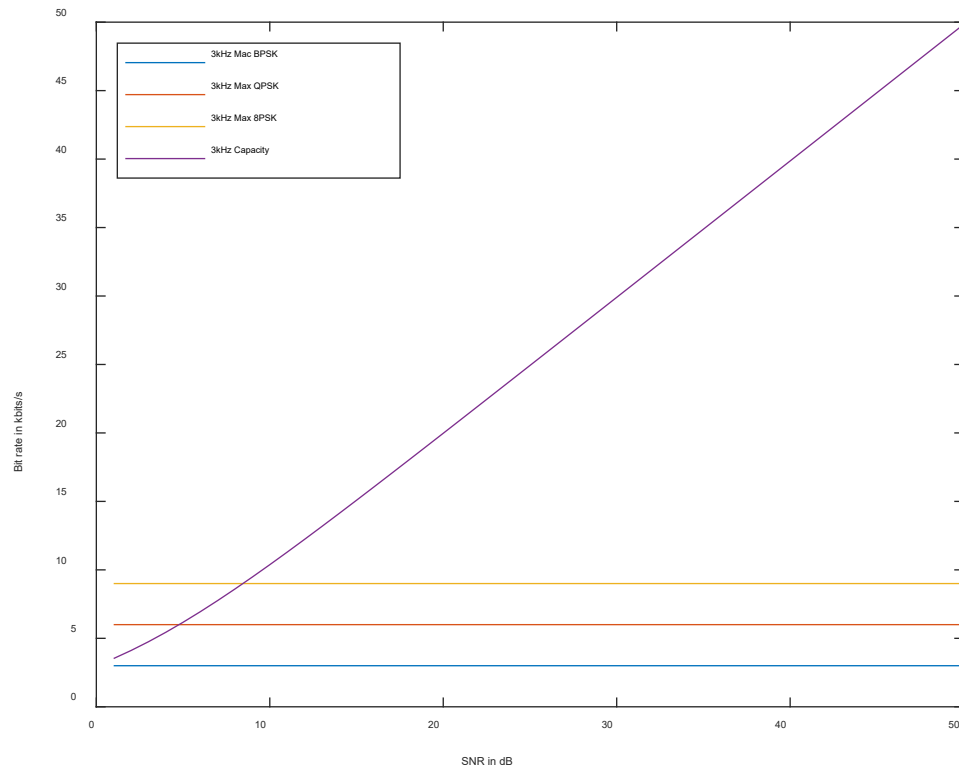
In studying various scenarios to achieve maximum data rate in HF communications, 3 possibilities were studied. Today's standard of HF channels (MIL-STD-188-110D) are characterized by 3kHz channels [20]. From experimentation with modeling and prediction software, most hours can support a 3Mhz bandwidth channel even with windows of truncated available bandwidth. Thus, three scenarios were studied: 3kHz, 1.5 MHz, and 3 MHz. Using both the equation for bit rate and Shannon-Hartley Capacity Theorem in equation (9), the predicted achievable data rates are listed in table (1) [21].

Table 1: Data Rate Calculations

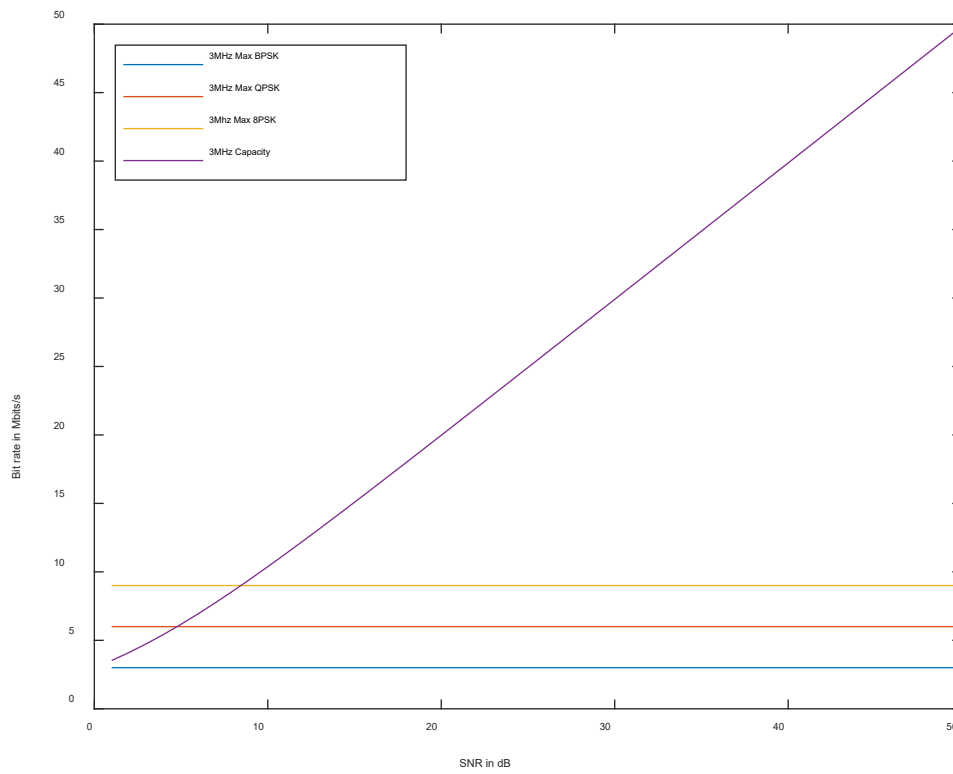
<b>Data Rate</b>	<b>BPSK (m=2)</b>	<b>QPSK (m=4)</b>	<b>8-PSK (m=8)</b>	<b>Capacity, SNR= 10dB</b>
<b>B=3kHz</b>	3 kbps	6 kbps	9 kbps	10.4 kbps
<b>B=1.5MHz</b>	1.5 Mbps	3 Mbps	4.5 Mbps	5.2 Mbps
<b>B=3MHz</b>	3 Mbps	6 Mbps	9 Mbps	10.4 Mbps

$$C = B \log_2(1 + SNR) \quad (13)$$

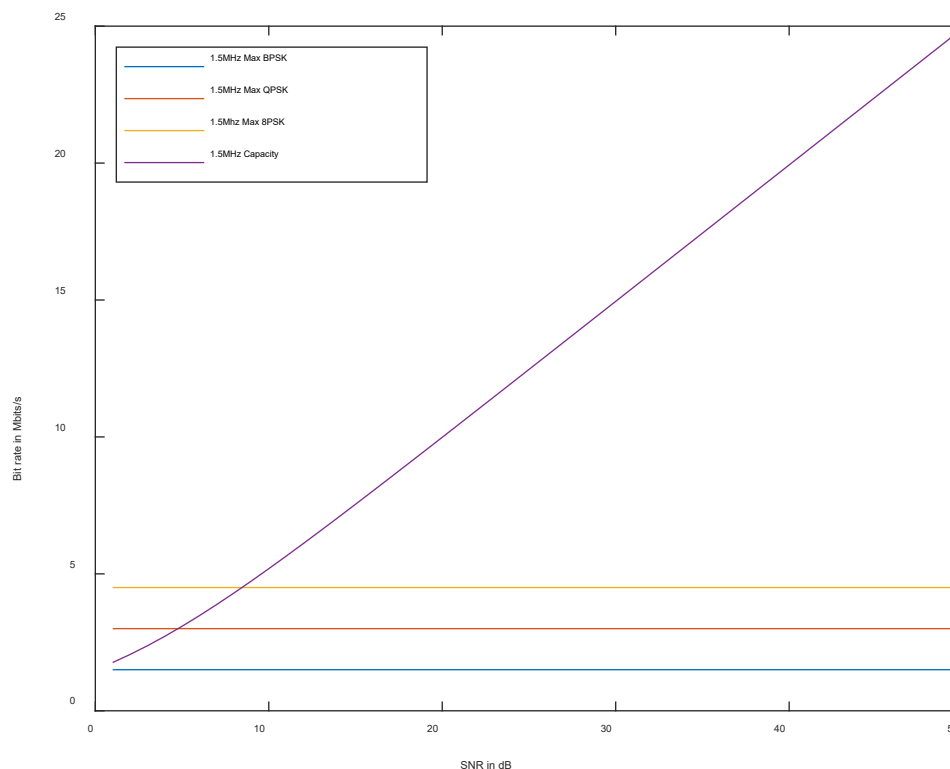
The relationship between modulation order, capacity based on available SNR, and bit rate can be summarized in the figures below. Due to the limited SNR available with long distances, higher order modulation schemes are limited due to the low SNR available. If assumed available SNR is at a minimum of 5 dB, then at least a BPSK modulation scheme is efficient. In cases where high SNR is available, QPSK or 8-PSK may be able to be supported.



*Figure 6: Bit Rate vs. SNR for 3 kHz Channel*



*Figure 7: Bit Rate vs. SNR for 3 MHz Channel*



*Figure 8: Bit Rate vs. SNR for 1.5 MHz Channel*

Due to the high time-variability of the of the HF channel, it is predicted that the optimal modulation technique to be implemented is BPSK. With software defined radio, however, it is possible to increase the modulation order when conditions are favorable and decrease when channel noise and interference is encountered.

SNR is highly variable and dependent on receiver location, transmitting power, and various losses within the channel. For the majority of the simulations discussed in this paper, the value of assigned SNR is 10 dB. For shorter distances, a much higher SNR value can most likely

be achieved and would result in fewer bit error and pixel errors received. Methods to improve the SNR is discussed within the simulation results.

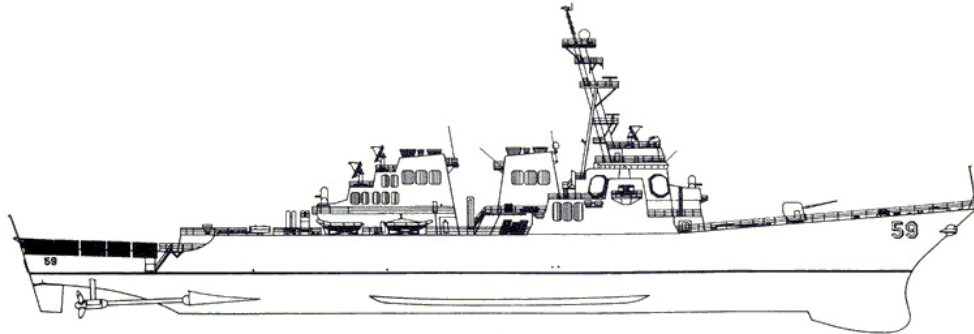
## CHAPTER 4: SIMULATION SETUP AND PARAMETERS

### 4.1 OFDM SIMULATION ARCHITECTURE

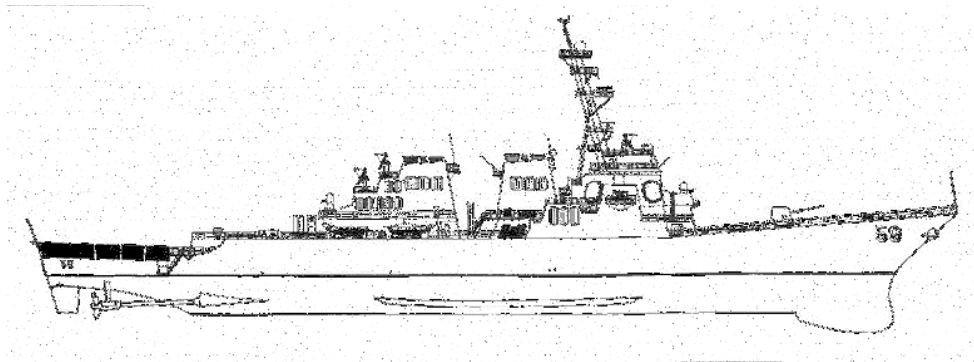
To implement OFDM communication system, the basic building blocks consist of the source data, the OFDM transmitter, the communication channel, the OFDM receiver, and then the received data. Within the OFDM transmitter, the source data is first divided to bins determined by the number of channels chosen for the system. This effectively takes the information as serial and transforms them into parallel bins. The data within these bins is then modulated based on the chosen modulation scheme (i.e. M-PSK or QAM). Then, each bin undergoes an Inverse Fast Fourier Transform (IFFT). The IFFT size is defined by 2 plus twice the quantity of channels within the system. After the IFFT, each bin adds a cyclic extension or guard interval in order to avoid inter-symbol interference [18]. The signal is then transmitted over the communications channel as a baseband OFDM signal. At the receiver, the signal is then demodulated in the reverse process by first removing the cyclic prefix, utilizing a Fast Fourier Transform (FFT), demodulate each bin, then cascade the signal from parallel bins into serial information. The received data is a digital copy of the transmitted data with minimal errors.

An existing MATLAB model was utilized and modified to test and understand various parameters of the OFDM system. This simulation utilizes an image sent through an additive Gaussian white noise (AGWN) channel and determines BER and image quality. The SNR, number of channels, modulation scheme, image, and IFFT size are determined by a user. The code was then altered to include a Rayleigh Fading channel to model fading often seen in HF communications. The Rayleigh Fading channel uses statistical techniques to predict random channel characteristics with variables in doppler spread (due to scattering) and path delays. As

an example, the below images represent the transmitted image and received image for 126 channels utilizing BPSK with 256 IFFT bins and a SNR requirement of 8 [15]. Alternate parameters support an HF OFDM model and are discussed later in this paper.



*Figure 9: Original Source Data at Transmitter [22]*



*Figure 10: Received Data with BER of 0.42% and 1246 of 1773200 data loss*



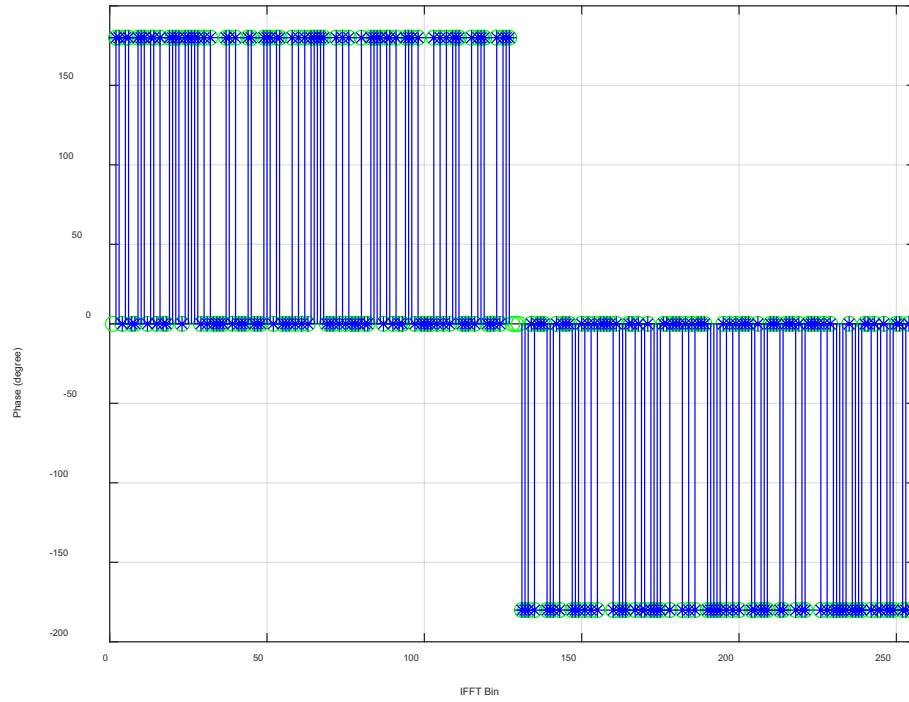


Figure 11: Phases of the OFDM Modulated Data at Transmitter

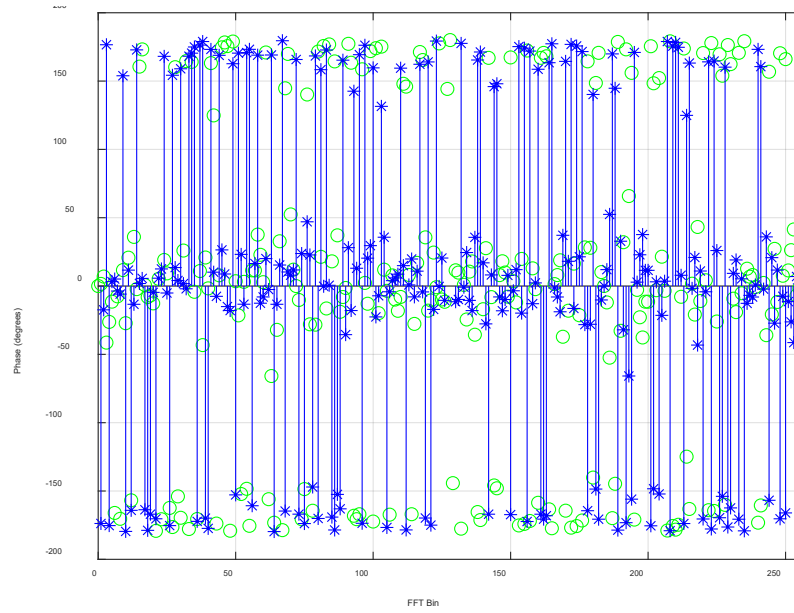
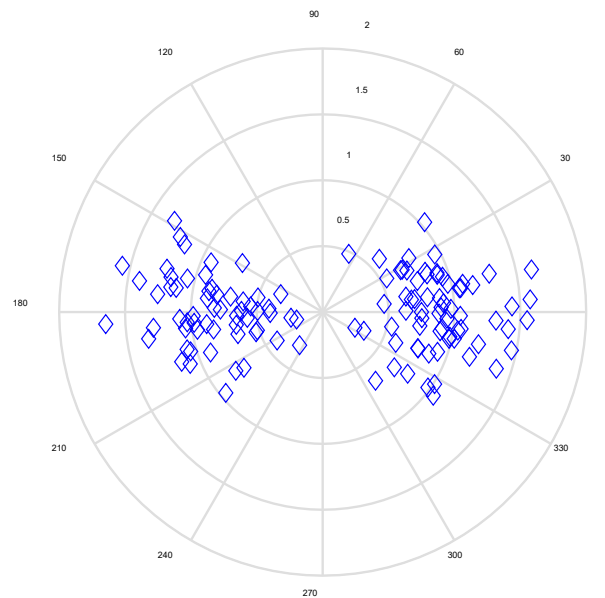
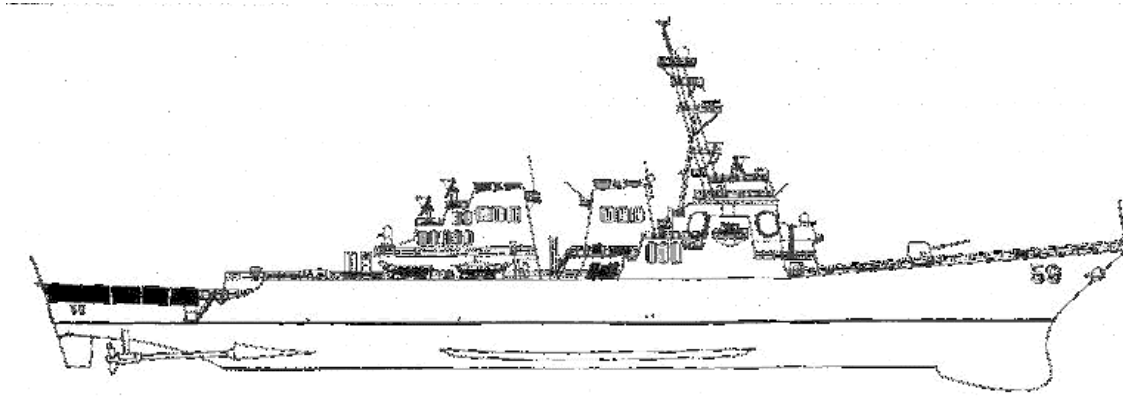


Figure 12: Phases of Received Spectrum within FFT Bins



*Figure 13: Phases of the Received OFDM Data*

With the SNR requirement increased to 12 and all other parameters kept the same, the improvement in BER demonstrated the benefits of increasing SNR values. With the previous simulation SNR value of 8, the BER was 0.42% and the simulation with the SNR value of 12 resulted in a BER of 0.02%. Simulation and assumption are for AGWN conditions.



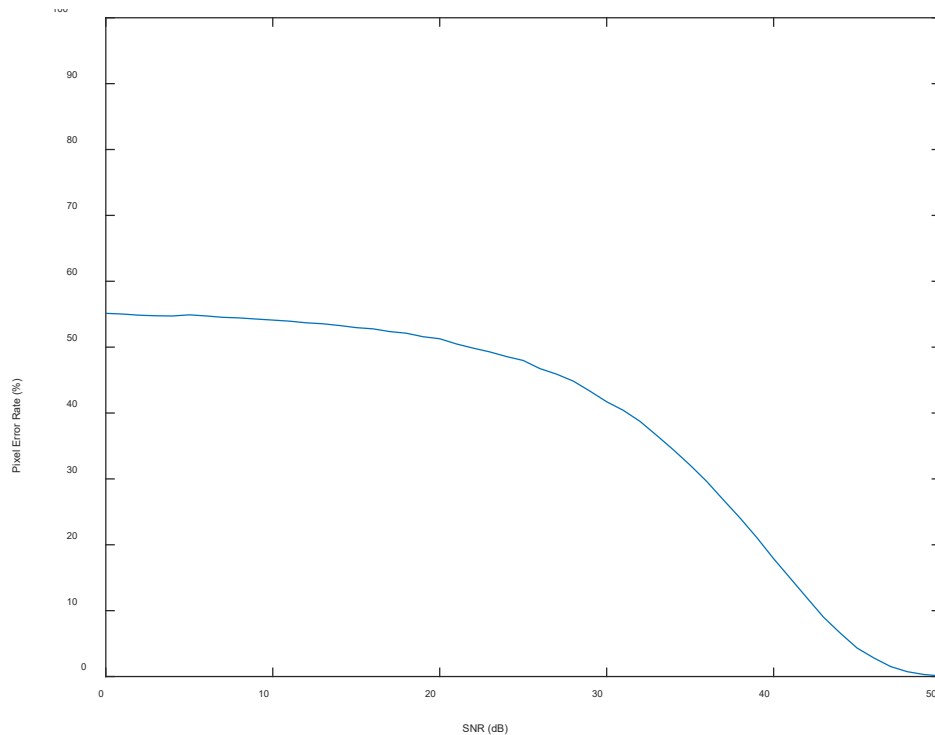
*Figure 14: Received Data with increased SNR and decreased BER of 0.02%*

## 4.2 HF CHANNEL ESTIMATION

As discussed previously, the physical channel in HF communications is challenging and unique. Noise and interference sources include solar and cosmic sources, atmospheric noise from lightning discharges in thunderstorms, and man-made noise [1]. To simulate some of the effects of noise, 3 different noise elements were introduced to understand barriers and to optimize parameters. Channel estimation was performed via MATLAB and added to the original signal to simulate transmission through a channel. Thus,

$$Data_{Received} = Data_{Transmitted} + noise \quad (14)$$

The first type of channel estimated was Additive Gaussian White Noise (AWGN), where the noise variance is increased as the SNR decreases. AWGN noise versus SNR was studied in a narrowband channel as an impact to percent of pixel distortion or error (see figure below). An SNR of 50dB provided a near zero rate of pixel errors with no other filter nor channel guard implemented.



*Figure 15: Monte Carlo Simulation of Pixel Errors vs SNR*

After AWGN was implemented, the simulations were conducted with the use of the MATLAB built-in function for a Rayleigh Channel. This is to simulate a multi-path scenario through exploring both path delay and doppler spread channel effects.

The Rayleigh Channel was chosen due to the likelihood of two or more propagation paths existing for a transmission due to the large amount of refraction in the ionosphere. For simulations, the Rayleigh Channel propagation chosen includes a two-path model with selected delays of 0.003 seconds and 0.0268 seconds. Propagation delay can be significant in HF channels due to the relatively low frequency assignment and long distance travelled with potential paths to include ground waves, sky waves, and multiple bounces within the ionosphere. Additionally, several simulations were conducted with variable Doppler spread assignment.

Maximum Doppler shift ranged from 0.001 Hz to 10 Hz for both narrowband and OFDM simulations. The Doppler spread, or spectral broadening, from the simulated fading channel had the most significant impact on image quality, which will be discussed later in this document. A summary of Rayleigh Channel parameters utilized for all simulations is listed in the table below.

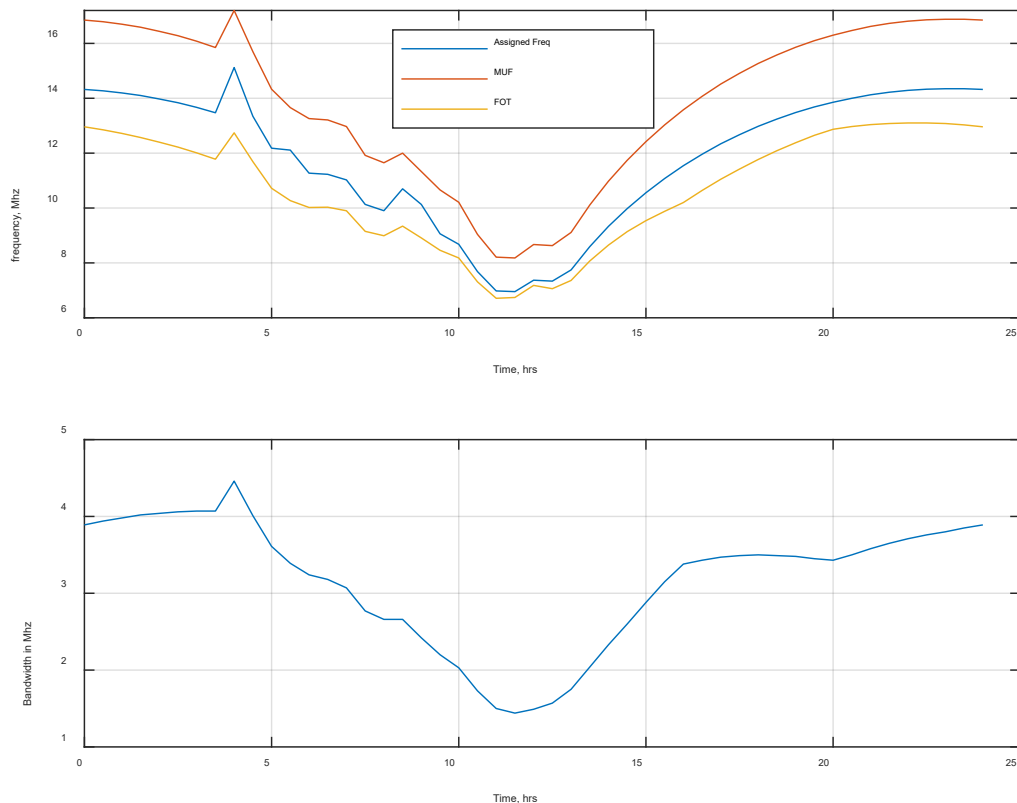
Table 2: Rayleigh Channel Parameters

<b>Rayleigh Channel Parameters</b>	<b>Parameter Value</b>
Sample Rate	1000 Hz
Path Delays	0.003 sec, 0.0268 sec
Average Path Gains	10, 15
Maximum Doppler Shift	0.001 – 10 Hz

#### **4.3 DYNAMIC FREQUENCY ASSIGNMENT**

Through the use of the open-source Advanced Refractive Effects Prediction System (AERPS) 3.0 software, a receiver location, transmitter location, and SNR values were arbitrarily chosen to obtain MUF frequency predictions based on a given day of 2021. The locations chosen were a suburban environment within the continental United States as well as shipboard in various locations in the Pacific Ocean.. The data was then exported to a text-file and read into MATLAB to calculate the predicted available bandwidth over the course of 24 hours. Based on the given MUF, the optimal frequency band is between 50% and 85% of the MUF. Transmission is possible outside of these percentages, but BER increases outside of this

percentage window. This is particularly true for the upper bound of the percentage range. While transmission is possible up to 100% of the MUF, the potential error rate due to the unpredictability of the ionosphere is as high as 50% [4]. This means that every other transmission is expected to be lost through penetration of the ionosphere. Thus, if additional bandwidth is required, the design parameters should require frequencies lower than 50% of the MUF. An example of data exported from the AERPS 3.0 software and calculated via MATLAB can be seen in the figure below.



*Figure 16: Calculated Available Bandwidth Based on Time of Day (top) and Calculated Available Bandwidth (bottom)*

For this communication link scenario, anywhere from 1.5 MHz to 4 MHz bandwidth is available in the optimum spectrum range. It is important to note that HF radio links are highly variable, and some scenarios could demonstrate much higher bandwidth while others would be considerably lower. For example, due to atmospheric conditions, Polar Regions would result in lower bandwidth while regions near the equator would have higher possible bandwidth.

To show variability in channel availability, a second simulation is presented. In this scenario, the transmitter and antenna are 7387 nautical miles apart, with rural noise, standard troposphere considerations, and sunspot number 75 (see figures below). The calculated available bandwidth is minimized to 2.6 MHz during peak hours of 1500 to 2000.

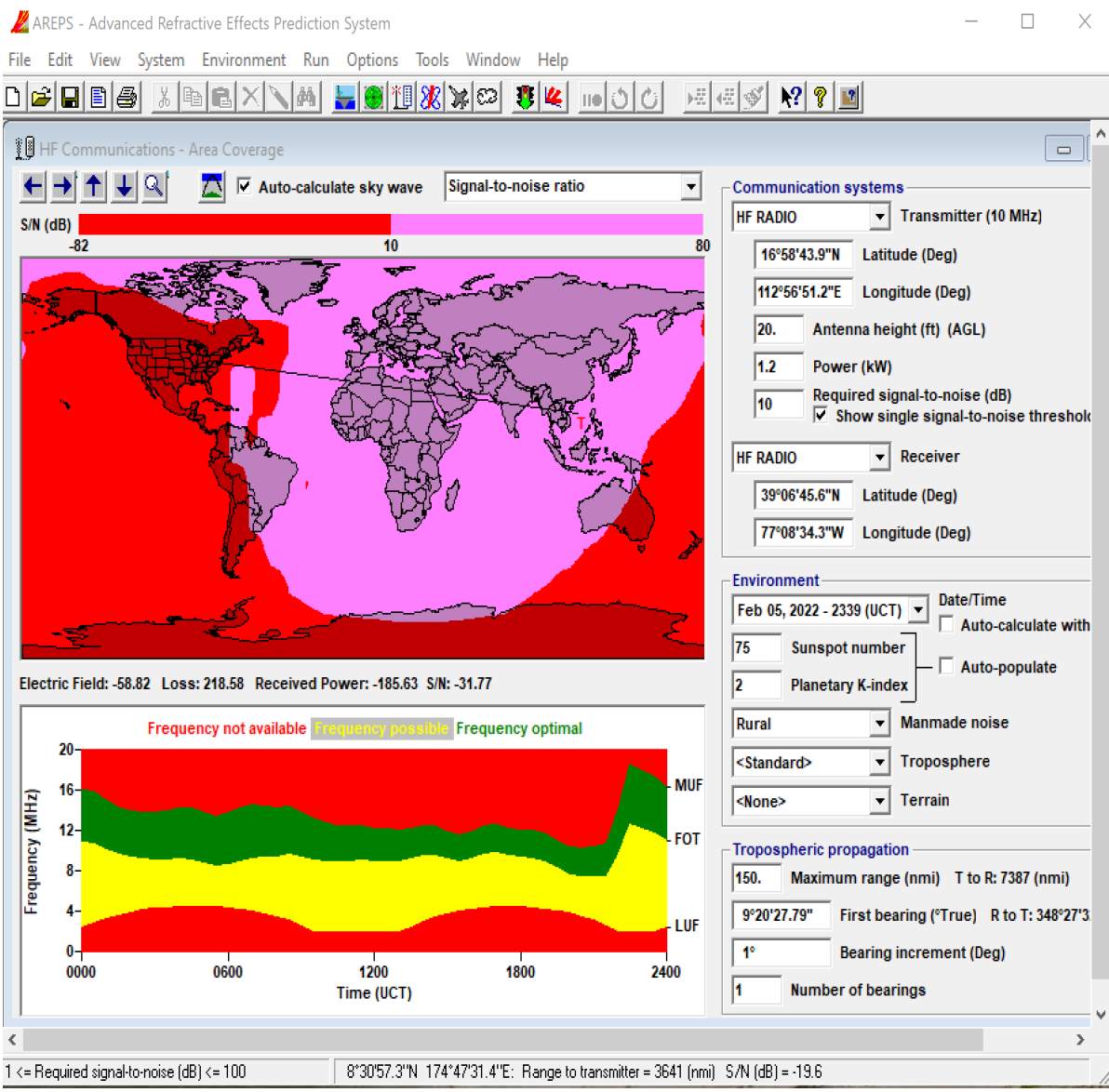
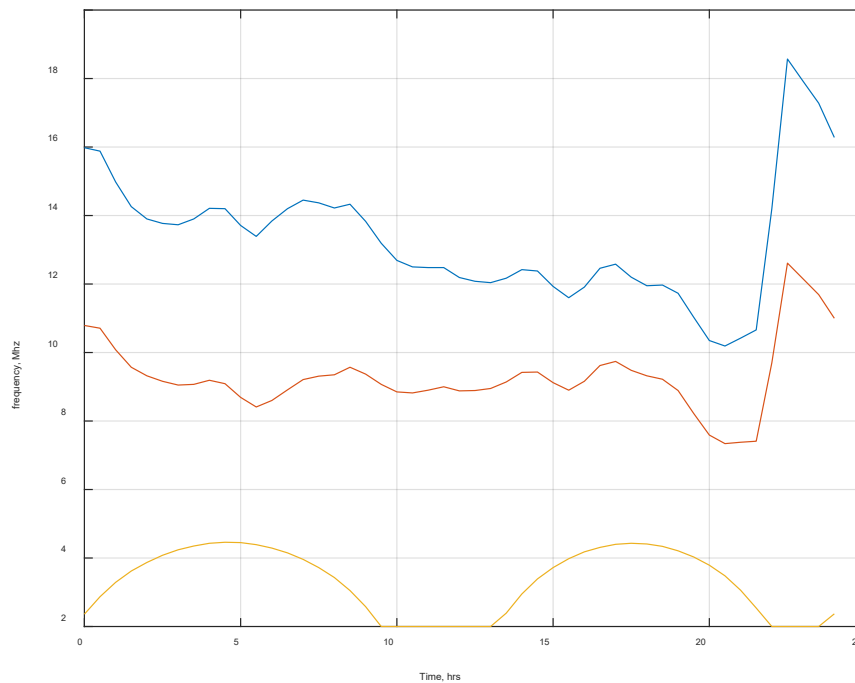


Figure 17: Output from AERP Software

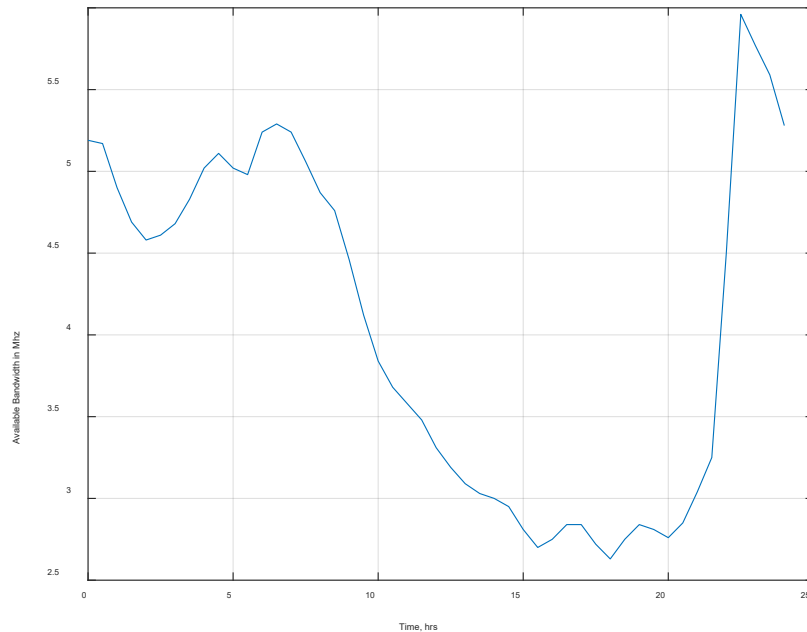
Exporting the data from the AERP program to MATLAB, the data can be utilized to develop to dynamic frequency assignments every 30 minutes to achieve the best chance to receive error free data. The two figures below demonstrate the MATLAB calculations to determine the center frequency. The center of the channel between the Maximum Usable Frequency (MUF) and the



Optimal Frequency (FOT) is chosen for center frequency assignment. If needed, the center frequency should be chosen to favor the lower frequency due to risk of penetrating the ionosphere as the carrier approaches the MUF. For example, if 5 Mhz of bandwidth is available between the MUF and FOT for a 3 Mhz channel, then the dynamic channel assignment should choose the frequencies closest to the FOT.



*Figure 18: Frequency Change Over 24 Hours*



*Figure 19: Bandwidth Available Over 24 Hour Period*

#### **4.4 SIMULATION ASSUMPTIONS AND LIMITATIONS**

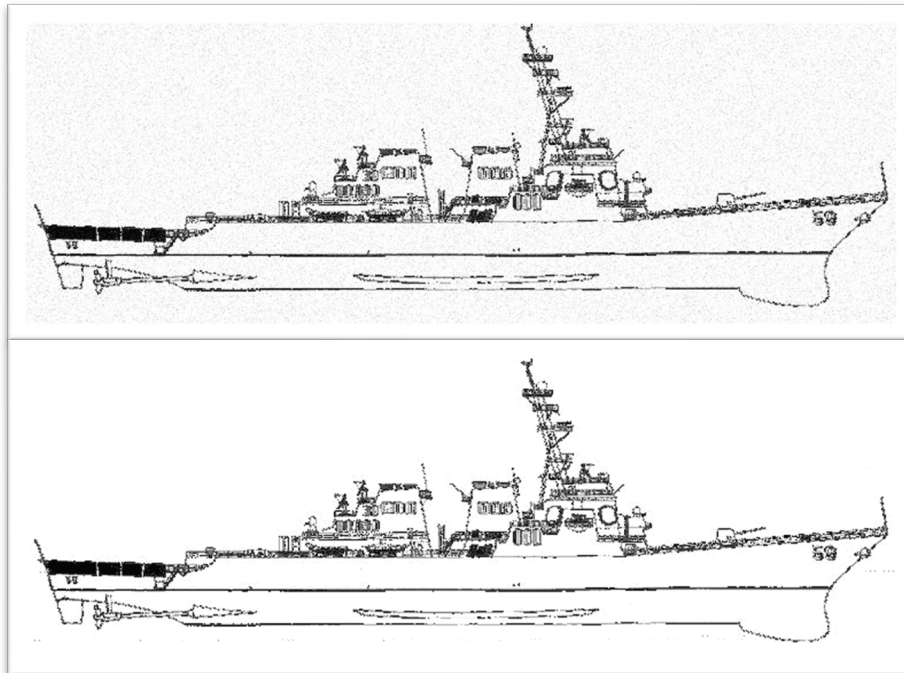
The channel and model assumptions include channel capacity is available for transmission. Additionally, spectrum allocation based on Electromagnetic Interference (EMI) standards were not considered and would limit available bandwidth if assigned frequencies are not in use.

The limitations of the MATLAB simulations include only utilizing AWGN and Rayleigh channels for an HF Channel. Additionally, the written code only supports black and white 8 bits per pixel Bitmap image formats.

## CHAPTER 5: RESULTS

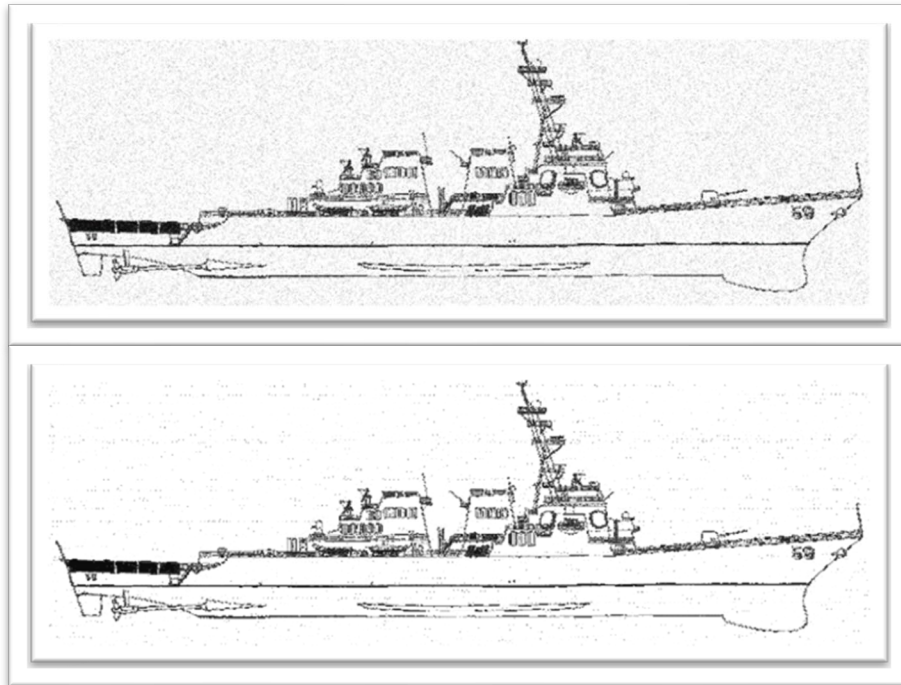
### 5.1 NARROW BAND AND OFDM WITH AWGN

For the same SNR value of 10 dB, the OFDM solution of 32 channels resulted in a much clearer image:



*Figure 20: Narrowband (top) vs 32 Channel OFDM (bottom) for  
BPSK and 10dB SNR*

When the SNR was lowered to 5 dB, both suffered image quality and the clearer picture remained the 32 channel OFDM model.

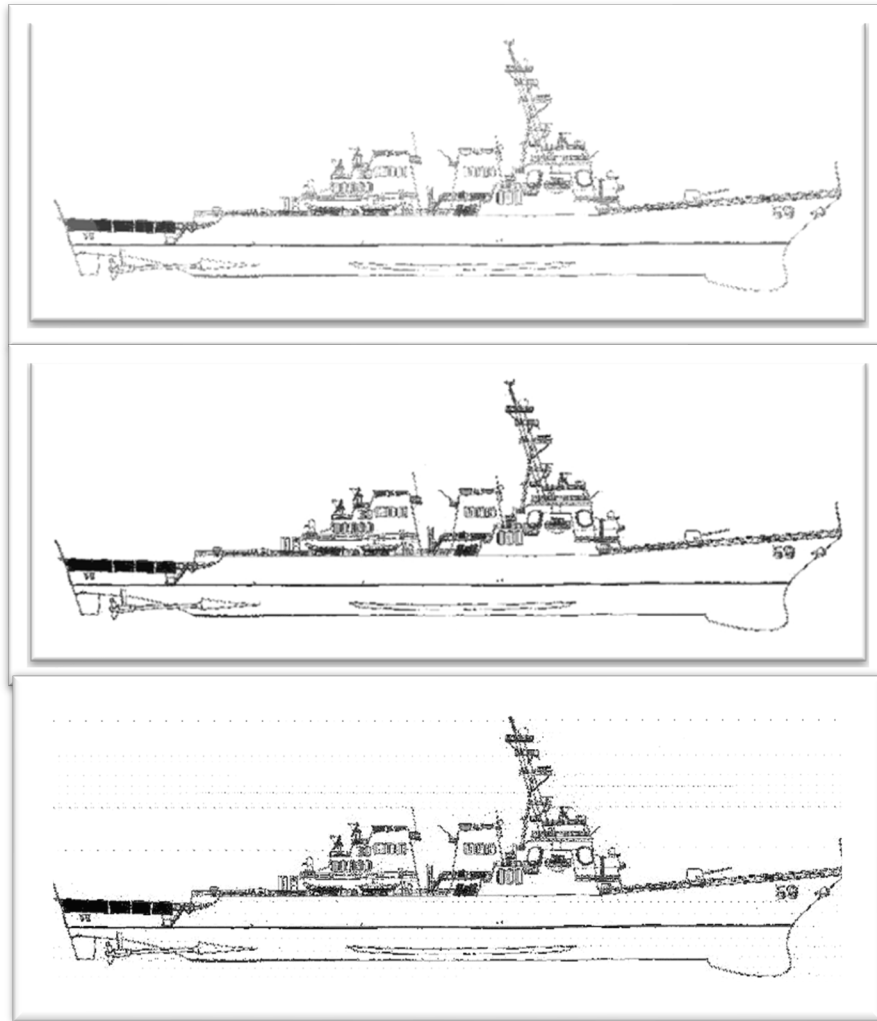


*Figure 21: Narrowband (top) vs 32 Channel OFDM (bottom) for*

*BPSK and 5dB SNR*

## **5.2 RAYLEIGH FADING CHANNEL SIMULATION RESULTS**

With the implementation of the Rayleigh Fading Channel in the simulation, effects of both path delay and spreading effect due to doppler shift in frequency was determined. When zero doppler was observed, channel quality was high with 32 channel BPSK providing the best image quality with a two-way path with delays of 0.003 seconds and 0.0268 seconds.

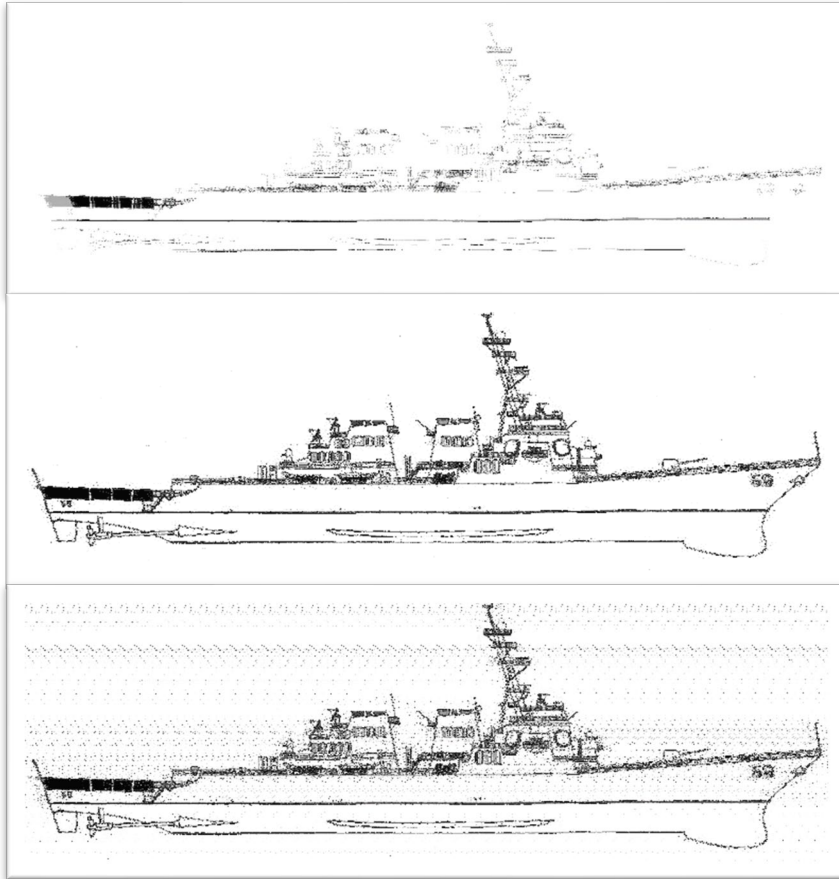


*Figure 22: Effects of Two-Way Path for Narrowband BPSK (top) 32 Channel BPSK (Middle), and 32 Channel QPSK (bottom)*

A small doppler shift (0.001 Hz) caused signal degradation on all channels with the exception of the 32 Channel BPSK model. In addition to the equations introduced in chapter 2, the doppler shift can be represented as

$$f_D = \frac{v_{rel}}{\lambda} \text{ (Hz)} \quad (15)$$

with  $\lambda$  being the wavelength of the carrier frequency. Mathematically, the doppler shift is directly proportional to the frequency of the carrier. Since high frequencies introduce advantageous bandwidth and thus data rates, it is not desirable to use lower frequencies. Instead, this effect is lowered by making the doppler shift so small that it is neglected with the short symbol duration [23]. The short symbol duration minimizes the relative velocity, and thus the doppler frequency. Thus, OFDM presents an advantage due to the parallel channels and shorter symbol duration than the narrowband channel. The effect of doppler spread can be seen below.

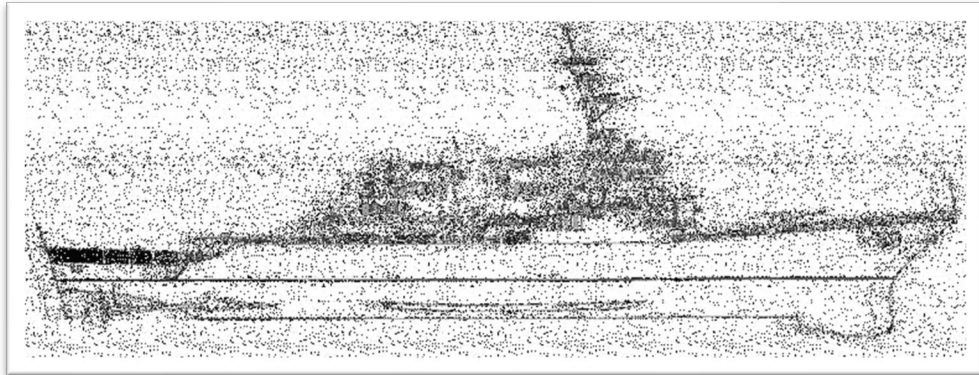


*Figure 23: Rayleigh Channel Fading with .001 Hz Doppler Spread. Narrowband BPSK (top), 32 Channel OFDM BPSK (middle) and 32 Channel QPSK (bottom)*

As the doppler spread was increased from 0.001 to 10 Hz, the signal highly degraded. The narrowband channel image was highly distorted beginning at 0.02 Hz while the 32 Channel BPSK image remained clear until 2 Hz.

Modulation order was also considered in the Rayleigh Channel. While the above image demonstrated a fairly clear image at 0.001 Hz doppler spread for a 32 Channel BPSK, the same

parameters caused high distortion with the same parameters for a 16-PSK modulation order (see figure below).



*Figure 24: Rayleigh Channel Fading with 0.001 Doppler Spread for 32 Channel 16-PSK*



## CHAPTER 6: CONCLUSIONS

### 6.1 CONCLUSIONS

Through research and Monte Carlo simulations in MATLAB, a set of assumptions and OFDM parameters were theorized to implement in a high bandwidth, frequency agile HF OFDM system. This included understanding design trade-offs between achievable SNR, transmission bit rate, and modulation scheme. Additionally, propagation models were explored to understand simulation of the HF channel.

The author utilized an existing OFDM MATLAB code and modified it to fit the simulation model. Dozens of simulations were conducted with both an AWGN channel and a Rayleigh channel to predict ionosphere propagation. Additionally, a narrowband channel was also simulation to compare results with OFDM simulations. The simulations for the narrowband channel included both an AWGN and Rayleigh fading channel.

Based on calculations, research, and simulation results, a 32-Channel OFDM radio link utilizing a BPSK modulation scheme will overcome challenging ionospheric fading and interference conditions and provide a gross data rate of 6 Mbps. If 75 percent of the data rate is reserved for transmitting information, a likely throughput scenario is 4.5 Mbps. If conditions are favorable and a higher SNR is allotted with little to no doppler spread, a higher data rate can be achieved through increasing the modulation order.

One of the primary disadvantages of OFDM implementation is the high PAPR compared to other systems. Additionally, noise figures for HF propagation can reach as high as 16 dB [24]. The high-power transmission requirements coupled with demanding receiver sensitivity requirements for high data rate transmission requires additional study.

Despite the advantages of OFDM, the implementation does bring certain drawbacks. These disadvantages include high peak to average power ratio (PAPR) and a sensitivity to frequency errors from the doppler effect [18]. Due to the high number of peaks across multiple frequencies that are being sent from the transmitter, the amplifier must have a wide linear range, and thus the power requirement is larger.

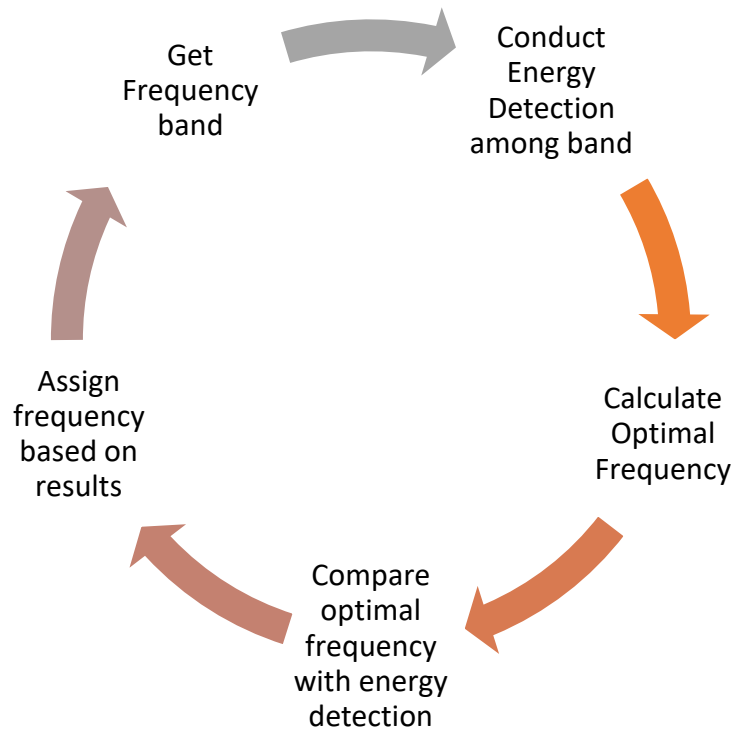
## **6.2 FUTURE WORK**

Future work includes expanding the current model and confirming simulation results. For the model, PAPR and receiver sensitivity will be most likely most challenging burdens to overcome. Additionally, implementation of the Watterson channel model may provide additional insight into the channel predictions of capability of ionospheric propagation. Additionally, the addition of filters at the receiver if cost allows can overcome errors encountered from phase and frequency differences with propagating through the channel.

As discussed extensively in reference [8], an HF broadband antenna design is possible with highly directional antennas with both high power and high gain. This study indicated that bandwidths up to 3 MHz is possible with little interference to primary users and up to 10 Mbps. Future work and application could leverage the antenna system and test for the agile frequency OFDM HF communication discussed in this work.

Additional work and capability can be added through the future implementation of cognitive radio as discussed in reference [25]. Cognitive radio networks look for “spectrum holes” or “white space” in the spectrum that are not currently in use can be leveraged by unlicensed users. The current HF spectrum is controlled by the Federal Communications Commission (FCC) and certain bands and frequencies are allocated depending on use. Cognitive

radio, however, can maximize spectrum utilization by identifying the white space not currently in use. Additionally, the implementation of narrow beam HF communication introduces fewer opportunities for interference along the same frequency. In order to maximize this capability and leverage and exploit the unused spectrum, a method to sense the surrounding RF environment must be implemented. Once the sensing data is gathered, the technology would then make an adaptive decision to access the vacant channels. One way to picture it is to spread the high demand mobile frequencies among the licensed “freeways” that do not have a large demand signal. Thus, to have this “cognitive” ability to gather information about the environment and make an optimized decision, cognitive radio networks follow a cognitive radio cycle of Spectrum Sensing, Spectrum Analysis, and Spectrum decision [26]. Future implementation of this cognitive radio concept is for dynamic frequency assignment based on real time sensors and channel availability vice a prediction model. Spectrum sensing capability and robust algorithms to determine the optimal frequency band based on atmospheric conditions could lead to a real-time dynamic system that would account for unpredicted ionospheric conditions.



*Figure 25: Cognitive Radio Adaption for Dynamic HF Frequency Assignment*

This concept would allow for increased spectrum efficiency and more reliable data links within HF radio systems.

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## APPENDIX: DYNAMIC FREQUENCY ASSIGNMENT MATLAB CODE

```

%%%%%%%%Script written by Erin Hill 2/10/22%%%%%%%%
%%%%%%%%Calculate Available Usable Bandwidth HF scenarios%%%%%%%%

clear all
close all
clc

%Variable Initialization
FreqRange=readtable('Dc_to_SCS.txt');
Time=FreqRange{1:49,1};
MUF=FreqRange{1:49,2};
FOT=FreqRange{1:49,3};
LUF=FreqRange{1:49,4};
%UsedFreqs=readtable('PrimaryUserFreqs.txt');
s=height(FreqRange);
Freqs=zeros(s,2);
%Do_Not_Use=zeros(s,2);
%Used_Freqs1=zeros(s,1);
%Used_Freqs2=zeros(s,1);
for s=1:s
    r=FreqRange{s,2};
    p=FreqRange{s,3};
    t=[r p];
    %m=UsedFreqs{s,2};
    % n=UsedFreqs{s,3};
    F=r;
    %if F==m

```

```

    %    F=m+0.5;
    %end
    %if F==n
    %    F=n+0.5;
    %end
% if F<p
%     fprintf('signal degraded at time',s)
% end
    Freqs(s,1)=FreqRange{s,1};
    Freqs(s,2)=F;
    Freq_Plot(s,1)=F;
    bw(s) = MUF(s)-FOT(s);
    %Do_Not_Use(s,2)=m;
    %Do_Not_Use(s,1)=FreqRange{s,1};
% Used_Freqs1(s,1)=m;
% Used_Freqs2(s,1)=n;

    %if n>=r
    %    Do_Not_Use(s,2)=n;
    %end
end
%Freqs
%Do_Not_Use
%array2table(Do_Not_Use,'variableNames',{'Time','Do Not Use
Frequencies'})
%array2table(Freqs,'variableNames',{'Time','Assigned
Frequencies'})

%%
%plot(Time,Freq_Plot,'DisplayName','Assigned Freq')
%grid

```

```
%title('Frequency Change Over 24hrs')
%xlabel('Time, hrs')
%ylabel('frequency, Mhz')
%hold on
%scatter (Time,Used_Freqs1,'DisplayName','Freq in Use')
%scatter (Time,Used_Freqs2,'DisplayName','Freq in Use')
figure()
plot (Time,MUF,'DisplayName','MUF')
hold on
plot (Time,FOT,'DisplayName','FOT')
plot (Time,LUF,'DisplayName','LUF')
grid
title('Frequency Change Over 24hrs')
xlabel('Time, hrs')
ylabel('frequency, Mhz')
hold off

figure()
plot(Time,bw,'DisplayName','Available Bandwidth')
grid
xlabel('Time, hrs')
ylabel('Available Bandwidth in Mhz')
title('Available Bandwidth over 24 hr Period')
```

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