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MATLAB Modeling of OFDM Modulation Technique Across a 24 kHz, 48 kHz, and 3 MHz Bandwidth in the High-Frequency Radio Band (3-30) MHz

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*MATLAB Modeling of OFDM Modulation Technique Across a 24 kHz, 48 kHz,
and 3 MHz Bandwidth in the High-Frequency Radio Band (3-30) MHz*

By

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A Senior Design Report Submitted to the Faculty of the Department of Electrical and Computer
Engineering

Old Dominion University in Partial Fulfillment of the
Requirement for the Degree of

BACHELOR OF SCIENCE

OLD DOMINION UNIVERSITY

Approved by:

Dr. Linda Vahala

(Advisor)

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Abstract

The goal of this project is to use MATLAB to model orthogonal frequency division multiplexing (OFDM) modulation technique across 24 kHz, 48 kHz, and 3 MHz bandwidths in the high frequency (HF) radio band (3-30 MHz). The purpose of our design is to make HF long distance communication faster and more reliable so that every part of the world, including the most remote parts, will have access to high speed, long distance wireless communication. Our MATLAB model will allow us to modify the bandwidth, carrier frequency, modulation type, signal to noise ratio (SNR), and image size to determine which combination of parameters provides reliable OFDM data transmissions in the HF radio band. To determine the success of our model, we will calculate the data rate and the bit to error ratio (BER) after data transmission. Ideally, we would like to have a BER of 10^{-5} for an SNR that is representative of the noise level experienced in the ionosphere. This report describes the current design of our MATLAB model and presents the results for the set of parameters that will achieve the best data transmission in the HF radio band.

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1. Introduction

1.1 Design Problem

The ionosphere is a layer of the earth's atmosphere that is made of charged particles. Radio signals travel to the ionosphere before they reach their destination [1]. Ionospheric propagation is currently the main method of radio communication in the high frequency (HF) radio band. In HF ionospheric propagation, radio signals leave a transmitter on the Earth's surface, travel towards the ionosphere, and return to Earth at the designated receiving end. By using HF ionospheric radio transmission, radio signals can be heard around the world. This type of communication is what initially connected the most remote portions of the globe and facilitated international broadcasting [2]. Throughout history, HF has been used for long distance communication in aviation, the military, various governments, law enforcement, and amateur radio, however, satellites began to replace HF because satellites' data speed far exceeded HF data transmission speed over long distances. Now, concerns over the vulnerability and high cost of satellite communications (SATCOM) and fiber optics communications have caused the United States to revisit using HF as a primary communication method.

Orthogonal Frequency Division Multiplexing (OFDM) is a wireless multicarrier modulation that uses many subcarriers that are orthogonal to one another to transmit signals. An OFDM signal contains closely spaced modulated carriers that each contain low bit data on each of the subcarriers. Although the subcarriers overlap, each symbol has a guard band added to it. These characteristics together make this modulation type very efficient, reliable, and resistant to interference [3]. To make HF a primary method of long-distance communication again, we designed a MATLAB program that models the OFDM technique across the 24 kHz, 48 kHz, and 3 MHz bandwidths in the HF radio band (3-30 MHz). This model will make HF long distance communication faster, cheaper, and more dependable than its counterparts.

1.2 The Function(s) of the Design

Long distance HF communication has been explored around the world for years. HF Skywave communications have been researched since 1901 and were used by Guglielmo Marconi to communicate across the Atlantic. In 1963, Dr. J Haselgrove was first to predict a HF ray path through the ionosphere [4]. Our design utilizes MATLAB to transmit an image using OFDM in the HF radio band. Today, the military has approved using 24 kHz and 48 kHz

bandwidths in the HF radio band. Our model includes a 3 MHz bandwidth as well, which is 125 times the bandwidth of the current limit set by the military and 1000 times the standard bandwidth of HF communication channels [4]. In our program the user is able to select the number of desired subcarriers, bandwidth, subcarrier frequency, modulation type, and image size. The program will then transmit a known image and display the transmitted image. To help the user determine the best combination of parameters to be used to get the best BER and data rate, we designed a code to test every possible transmission. This code allows the user to determine every combination of parameters that meets our standards for an acceptable transmission. Our design takes previous OFDM modulation programs and engineering standards into consideration to ensure quality and consistency are applied.

1.3 Quantitative Performance Objectives

The goal of our design is to quantitatively determine which group of parameters will produce an acceptable data transmission. The group of parameters being analyzed are the image size, number of subcarriers, carrier frequency, bandwidth, and modulation type. An acceptable data transmission was determined by calculating how fast the data was transmitted (data rate) and how well the data was transmitted (BER). Any transmission with a time per symbol rate less than 150 microsecond per symbol were eliminated due to unreliable results caused by the spacing of symbols being too close to one another for proper analysis. Once the data was transmitted, the modulation constellation plot was analyzed for accuracy.

2. Design Approach

2.1 Design Function

The MATLAB code created to meet program requirements consists of user inputs, internal signal processing, and data output. Once the user selects the desired combination of inputs, the program processes a signal in accordance with the user inputs and displays a visual representation of the results along with data metrics.

The team began by researching known designs both in Simulink models and in MATLAB. We then recognized major functions within the researched designs and their validity regarding our project goals. These major functions needed in the design were as follows: a signal

generator, a modulator, FEC, inverse Fast Fourier Transform (IFFT), cyclic prefix addition and removal, bandwidth implementation, frequency shift, Gaussian noise, Fast Fourier Transform (FFT), a demodulator, error correction removal, and BER calculation. These functions can be regrouped into three major categories: transmitter, receiver, and analysis as seen in Figure 2.1.

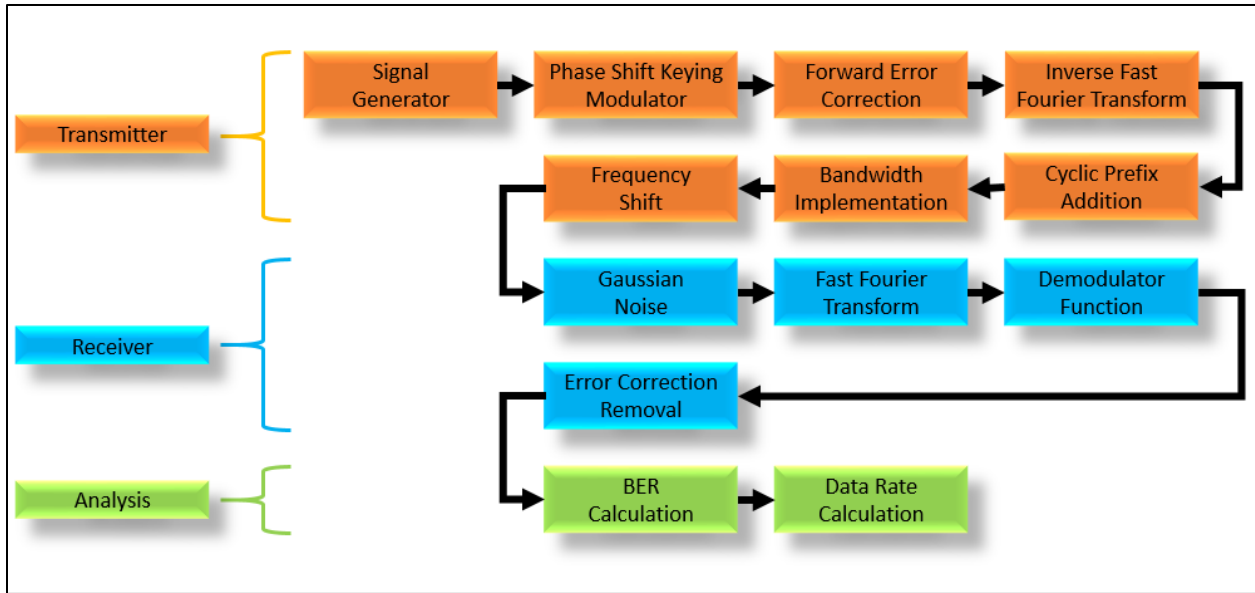


Figure 2.1: OFDM Design Function Flowchart demonstrating the flow of the data signal. For each simulation four different inputs will be entered into the OFDM modulator including the modulation technique, bandwidth selection, input signal, and frequency settings. After the settings are inputted into the OFDM modulator, the result will then be sent to a demodulator and BER's will be calculated.

2.1.1 Transmitter

The components responsible for transmission is responsible for generating and modulating the signal. The first function is the signal generator. The purpose of a signal generator is to create a signal that will be modulated, transmitted, and received utilizing OFDM in the high frequency range. The signal generator can be built to support specific types, lengths, and amounts of data. In our model, the signal generator is represented by images that are converted into a binary format.

The phase shift keying modulator converts binary data to symbols. The symbols can represent one or more bit of information depending on the type of modulation used. This allows for an increased data rate. BPSK modulations use one bit per symbol which consists of two

constellation points. QPSK modulations use two bits per symbol which consist of four constellation points. 8PSK modulations use three bits per symbol which consist of eight constellation points. 16-QAM modulations use four bits per symbol which consist of 16 constellation points [5]. FEC was included to ensure the program meets standards set by Mil-STD-188 110C [6]. FEC adds redundant bits which allows the receiver to correct errors from the transmission [7]. The IFFT converts the signal into the time domain. It also separates the signal into the desired number of subcarriers.

The cyclic prefix addition is a standard from IEEE Standard 802.11n which requires cyclic prefix addition and removal for wireless transmitted signals [8]. A cyclic prefix copies the end of a symbol and places it at the beginning of the symbol to reduce inter-symbol interference [9]. Bandwidth implementation is required per project guidelines. In OFDM, the bandwidth is determined by the time per symbol and number of symbols. The desired bandwidth is divided by the number of subcarriers which is then used to set the time per symbol. Frequency shifting takes the original signal and moves it to a signal in a specified range. This project requires the carrier frequency to be within range of 3-30 MHz. To meet this requirement, the signal was multiplied by a sinusoid with the proper carrier frequency.

2.1.2 Receiver

The receiver group demodulates the transmitted signal along with removing error correction and prefixes. In our code, we included Gaussian noise in the receiver. Noise, which represents the environment the signal is passing through, could be added at either the end of transmission or at the beginning of receiving the signal. Gaussian noise is needed in the model to reflect realistic conditions. Within this function, SNR measured in dB, can be adjusted to simulate the desired environment. The FFT converts the signal into the frequency domain. It also compiles the subcarriers into one signal. The demodulator transforms the symbols back into bits. This brings the signal back into its original form. Error correction removal takes away redundant bits that were originally added by the error correction function and modifies adjacent bits if an error has been made. This is determined by comparing the received signal to the duplicate bits added.

2.1.3 Analysis

The BER is used to determine how effectively the signal is being transmitted. With this method, the values of our code can be verified, and the quality of the modulation can be displayed. Data rate will also be used to evaluate how fast the signal can be transmitted and received.

2.2 Quantitative Performance

The following tables demonstrate the observed results from our MATLAB program using SNR values of 10, 15, and 20 dB with and without FEC. Table 2.1 shows the average data rate in bits per second for each modulation type using bandwidths of 3 MHz, 48 kHz, and 24 kHz. The average data rate was calculated by averaging the data rate for the different number of subcarriers (64, 128, 256, and 512). This allowed us to determine the relationship between the modulation type, the data rate, and the bandwidth. 16-QAM always transmitted the data the fastest despite the image size, number of subcarriers, and carrier frequency. 8PSK was the second fastest type of modulation followed by QPSK and lastly BPSK. A graphical representation of this data is also shown in Figure 9.4 in Appendix D.

Table 2.1: Average Data Rate (bps) Per Modulation Type at Varying Bandwidths

Modulation Type	Bandwidth	Average Data Rate (bps)
16-QAM	3 MHz	1.16E+07
	48 kHz	1.66E+06
	24 kHz	1.09E+06
8PSK	3 MHz	8.73E+06
	48 kHz	4.17E+05
	24 kHz	6.66E+04
QPSK	3 MHz	5.82E+06
	48 kHz	8.64E+04
	24 kHz	4.32E+04
BPSK	3 MHz	2.91E+06
	48 kHz	4.32E+04
	24 kHz	2.16E+04

Table 2.2 shows the average BER for each modulation type at varying SNR values (10, 15, and 20 dB) with and without FEC. The average BER was determined by averaging the BER of the different number of subcarriers. This allowed us to see how changing the noise level affected how well the signal was transmitted. Acceptable BER values (less than 10^{-5}) are highlighted in the table. Out of all the modulations, 16-QAM with FEC had the most errors. An SNR level of 20 dB consistently provided acceptable BERs for every modulation whether FEC was applied or not. A graphical representation of this data is also shown in Figure 9.5 in Appendix D. The results for the BER values for data transmissions using each modulation type at 20 dB, 15 dB and 10 dB are shown in Figures 9.6, 9.7, and 9.8 respectively in Appendix D.

Table 2.2: Average BER Per Modulation Type at Varying SNRs

Modulation Type	SNR	Average BER	Average BER (FEC)
16-QAM	10	7.59E-02	2.28E-01
	15	5.05E-03	3.06E-04
	20	2.69E-06	0.00E+00
8PSK	10	5.04E-02	1.31E-01
	15	1.35E-03	3.84E-05
	20	5.61E-08	0.00E+00
QPSK	10	1.16E-03	1.38E-05
	15	7.85E-09	0.00E+00
	20	0.00E+00	0.00E+00
BPSK	10	3.12E-06	0.00E+00
	15	0.00E+00	0.00E+00
	20	0.00E+00	0.00E+00

Table 2.3 shows which modulation type had the best data rate for each SNR level with and without error correction within the acceptable BER level. This allows us to see which modulation type produced the best overall results (data rate and BER) for each SNR level. A value of zero for the BER means that the BER is less than 10^{-5} without FEC applied and 10^{-7} with FEC applied due to the number of bits being processed.

Table 2.3: Modulations with the Best Data Rate (bps) at Varying SNR Values

SNR	Best Acceptable Data Rate (bps)	Modulation Type	BER
10 (No FEC)	2.91E+06	BPSK	3.12E-06
15 (No FEC)	5.82E+06	QPSK	7.85E-09
20 (No FEC)	11.6E+06	16-QAM	2.69E-06
10 (With FEC)	5.82E+06	QPSK	1.38E-05
15 (With FEC)	8.73E+06	8PSK	3.84E-05
20 (With FEC)	11.6E+06	16-QAM	0

2.3 Realistic Constraints

2.3.1 Economic Constraints

Creating the model in MATLAB required no major economic constraints. MATLAB is available for use by ODU students for free by accessing the ODU desktop program remotely through ODU's VMware Horizon application. During our initial research and design process we often used the Communications Toolbox in MATLAB, however, we were not required to purchase the software for that either because one of our advisors, Dr. Watson, was able to get the additional toolboxes we needed added to ODU's 2019B version of MATLAB at no additional cost to the students. The only constraint is that we could solely access the toolboxes through the VMware Horizon application.

2.3.2 Environmental Constraints

If implemented, our MATLAB code must be able to withstand the effects of the real environment it is designed to transmit signals in. The ionosphere is the main environmental factor that plays a role in the transfer of signals using the HF radio band, so when designing our code, we had to make sure that we could transmit the image in conditions representative of the ionosphere. The ionosphere is constantly changing because it is formed when particles are ionized by the Sun. Any disturbance can disrupt signals traveling through to get to their destination [1]. To account for the changing conditions, we discovered, with the help of Dr. Watson, that to represent the ionosphere we could set the SNR between 10 and 20 dB. For this reason, testing was done only for SNR values of 10, 15, and 20 dB.

2.3.3 Societal Constraints

During the development of our MATLAB model, we used an image of Big Blue, ODU's mascot, to serve as the image that we wanted to transmit. "ODU owns the copyright and other rights" to their images, so when using the image, we made sure that we properly cited our use of it [10]. If this program is used for commercial reasons to transmit images, it is imperative to gain permission from and properly give credit to the owner as well.

2.3.4 Time Constraints

The research, development, preliminary design, and initial proposal were completed last semester. The final design is limited to this semester. Since the time allotted to complete this project was limited, there are major time constraints to complete our design and test the performance of the program. We wanted to develop a program in MATLAB and Simulink, but the time constraint guided us towards focusing mainly on MATLAB and discussing a model in Simulink as an alternative design and as an opportunity to improve our program in the future.

2.3.5 Health and Safety Constraints

As the coronavirus outbreak worsened, all classes were moved to meeting solely online. This prevented our group from being able to meet in person and with our advisors. We meet on Zoom with our advisors every Monday from 5:45pm to 6:45pm. We meet as a group to work on the project together during class time on Thursdays from 3:15pm to 4:15pm and on Fridays from 9:00am to 11:00am. Meeting on zoom allowed us to stay safe and all participate in the creation of our model, however, meeting in person would have allowed us to create our model easier.

2.3.6 Manufacturability

All the software needed to support the research and development of our model is readily available on the MathWorks website to order. To purchase MATLAB for commercial use, the price is approximately \$2,150 for a perpetual license or \$860 for an annual license [11]. Since our model was developed from relatively inexpensive software, it will be easily duplicated for use to improve HF long distance communication for the military and for use in countries that do not have access to high-speed data.

2.3.7 Sustainability Constraints

Sustainability of our model relies on MathWorks, the developer of MATLAB, to continuing providing MATLAB as a product and continuing to provide updates to the software as older versions become obsolete. As of January 2019, MATLAB users receive notifications on the MATLAB desktop when an update is available [12].

2.3.8 Qualitative Risk Assessment

In our code, the user is able to select a list of parameters utilized to create, modify, transmit, receive a signal and then determine the quality of transmission. Failure could occur in our program if the code fails to compile. This could be caused by changes to the functions utilized in the program, or software version updates to MATLAB which affect portions of the code. In order to mitigate these risks, the program utilizes the current standard functions for each portion of the code. By avoiding out of date functions, the functions utilized in the code are less likely to be discontinued by MATLAB or impacted severely by a new software update.

2.4 Alternative Designs

2.4.1 Additional Modulation

Our design utilizes BPSK, QPSK, 8PSK, and 16-QAM ODFM modulation techniques. There are several alternative ODFM modulation techniques that could be used which each have their own benefits. 32-QAM and 64-QAM are alternative choices for modulation [13]. 32-QAM and 64-QAM are common modulation techniques which utilize 5 and 6 bits per symbol, respectively. As the number of bits per symbol increases, so does the amount of data that can be transmitted. However, the BER also increases with the bits per symbol which causes more errors [5]. In this alternative design, 32-QAM and 64-QAM would be used in addition to the other modulation types already implemented.

2.4.2 Simulink

Simulink is a program within MATLAB that allows users to visually place function blocks in a mapping sequence to complete an array of different system applications. One of the systems that is readily supported is OFDM. Simulink offers modulation, Gaussian noise, FFT,

constellation mapping, and error rate blocks which directly support the tasking involved with OFDM signal processing. Simulink also allows users to witness the process flow if the system as it runs through its progression. This can be useful in that it may help network designers in their ability to troubleshoot and confirm the process flow is doing what they want.

2.4.3 LabVIEW

LabVIEW is a GUI interface that has similarities to MATLAB in that it allows users to place tools in the form of blocks in a workspace and witness the process flow as the system runs. LabVIEW has a library for OFDM processing. The team has experience in using LabVIEW and despite it not being a direct option for the completion of this project, it should be noted that there are options for OFDM processing outside of MATLAB.

2.5 Analysis Used to Select Alternative Design

Simulink offers a robust amount of support in OFDM signal processing. Not only does Simulink offer libraries specific to OFDM, but the software also itself is professionally supported and is a common tool found in engineering practice. Not only is the tool supported professionally, the user and community support can also be identified as a valuable resource. The team was able to find designs that were pre-built as seen in Appendix D, Figure 9.1 that offer a baseline concept design that could be expanded upon to meet OFDM signal processing tasks; however, we were not able to get constellation plots representative of the modulation types that we used. Therefore, we ultimately decided to create a MATLAB program for our final design [14].

2.6 Team Organization and Performance

The group met with our advisors, Dr. Vahala and Dr. Watson, virtually on Zoom every Monday from 5:45pm to 6:45pm to discuss our upcoming assignments and to receive advice and suggestions for our MATLAB model. Josiah was our team leader, he discussed our progress, deadlines, and the agenda for the meeting. The person in charge of the assignment or topic being discussed then took over the discussion and solicited feedback from the advisors and other group members. We also met during class time on Thursdays and on Fridays from 9:00am to 11:00am to work together on designing our MATLAB model. The group also had a shared drive where we

keep all our reference materials including copies of our assignments to be reviewed and assignments that have already been submitted. During the advisor and official group meeting on Fridays, Sarah took meeting notes that are stored on our shared drive as well to document the important topics that were discussed.

3. Project Deliverables

3.1 Tasks and Responsibilities

Natalia Anglero was responsible for defining software and toolboxes used within MATLAB. She investigated how our program evaluates BER to ensure its validity and compared the results of our program with similar designs. She worked on testing the program and analyzing the results along with Tyler and Sarah. Natalia also provided guidance for the design of our project during our group meetings.

Tyler Collins is the design lead for our project. He worked on developing and cleaning up our code and implementing the frequency shift, bandwidth constraints, and FEC to ensure that all input parameters could be incorporated to give us our desired results. Tyler also worked on testing the program and analyzing the results along with Natalia and Sarah.

Sarah Taylor was responsible for leading the testing and documentation aspects of our project. She ensured proper testing and documentation of the results. She worked on running the tests on our program and analyzing the results with Natalia and Tyler. She assigned roles for the completion of the report. She also provided guidance for the design of our project during the group meetings.

Josiah Myer is the team leader. He was responsible for organizing the schedule and delegating general tasks. He assisted with implementing the different modulation techniques within the program to support the ability of evaluating which modulations worked best using certain frequencies and bandwidths. He also helped provide guidance for the design of our project during our group meetings.

3.2 Milestone Timeline

The Gantt chart shown in Figure 3.1 below, illustrates our project schedule. The chart lists the tasks that have been performed and that will be performed on the vertical axis. The horizontal axis shows when these tasks were completed. Our schedule and target dates were all met in advance which leveraged out opportunity for internal and external review.

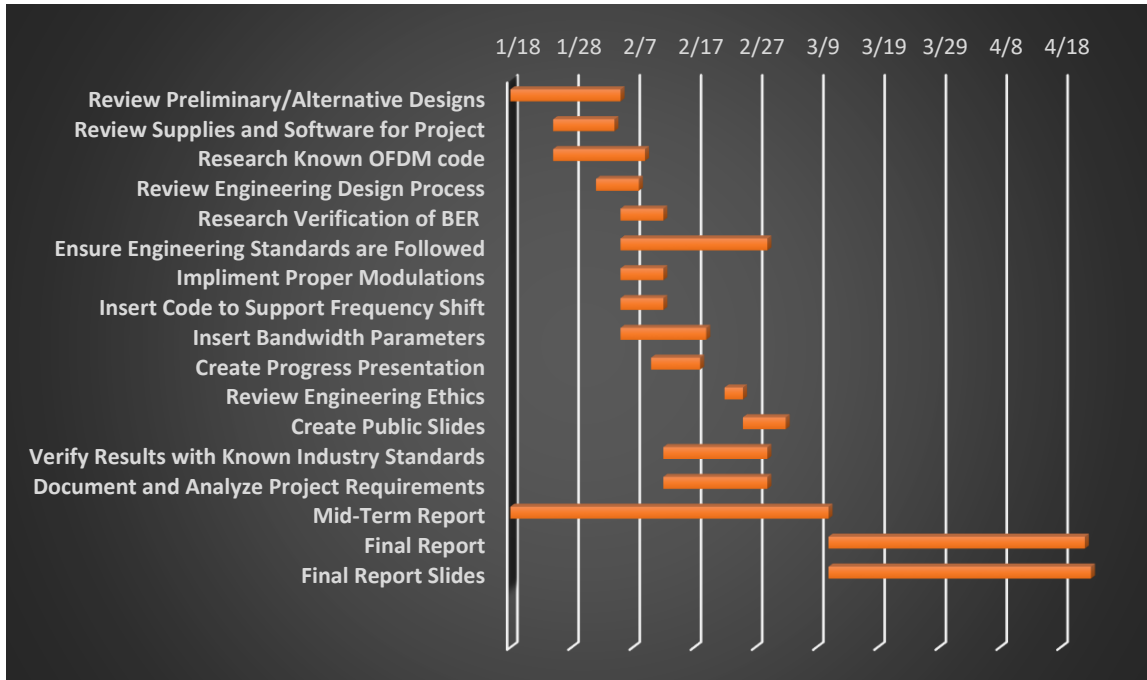


Figure 3.1: Gantt Chart demonstrating Group 10’s schedule for the Spring semester

4. Design Specifications

4.1 Details of the Engineering Design

MATLAB was utilized in this project using the baseline of a preexisting code to develop a new code that generates a signal, applies FEC, phase shift keying, performs OFDM modulations, implements bandwidth and carrier frequency restrictions, adds Gaussian noise, demodulates the signal, and compares the transmitted signal to the received signal to determine the quality of the transmission [15]. When the program first runs, the user must select options for the size of the image, in pixels squared, modulation type, number of subcarriers, bandwidth, and carrier frequency. To generate a signal, the MATLAB code reads in an image, using the “imread” function, and converts it to binary, using the “dec2bin” function. The user of the

program then chooses from a list of image sizes which represent varying sizes of data to be transmitted. After the signal is generated, FEC is applied by using the “Dataenc” function along with the “poly2trellis” function. The “poly2trellis” function utilizes matrices corresponding to a 2/3 data rate FEC implementation [16].

Next, the user has a choice between 4 different modulation styles: BPSK, QPSK, 8PSK, and 16-QAM. Based on the user’s selection, the code applies the modulation by multiplying the signal by phase shifted sinusoids. The next selection available to the user is for the number of subcarriers. The user can select 64, 128, 256, or 512 subcarriers for the modulation. The signal is then split into the correct number of subcarriers, using the “reshape” function, before the IFFT is performed, using the IFFT function. After the signal is modulated, the cyclic prefix is added, and the signal is converted from parallel to serial. The user then chooses a carrier frequency of 3 MHz, 15 MHz, or 30 MHz and a desired bandwidth of 24 kHz, 48kHz, or 3 MHz. Then, the duration of each symbol is calculated based on the bandwidth and number of subcarriers selected by the user. The symbol duration is then used when shifting the frequency to the selected carrier frequency. A for loop is used for the frequency shift which utilizes the formula in Equation 4.1 where X is equal to the signal, f_c is equal to the selected carrier frequency, and t is incremented by the time per symbol for each duration [17].

Equation 4.1: Frequency Shift Equation

$$X = X e^{-j f_c t}$$

After the signal has been shifted to the desired frequency, Gaussian noise is added based on a desired SNR range. The SNR value can be adjusted to match the desired environment that the signal will be traveling through. Then, the frequency of the signal is shifted back by multiplying it by a positive exponential from Equation 4.1 and the cyclic prefix is removed from the signal using the reshape function. Once the cyclic prefix is removed, a FFT is performed on the signal, using the FFT function, to bring the signal back into the time domain. Then, the symbols are demodulated based on the modulation type selected by the user and the FEC is removed, utilizing the “vitdec” function with a hard decision algorithm.

Once the error correction is removed, the received signal is compared to the transmitted signal and the BER is calculated by dividing the number of errors by length of the signal. Lastly,

the transmitted and received constellations are plotted along with the BER to display to the user the quality of the modulation and transmission, along with the parameters chosen.

While developing our design we encountered issues when trying to implement FEC, the data rate, and the time per symbol. Initially when trying to implement FEC, the program would not run. We discovered that our signal was using characters but to use the “convenc” command, which is required for FEC, the data had to be converted to double. When trying to determine the data rate and time per symbol we were not sure what equations should be used to accurately calculate these values. After meeting with the advisors, Dr. Watson helped us determine which equations should be used to accurately represent these values. We also initially had an issue with determining the most efficient way to test our program. If we tested each combination of parameters manually, we would have had to run the code 1000’s of times. We designed a code that could test every possible combination of parameters and output the results. This helped us determine which group of parameters produced the best results much faster than we could have manually.

4.2 Parts List/Software Components

The software used to create our model is MATLAB R2019B. MATLAB is a programming software primarily used to support mathematical, scientific, and engineering processes. For this design, toolboxes within MATLAB were utilized to use MATLAB’s technical computing functions. The toolboxes used were Simulink, Communications, DSP System, Signal Processing, Statistics/Machine Learning, and Symbolic Math toolboxes. The toolboxes provided specific signal analysis or image processing [18]. The Communication toolbox was the main toolbox used to analyze the link performance, signal synchronizes, and subcarrier modulation selections.

4.3 Engineering Standards

Engineering standards ensure consistency, quality, and safety are adhered to in engineering designs. The major sources of engineering standards that relate to our project are the United States Military and IEEE. Mil-STD-188 110C and IEEE standard 802.11n both relate to our project. Mil-STD-188 110C sets the standards for the structure of modulated signals and signal overview in the high frequency range. IEEE standard 802.11n does not cover our project's

frequency range but sets the standard for modulated signals that are transmitted wirelessly [8]. The modulated signals in our project follow these standards to be easily understood by engineers outside of our group. This also allows for continuation of our research.

Our group project involves the modulation of signals utilizing OFDM in the HF radio band. Mil-STD-188 110C sets the standard for the structure of OFDM modulated signals and the error correction coding. One of the major points of Mil-STD-188 110C is the modulation frame structure. Following the Mil-STD-188 110C standard for OFDM modulated signals, our code begins with a preamble code to synchronize the channel. The preamble is followed by the OFDM modulated signal and data. Each of these sections also contains further constraints for the length, duration, number of subcarriers, and additional signal information [6]. When we developed our MATLAB program, we followed both guidelines to determine how our program should be formatted. We also followed Mil-STD-188 110C requirement for how error correction should be applied during the transmission of signals [6]. This is used in our testing code. By following these standards, our work is consistent with other OFDM modulation techniques and therefore allows further continuation of our project while avoiding replicating past research mistakes.

5 Design Performance

5.1 Transmission Performance using 10 dB

When the signal was transmitted at an SNR level of 10 dB without forward error correction, the group of parameters that performed the best (produced the smallest BER with the fastest data rate (2.91 Mbits/s)) was transmitted using BPSK at a bandwidth of 3 MHz and utilized 512 subcarriers. Only the signals using 512 subcarriers were displayed at this bandwidth for every SNR level because they were the only transmissions that met the time per symbol requirement of being greater than 150 microseconds per symbol. 16-QAM, 8PSK, and QPSK transmitted the image faster at this bandwidth using these parameters but were not considered because their BERs fell below the acceptable level. This shows us that the bandwidth, modulation type, and number of subcarriers had the most significant effect on how fast the image was transmitted. The image size and the carrier frequency did not significantly impact the data rate for any of the SNR values tested. At 24 kHz and 48 kHz, the time per symbol was higher

than the minimum requirement of 150 microseconds for each of the number of subcarriers tested. However, as shown in Table 2.2, BPSK was the only modulation type to have acceptable BER results without FEC applied at this SNR level.

When the signal was transmitted at 10 dB with FEC, the same trends as the data transmissions without error correction were observed for BPSK, but the BER values were zero for every transmission. This means that with FEC, any combination of parameters that fit the time per symbol requirement when using BPSK can be used to get a successful transmission. As shown in Table 2.1, with FEC applied, QPSK also became a viable option at 10 SNR which increased the possible data rate to 5.82 Mbits/s, doubling the data rate that can be achieved without FEC. An acceptable BER was never achieved using the other two modulation types. Figures 5.1 and 5.2 show transmitted images using parameters that produced an acceptable and unacceptable BER without using error correction to demonstrate the differences that affect the program's performance at an SNR level of 10 dB.

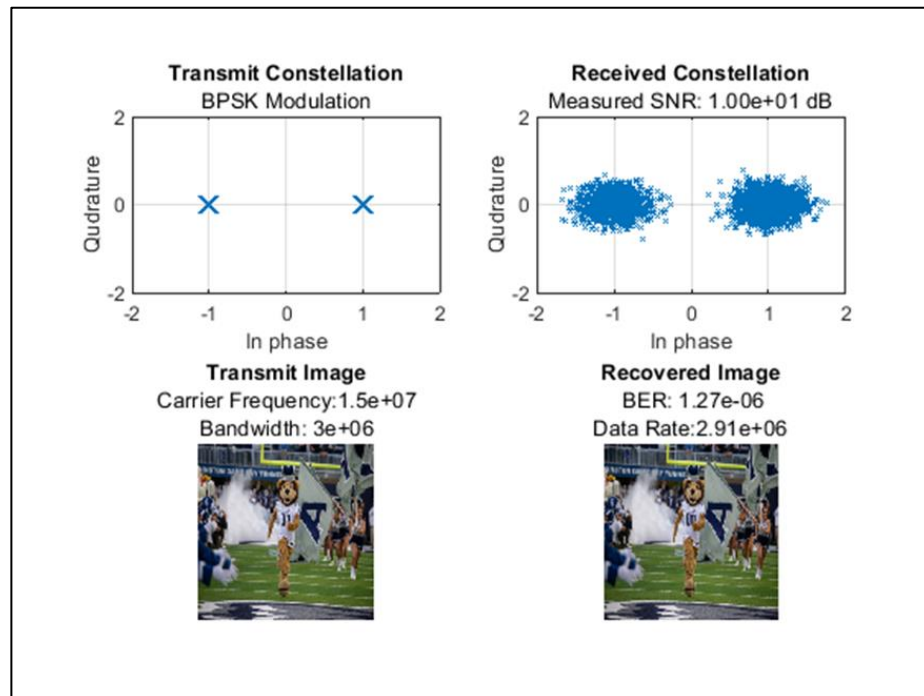


Figure 5.1: Transmitted constellation and image versus received constellation and image. BPSK modulation using a carrier frequency of 15 MHz, a bandwidth of 3 MHz, an image size of 256 x 256 pixels, 512 subcarriers at an SNR value of 10 dB without forward error correction. The image is recovered at an acceptable BER of 1.27e-06 errors per bit. The constellation shows the information transmitted as one of two symbols, each representing one bit of data. Each symbol is encoded with a different phase shift. The data is dense around the two symbols, exemplifying a good data transmission.

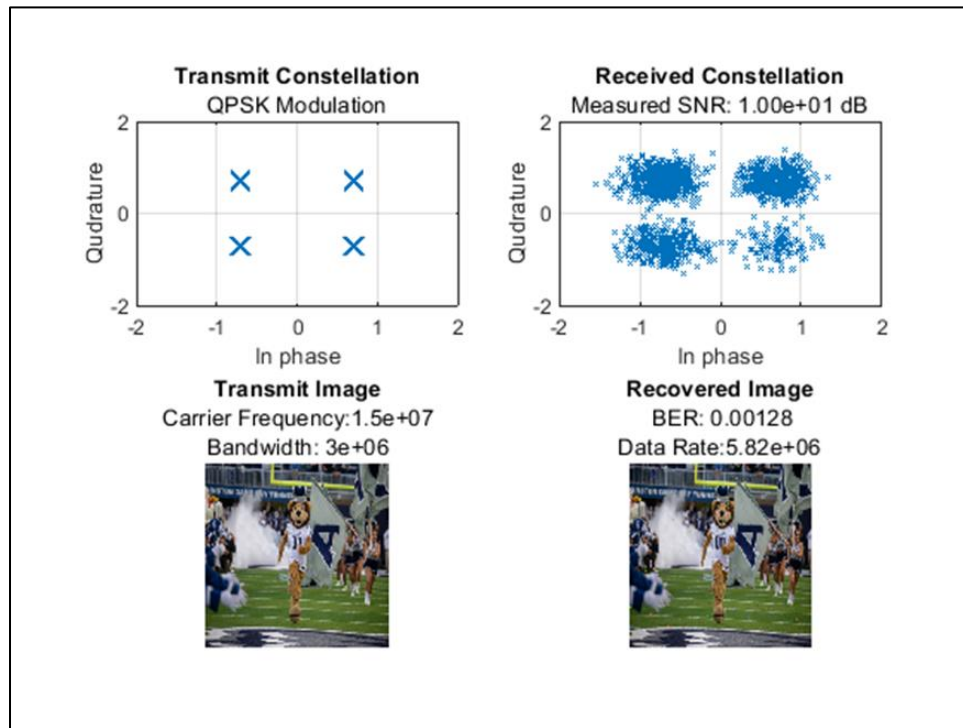


Figure 5.2: Transmitted constellation and image versus received constellation and image. QPSK modulation using a carrier frequency of 15 MHz, a bandwidth of 3 MHz, an image size of 256 x 256 pixels, 512 subcarriers at an SNR value of 10 dB without forward error correction. The image is recovered at an unacceptable BER of 1.28e-03 errors per bit. The constellation shows the information transmitted as one of four symbols, each representing two bits of data. Each symbol is encoded with a different phase shift. The data is not tightly grouped around the four symbols, exemplifying a bad data transmission.

5.2 Transmission Performance using 15 dB

When the signal was transmitted at an SNR level of 15 dB without FEC, the group of parameters that produced the smallest BER with the fastest data rate (5.82 Mbits/s) were all transmitted using QPSK, at a bandwidth of 3 MHz, and used 512 subcarriers. 16-QAM and 8PSK transmitted the image faster at this bandwidth but they were not considered because their BERs fell below the acceptable level. As shown in Table 2.2, at 24 kHz and 48 kHz, the BER for 16-QAM and 8PSK still never reached the acceptable level. Therefore, only BPSK and QPSK (using any combination of parameters) would produce an acceptable BER at 24 kHz and 48 kHz.

When the signal was transmitted at 15 dB with FEC, BPSK and QPSK were still viable for all combination of parameters, but all the BER values were zero for every transmission. This means any combination of parameters using these two modulations can be used to get a

successful transmission. With FEC applied, 8PSK BER values began to fall into the acceptable BER range. As shown in Table 2.1, utilizing 8PSK, the fastest data rate that can be achieved increased to 8.73 Mbits/s at this SNR level. Some acceptable BER values for 16-QAM were also produced, however, based on the results there was no way to consistently get an acceptable BER. The BER values for each modulation type are shown in Figure 9.7 in Appendix G. Figures 9.10 and 9.11 in Appendix G show transmitted images using parameters that produced an acceptable and unacceptable BER without using error correction to demonstrate the differences that affect the performance of the program at an SNR level of 15 dB.

5.3 Transmission Performance using 20 dB

As shown in Table 2.2, when the signal was transmitted at an SNR level of 20 dB, the BER for every transmitted signal produced an image with an acceptable BER with and without FEC. The group of parameters that produced the smallest BER with the fastest data rate (11.6 Mbits/s) were all transmitted using 16-QAM, at a bandwidth of 3 MHz, and used 512 subcarriers. At this SNR level, 16-QAM had the fastest data rates with an acceptable BER for each bandwidth tested, 8PSK had the second fastest rates, followed by QPSK then BPSK.

When FEC was applied, the same trends as the data transmissions without error correction were observed, except the results for the BER were equal to zero for every transmission. The BER values for each modulation type are shown in Figure 9.7 in Appendix G. Figure 9.12 in Appendix G shows a transmitted image using parameters that produced an acceptable BER without using error correction and Figure 9.13 in Appendix G shows a transmitted image using parameters that produced an acceptable BER using error correction to demonstrate the differences that affect the performance of the program at an SNR level of 20 dB.

5.4 Overall Performance

The goal of our design was to successfully transmit signals using OFDM modulation across a 24 kHz, 48 kHz, and 3 MHz bandwidth in the HF radio band (3-30 MHz). How fast the data was transmitted (data rate) and how well the data was transmitted (BER) were the two criteria used to determine a successful transmission. As mentioned in the quantitative performance, the modulation type and bandwidth have a direct effect on how fast the signal was transmitted. Figure 9.4 located in Appendix D provides a visual representation of this

relationship. As shown in Table 2.1, 16-QAM was able to transmit the images the fastest despite the other parameters because 16-QAM uses four bits for every symbol it transmits. This means that more data can be packed into the same amount of space in comparison to other modulation types because they use less bits per symbol.

The transmission rate increases as the bandwidth increase because more space is available to send information. However, as the number of bits being transferred at one time increases, the possibility of error is increased as well. This is proven by Table 2.2 showing that 16-QAM and 8PSK always had the largest average BER at each bandwidth. The BER for the two modulations were large despite the application of error correction because at an SNR level of 10 dB, the BER was too high that error correction could not improve the value. Table 2.2, however, does show that the total number of modulations that produces acceptable BER values does increase when error correction is applied as expected. Figures 9.6, 9.7, and 9.8 in Appendix D show how the SNR value affects the BER. An SNR level of 20 dB with and without FEC consistently provided acceptable BERs for every modulation whether FEC was applied or not because the BER and SNR have an inverse relationship. As the SNR value increases, the BER decreases, regardless of the combination of parameters. The modulation type that produced the best results for each SNR value, with and without FEC is found in Table 2.3. This shows us that as the SNR increases, more bits per symbol can be sent during each transmission.

6 Project Broader Impacts

6.1 Ethical Implications or Issues

Technology is an important aspect in every part of our lives. When designing new technology or reengineering existing technology, it is important to commit to the highest professional and ethical conduct during the entire design and manufacturing process. While completing our project, we have been using the IEEE Code of Ethics when assessing the ethical implications of our project. While completing our project we found that tenets one, two, five, six, seven, and ten have the biggest impact on our project.

The first tenet in the IEEE code of ethics states that we must make decisions consistent with the safety, health, and welfare of the public. In agreement with this tenet, we are trying to improve the quality of life for people that do not have access to high-speed data by bringing a

less vulnerable and stable communication system to those areas. In doing so, we will be improving the welfare of the public. We will also be complying with sustainable development practices by improving our method of communication with the world without adding additional stress and harm to the environment because, if our design is implemented, we will be using preexisting infrastructure. During the development of our design, we are adhering to this tenet by using this tenet as a standard to not cheat and steal from designs that are already being used and ensuring that we properly cite any existing code that we use within our model.

The second tenet is to improve understanding of the capabilities and societal implications of technology [19]. The ultimate outcome of our project is to help those who do not have much. The original concept for this design was the military. Doing something for the military may be consequential if someone does not support military functions. In accordance with this tenet, we will ensure that the societal implications of this technology, if used for a specific group such as the military, is understood. We will also ensure that those who will physically develop and use this new technology understands the applications and potential consequences if misused.

Tenet five states to seek and offer honest criticism of work, correct any errors, and to give credit to those who contribute to your project. Tenet six states to maintain and approve our competence and only take on tasks that you are qualified to do [19]. To be in accordance with these two tenets, our group has been continuously seeking the expertise and advice of our advisors to improve our design. We have been incorporating all advice into the final product as well. We are also fully aware of the limitations of our knowledge about our project and have been conducting our own research to increase this knowledge. We all know our roles within our group, follow the rules, and do not engage in anything that we are not required to do.

Tenet seven is to treat all persons fairly and to not discriminate based on any differing characteristics. The last tenet (tenet ten) states to support one another in following this code of ethics and ensuring that this code is upheld [19]. To adhere to these tenets, we have been working as a group to hold each other to all IEEE standards including not discriminating against one another. We all come from different backgrounds, so we will continue to encourage our members to speak up if they do not feel comfortable because everyone has an equal voice. Once our design is complete, we will also ensure that our product will be available for use by anyone in the target user group, such as the military, without regards to race, religion, gender, disability, age, national origin, sexual orientation, gender identity, or gender expression.

Our project focuses on making a MATLAB program that models OFDM modulation across different bandwidths in the high frequency zone, so the main ethical issue related to our final product is protecting our group's information. During our design process we have been making sure that the group's information is secure and that we do not share any personal information with unauthorized personnel.

As future members of the IEEE, we must behave ethically when designing and working with technology. It is our responsibility to protect the public when developing new and remodeling preexisting technology. Continuing to adhere to the IEEE code of ethics while designing our new communication system will help protect and further develop the engineering profession.

6.2 Public Health Considerations

The MATLAB model will not jeopardize the health of the public directly. This program will be created in MATLAB so it will not create a risk or hazard for the public by existing. However, it is important to note that the information and data being processed through our OFDM program could impact the public health as detailed in Appendix B.

6.3 Safety Considerations

This project does not put the safety of the public at risk. This technology, if implemented, will make the world a safer place because everyone will be able to communicate with each other. These impacts can be seen further in Appendix B.

6.4 Welfare Considerations

The creation of this MATLAB model will not threaten the welfare of the public because it is just a software program. If implemented, it will improve the welfare of the public because it will give everyone in the world access to long distance communication. Being able to communicate will improve people's quality of life because people living in remote regions will be able to communicate with family members and emergency service providers as needed. These considerations will depend on the reliability of the program as detailed in Appendix B.

6.5 Cultural Considerations

Although our group only consists of four members, our group is still very diverse. Therefore, during the creation of our project, we ensured that we respected each other's cultural beliefs and values. Our project does not infringe on any cultural beliefs or values of the public either. If our model is implemented, it also will not violate anyone's cultural beliefs. Instead, it will allow for the easier dissemination of one's culture since it will bring a more reliable method of communication to everyone around the world.

6.6 Knowledge of Contemporary Issues

For years HF communication has been important for long distance communications. In some places, it is the only method of communication. In the past communications have been limited to channel bandwidths no wider than 3 kHz, as the demand for higher speed data transmission over HF has increased, using bandwidths greater than 3 kHz is being explored [20]. We will be using OFDM across 24 kHz, 48 kHz, and 3 MHz bandwidths to improve HF long distance communication. OFDM is already used in wireless communication systems. In 2014, OFDM was used in 4G technology LTE mobile communication systems to enhance data-rates. OFDM performs well in multipath environments which is what is needed by mobile wireless systems [21]. OFDM is also used in digital audio, terrestrial TV broadcasting, and wireless LAN as well. For wireless data a high bit rate is needed, however the radio environment limits the bit rate. By transmitting data over many narrow sub channels, OFDM overcomes the bit rate limit. With the model that we have developed, we were able to overcome this data rate issue as well.

6.7 Lifelong Learning (Everyone)

Sarah Taylor- Prior to working on this senior project I had no knowledge about high frequency radio communications and OFDM. While working on this project I have learned what OFDM is and how HF radio communications systems are used. My previous experience in coding classes involving MATLAB helped me understand the existing code we used and helped me provide guidance on the design of our program during our group meetings. Learning about how signals are transmitted has helped me gain a better understanding of how signals are transmitted in my ECE 474 Optical Fiber Communication class I am currently taking this semester. I plan to further

my knowledge in both of these topics as I pursue my master's degree in Electrical Engineering and as I further my career because this technology may ultimately be used on the aircraft carriers I currently help build at the Newport News Shipyard.

Josiah Myer- In completion of this project, I have expanded my understanding in not only the reasoning for a need of OFDM but also a better understand in how signals are processed. My understanding of different modulation types and the benefits of each have improved my ability to choose which modulation technique may be best when needing to meet specific design requirements. The learning achieved by completing this project will have value in both my ability to solve problems but also improve my skills when working in a team environment. As an engineer, upholding and implementing standards was another learning goal of mine in this project due to the nature of my job. Working on military funded projects at Newport News Shipbuilding requires engineering to uphold standards and ensure that ships are built to the quality that the customer requires.

Natalia Anglero- Before this project, I didn't have much knowledge about the OFDM systems. After focusing on the process, development, and benefits of an OFDM, I was able to gain skills with MATLAB, signal processing, modulations, and more. Team cooperation was another skill that was improved through the course of this project. With the team and the advisors' efforts, I was able to improve on my original weaknesses. I intend to proceed with this course and apply it to my career path. Through this project's in-depth research, I acknowledge that OFDM signal technology will come across again.

Tyler Collins- Before this project, I had no prior experience with OFDM or signal modulation. Through researching and developing the code for this project, I have significantly increased my MATLAB skills, along with learning about signal processing and OFDM. I had never had the intention of working with signal processing, however after this project I intend to continue furthering my education in this area. This project has broadened my skills as an Engineer, and I plan to continue furthering my understanding of OFDM and signal processing throughout my career.

6.8 Impact of Engineering Solutions in a Global, Economic, Environmental, and Societal Context

OFDM maximizes the amount of information that can be transmitted over a given bandwidth by allowing a single channel to use multiple overlapping sub channels orthogonally to one another [22]. The data is then transmitted parallel across the sub channels within the OFDM signal, allowing the overall data rate to be 10 to 1000 times the speed of a standard 3 kHz channel [23]. Our design will effectively improve communication systems resulting in positive global, economic, environmental, and societal impacts. Improving high speed OFDM HF communication will have an enormous impact globally. The global economic effect is more dramatic for the developing world. Many in the developing world do not have access to the global economy because of the lack of high-speed data (internet). OFDM HF could provide high speed data a fraction of the cost of satellite systems or fiber optic cable infrastructures. The economic impacts depend on how much OFDM HF can drive down the cost of high-speed data. Environmental impacts will be minimal because it requires little additional infrastructure. OFDM HF refracts off the ionosphere which is nature's satellite and is solar powered.

6.8.1 Global Impacts

Our design has the possibility of having a global impact because HF communication is readily available in and is used by most countries around the world. HF is currently used in military and government communications, relief organizations, aviation communications, amateur radio, and international and regional broadcasting. The High Frequency Global Communications System is used by the United States Air Force to communicate with ground stations and aircraft during flight world-wide [24]. With the rise of satellite communications, HF radios are used less often in the military, however they are still used as a backup method for when SATCOM is unavailable [25]. Like this, the United Nations uses HF radio communications for relief operations when satellites are not available or when in insecure environments [26]. HF is used by the airline industry to provide coverage in regions where SATCOM is unreliable. HF is used by air traffic control for en route services for over 75% of the Earth's surface [27]. Although HF has mostly become a backup option to SATCOM, as cyber threats continue to grow, many countries are looking for a safer method of communicating. If our model is implemented, HF may once again become a main source of communication across the

globe. If OFDM modulation is able to speed up data transmission in the HF range, we may be able to bring a less vulnerable and stable communication system with high-speed data to areas that do not have access to many cell towers such as Africa and Siberia.

6.8.2 Economic Impacts

The economics behind OFDM High-Frequency radio is not as complicated as it might seem. OFDM High-Frequency is part of the electromagnetic spectrum; this spectrum is as limited as other natural resources, especially since there is a massive increase in radio technology demand, which requires electromagnetic spectrum resources. As a result of this demand, it is critical to focus on the economics behind this scarce resource [28]. Since the creation of this resource, it has made a powerful impact on today's economic growth and job opportunities. Communities across the nation, and industries such as healthcare, agriculture, automobiles manufacturing, appliance manufacturing, and energy, have already started utilizing the power of wireless connectivity [29]. The high demand for OFDM High-Frequency has a large impact on today's economics.

6.8.3 Environmental Impacts

The proposed model has a positive environmental impact. We will be able to reuse existing HF antennas, so it will not have a major impact on the environment in regard to space because it would not require any additional infrastructure. It would be better for the environment because we could potentially reduce the number of cell towers since the HF signal would be able to travel farther. We would also no longer need as many satellites to communicate. The main components needed for HF communication is the radio, an antenna, a data modem, and other smaller accessories. In addition to this, the HF radios can be in fixed, man-pack, or vehicular forms, which limits the amount of additional space needed to implement the model, further minimizing the impact to the environment. [30].

6.8.4 Societal Impacts

The evolution of technology has gone on for centuries; in terms of communication, it has become easily accessible by wireless communication. This type of communication can be done by devices such as laptops, phones, radios, and much more [31]. With this unbound access to social interaction, many individuals fear that people may be too immersed in the digital world

and not present in the real world. It is unknown if the different forms of technology influence social relations, health, and well-being; however, research has shown, technology has caused a weakness in social ties. Many believe that this access to wireless communication is ruining in person communications [32]. Another argument is that it provides its users with opportunities to network and to find career opportunities. Is wireless technology becoming too much for human beings to handle? Or will new skills be developed through the constant usage of wireless communication result in a workforce that qualifies an individual with skills because of their experience? With technology advancing every second and with human interaction changing just as fast, we must not feel overwhelmed by these resources.

7 Summary

The goal of this project is to use MATLAB to model OFDM modulation technique across 24 kHz, 48 kHz, and 3 MHz bandwidths in the high frequency (HF) radio band (3-30 MHz) to make HF long distance communication faster and more reliable. Our MATLAB model allows the user to modify the bandwidth, carrier frequency, modulation type, SNR, and image size to determine which combination of parameters provides the most reliable OFDM data transmission in the HF band. To determine the success of the model, we observed the data rate and the BER after data transmission. Ideally, we wanted to have a BER of 10^{-5} or less for a SNR that is representative of the SNR level experienced in the ionosphere (10-20 dB). We found that the modulation type and bandwidth have a direct effect on how fast the signal was transmitted. As the bandwidth and number of bits per symbol transmitted increased, the signal was able to be transmitted faster. However, as the number of bits being transferred increased, the possibility of error increased as well. Therefore, the modulation type has a direct effect on the BER level. Thus, BERs for 16-QAM and 8PSK tend to have higher BERs than BPSK and QPSK. Our results also showed that the noise level affects the BER level as well. We discovered that as the SNR increases, the BER decreases. Overall, we found that at a SNR level of 20 dB, with or without error correction, a signal can be transmitted with an acceptable BER using any combination of parameters, whereas at the lower end of our band (10 dB), only BPSK and QPSK modulations can be used to transmit a signal in the acceptable range.

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9 Appendices

9.1 Appendix A – Executive Summary

The ECE 487 project, MATLAB Modeling of OFDM Modulation Technique across a 24 kHz, 48 kHz, and 3 MHz Bandwidth in the High-Frequency Radio Band (3-30) MHz, was created by advisors, Dr. Linda Vahala and Dr. Dennis Watson. Group 10, which consists of Natalia Anglero, a computer engineering major; Tyler Collins, an electrical engineering major; Josiah Myer an electrical engineering major; and Sarah Taylor, an electrical engineering major, selected this project as the one that they would like to complete. The purpose of this project is to make HF long distance communication faster and more reliable so that every part of the world will have access to high speed, long distance wireless communication. Throughout history, high frequency has been used for long distance communication. However, the production of satellites greatly reduced the need for HF long distance communication because satellites' data speed far exceeded HF data speed over long distances. Now, concerns over the vulnerability of SATCOM has caused the United States to revisit using HF as a primary method of communication. To perform OFDM modulation on HF signals, MATLAB will be used. The group was able to use ODU's latest version of MATLAB so there was not an economic constraint regarding obtaining the needed software.

In our program, the user will be able to select the number of desired subcarriers, bandwidth, subcarrier frequency, modulation type, and the image size. The program will then transmit a known image with and without FEC and display the transmitted image. The design will be sure to take previous OFDM modulations and engineering standards into consideration. The parameters used in OFDM modulation are based on standards 802.11n and Mil-STD-188 110C.

Prior to selecting the method for creating the model, other types of modulation techniques were considered. These included 32-QAM and 64-QAM. 32-QAM and 64-QAM utilizes 5 and 6 bits per symbol, respectively which means that they can transmit data faster than the modulations used in our program. As the number of bits per symbol increases, so does the amount of data that can be transmitted. However, the BER also increases with this increase in data which causes more error correction to be needed [5]. Simulink and Labview were also considered, but we did not have enough time to explore these options fully. With the design being for long range

wireless communication, BER is more important than speed so it was determined that BPSK, QPSK, 8PSK, and 16-QAM would be used in the model.

The goal of our design was to successfully transmit signals using OFDM modulation across a 24 kHz, 48 kHz, and 3 MHz bandwidth in the HF radio band (3-30 MHz). How fast the data was transmitted and how well the data was transmitted were the two criteria used to determine a successful transmission. The modulation type and bandwidth have a direct effect on how fast the signal was transmitted. As the bandwidth increased, the signal was able to be transmitted faster. However, as the number of bits being transferred over time increases, the possibility of error is increased. Therefore, the modulation type has a direct effect of the BER level. Thus, BERs for 16-QAM and 8PSK tend to have higher BERs than BPSK and QPSK. Our results also showed that the noise level affects the BER level as well. We discovered that the SNR level increases, the BER decreases.

9.2 Appendix B - System Reliability

The OFDM or Orthogonal Frequency Division Multiplex is a method used widely in broadcast systems. It forms signal waveforms or modulations that provide significant advantages for data links [33]. We will be implementing, analyzing, and testing our OFDM waveform and perform a link simulation with specific functionalities. The parameters used in our code provide inputs of data transferred through a channel. Our code's process will have functionalities for calculating the number of subcarriers, cyclic prefix length, maximum number of bits transmitted, noise variance, and binary data generation. We strive to create a highly efficient and reliable communication system by developing a function that can monitor errors, collect error statistics, and reset the error rate calculations. By collecting this data, we can minimize the potential risk. Some of the possible risks include frequency error, maximum power consumption, or the risk observations becoming too noisy [34]. High-resolution functions will be used to take this data and generate a diagram demonstrating the failures collected during the software execution. Industry standards for wireless transmission bit error rates is declared to be satisfactory between 10^{-9} or 10^{-13} . A bit error rate, BER, of 10^{-9} means that one bit out of every 10^9 is on average read incorrectly and thus considered invalid [35]. We will monitor both thresholds when testing to verify reliability.

These messages could be sending critical information that could affect the health and wellbeing of the public. So, to ensure that our system is reliable and safe, we will use communication streams to verify that messages are sent and received correctly. If a message is sent or received with errors outside of the range of our acceptable threshold, a warning will be issued to notify the sender and or receiver that the data is incorrect.

For maintainability, the team is using MATLAB, which is a well-supported software program. Due to this, the longevity of use of programs within MATLAB can be used for the foreseeable future. To ensure that the code is still functional, the code will be tested against any new software versions. Comments will be incorporated in the MATLAB code so that the program is easily understood by end users. This will support any adjustments made by future users to both modify the program for other uses or to support software changes in MATLAB.

9.3 Appendix C - Engineering Design Process Map

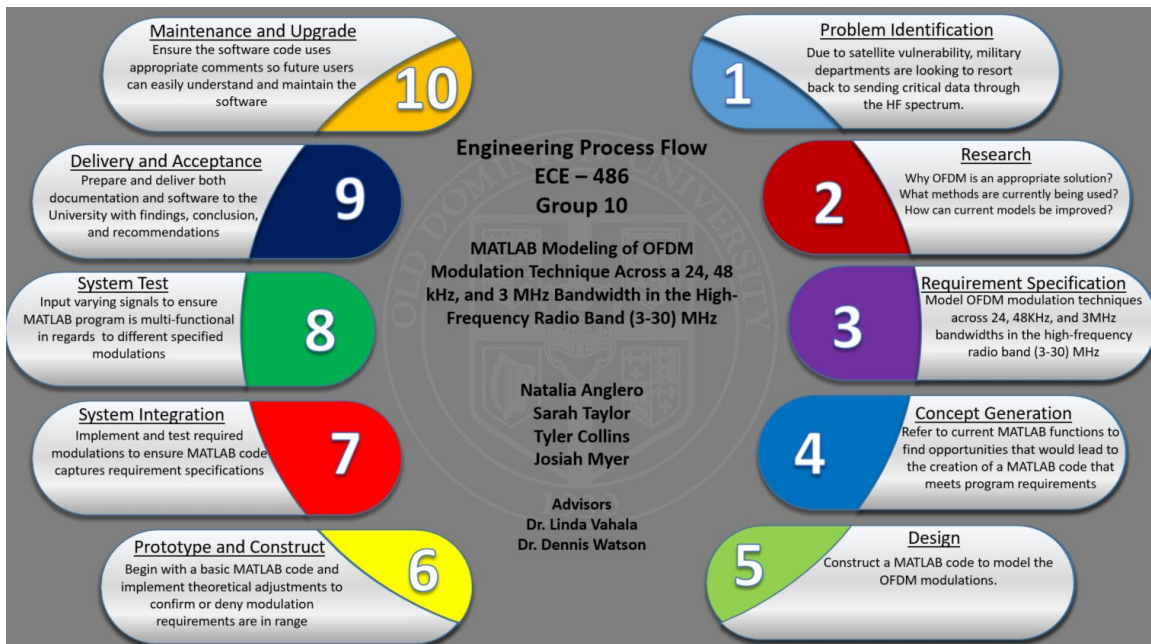


Figure 9.1: The Engineering Design Process Map used by the team captures all capstone events taken to complete the project. The first five events in Problem Identification, Research, Requirement Specification, Concept Generation, and Design were completed over the course of one semester. The remaining processes were completed in the second semester to completion of the project.

9.4 Appendix D – Additional Graphs and Figures

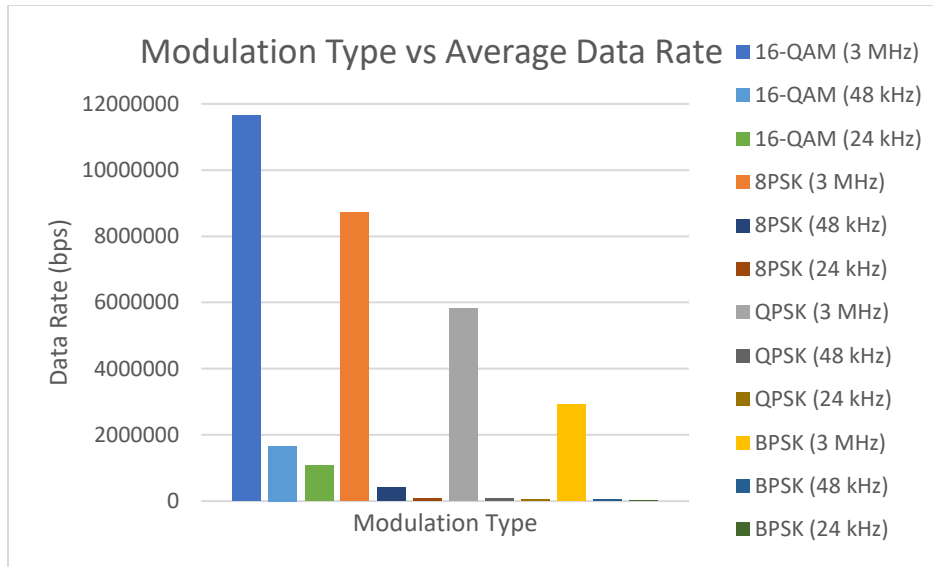


Figure 9.2: Modulation type versus average data rate across 3 MHz, 48 kHz, and 24 kHz bandwidths. The data rate for the different number of subcarriers (64, 128, 256, and 512) was averaged to focus on the relationship between the modulation type, data rate, and bandwidth. The data rate for 16-QAM was the largest across each bandwidth when compared to the other modulation types.

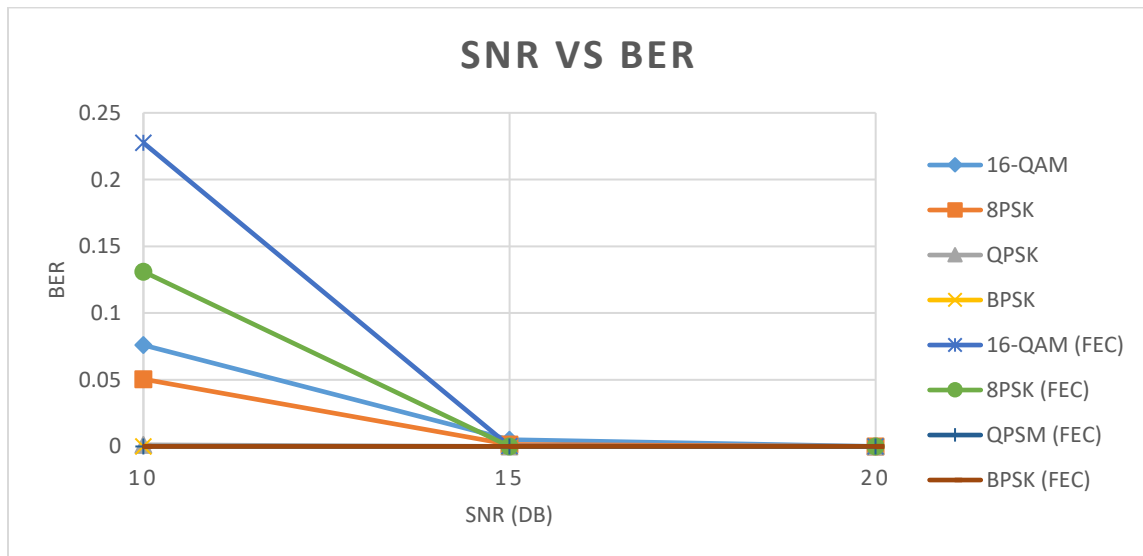


Figure 9.3: Signal to noise ratio (SNR) versus the average bit error rate (BER) for each modulation type with and without forward error correction (FEC) applied. The BER for the different number of subcarriers (64, 128, 256, and 512) was averaged to focus on the relationship between the modulation type, SNR, and BER. Optimal results with and without FEC were always obtained using an SNR value 20 dB.

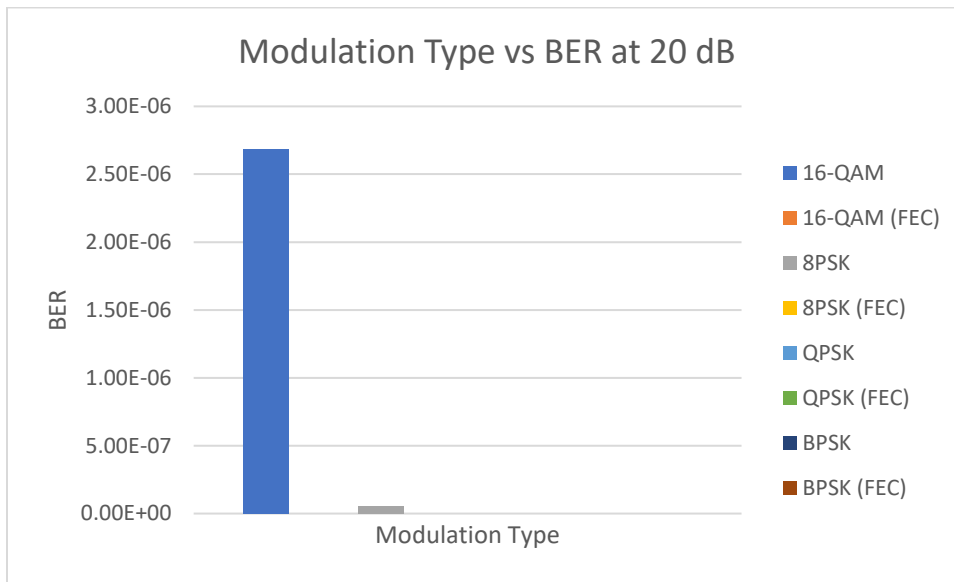


Figure 9.4: Modulation type versus BER at 20 dB. The BER for the different number of subcarriers (64, 128, 256, and 512) were averaged to focus on the relationship between the modulation type and the BER with and without forward error correction (FEC). The average BER without FEC for 16-QAM was the largest when compared to the other modulation types, but it remained within the acceptable range.

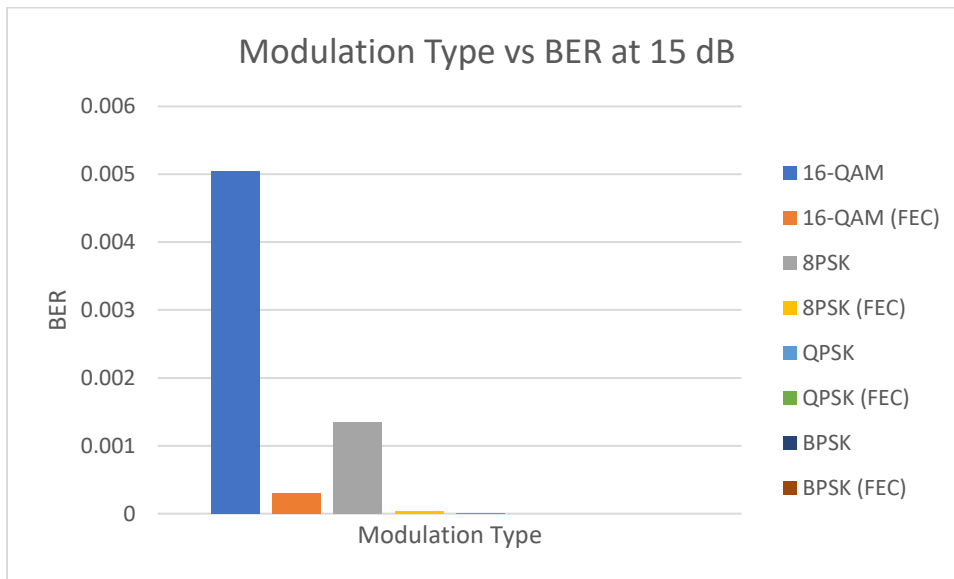


Figure 9.5: Modulation type versus BER at 15 dB. The BER for the different number of subcarriers (64, 128, 256, and 512) were averaged to focus on the relationship between the modulation type and the BER with and without forward error correction (FEC). The average BER for 16-QAM and 8PSK without FEC were the largest when compared to the other modulation types, however only 8PSK remained within the acceptable range.

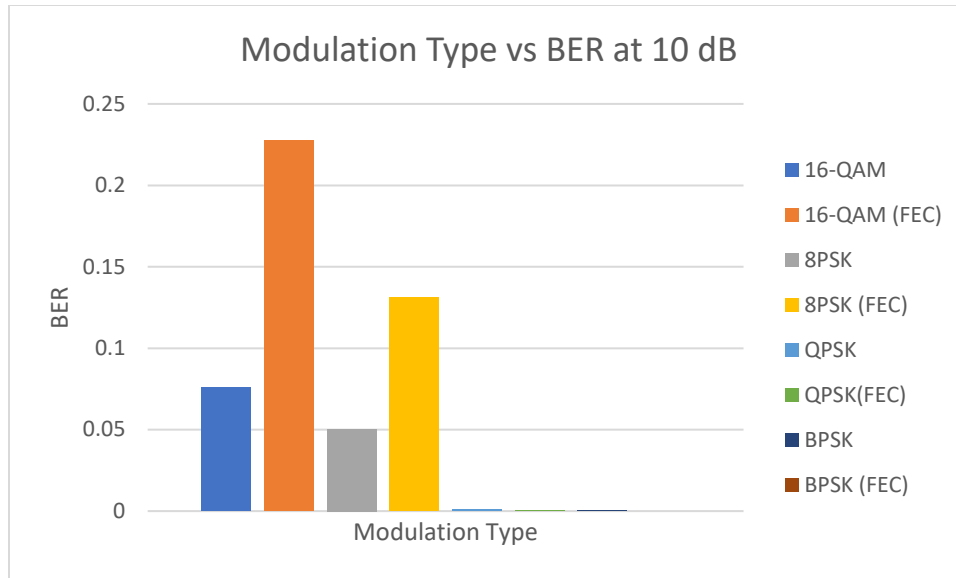


Figure 9.6: Modulation type versus BER at 10 dB. The BER for the different number of subcarriers (64, 128, 256, and 512) were averaged to focus on the relationship between the modulation type and the BER with and without forward error correction (FEC). The average BER for 16-QAM and 8PSK with and without FEC were unable to reach the acceptable BER range.

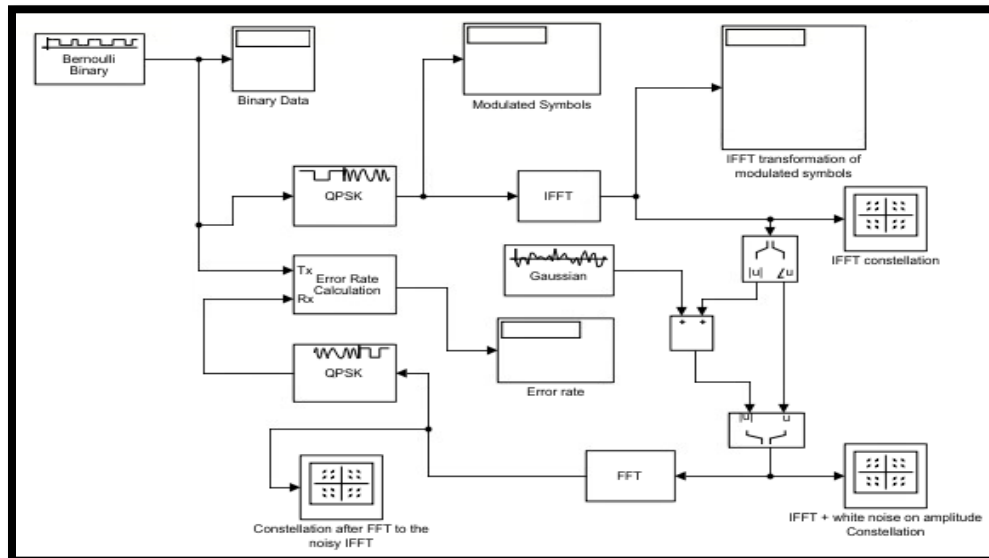


Figure 9.7: Alternative Simulink Model. This model utilizes a Bernoulli Binary signal generator to represent our inputted signal. It then applies QPSK modulation, followed by an IFFT. At this point the OFDM modulation is complete and the model graphs the constellation of the modulated signal. Then, Gaussian noise is added to represent actual noise in a signal and the constellation is graphed again. Next, the signal goes through a FFT and QPSK demodulation to return to the original signal. A final constellation of the signal is graphed, and the error rate is calculated based on the original signal and the final signal. This model will be modified to include other modulation techniques other than QPSK based on the amount of error detected. A frequency shift will also be added to move the signal into the high frequency range after it has been modulated.

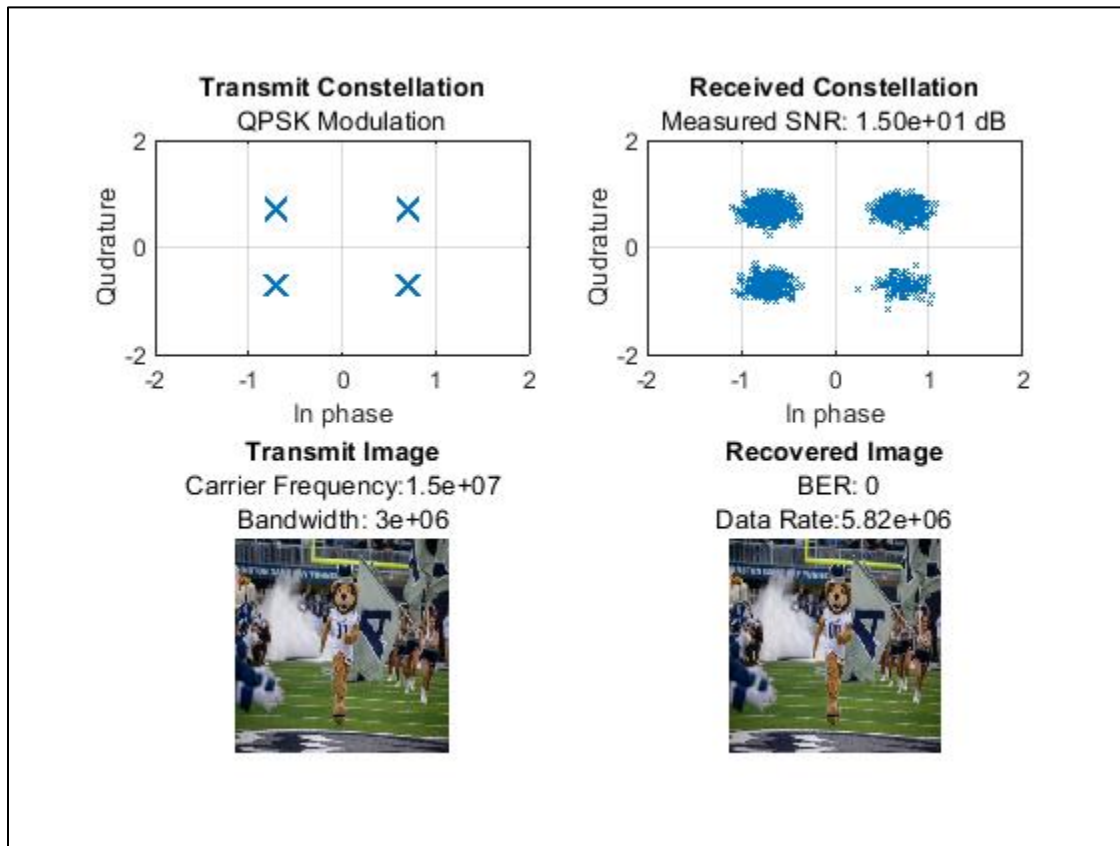


Figure 9.8: Transmitted constellation and image versus received constellation and image. QPSK modulation using a carrier frequency of 15 MHz, a bandwidth of 3 MHz, an image size of 256 x 256 pixels, 512 subcarriers at an SNR value of 15 dB without forward error correction. The image is recovered at an acceptable BER of zero (less than 10^{-5}) errors per bit. The constellation shows the information transmitted as one of four symbols, each representing two bits of data. The data is tightly grouped around the four symbols, exemplifying a good data transmission.

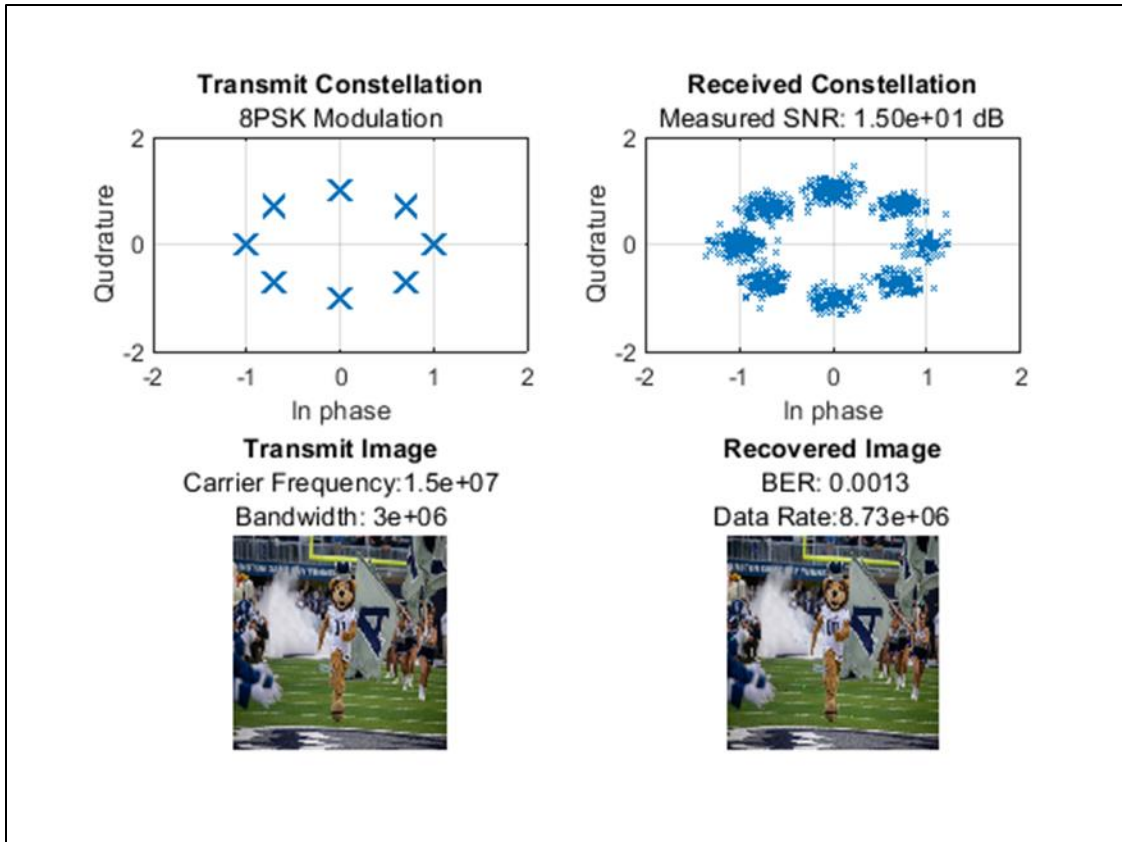


Figure 9.9: Transmitted constellation and image versus received constellation and image. 8PSK modulation using a carrier frequency of 15 MHz, a bandwidth of 3MHz, an image size of 256 x 256 pixels, 512 subcarriers at an SNR value of 15 dB without forward error correction. The image is recovered at an unacceptable BER of 1.3e-3 errors per bit. The constellation shows the information transmitted as one of eight symbols, each representing three bits of data. The data does not congregate tightly around all eight symbols, exemplifying a bad data transmission.

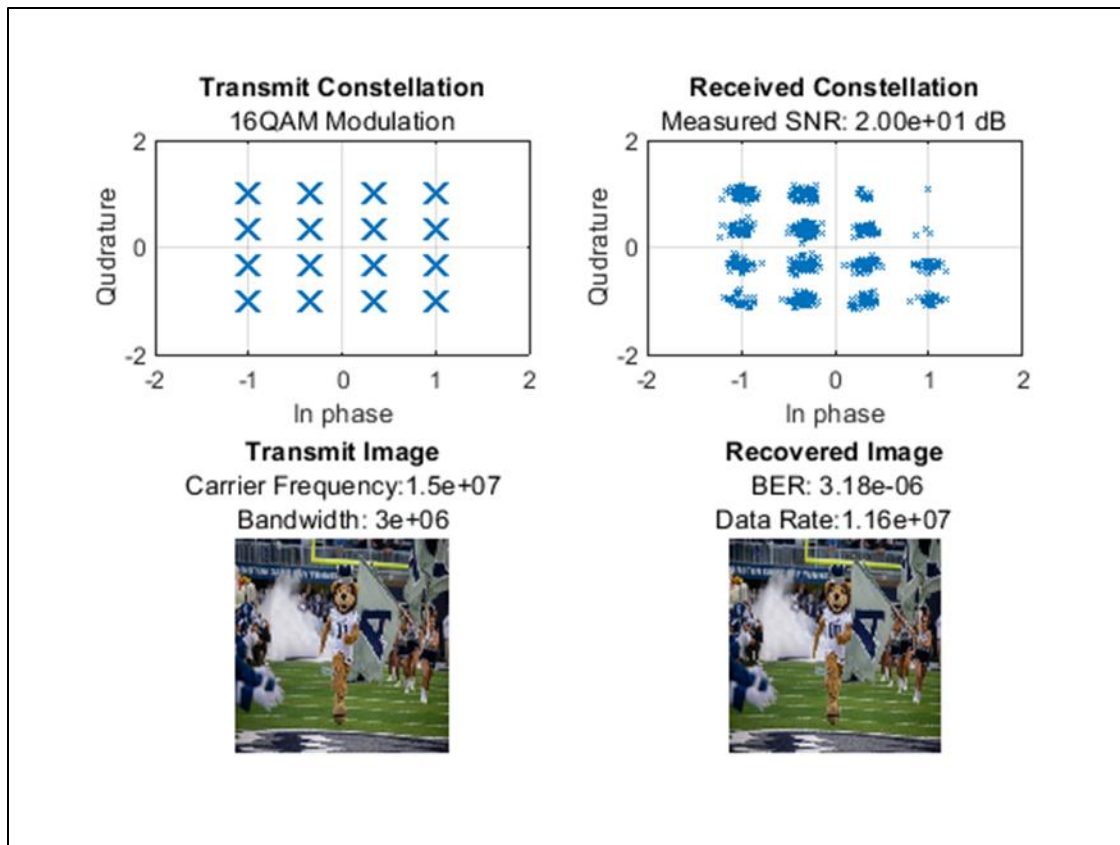


Figure 9.10: Transmitted constellation and image versus received constellation and image. 16PSK modulation using a carrier frequency of 15 MHz, a bandwidth of 3 MHz, an image size of 256 x 256 pixels, 512 subcarriers at an SNR value of 20 dB without forward error correction. The image is recovered at an acceptable BER of zero (less than 10^{-5}) errors per bit. The constellation shows the information transmitted as one of 16 symbols, each representing four bits of data. The data is tightly grouped around the 16 symbols, exemplifying a good data transmission.

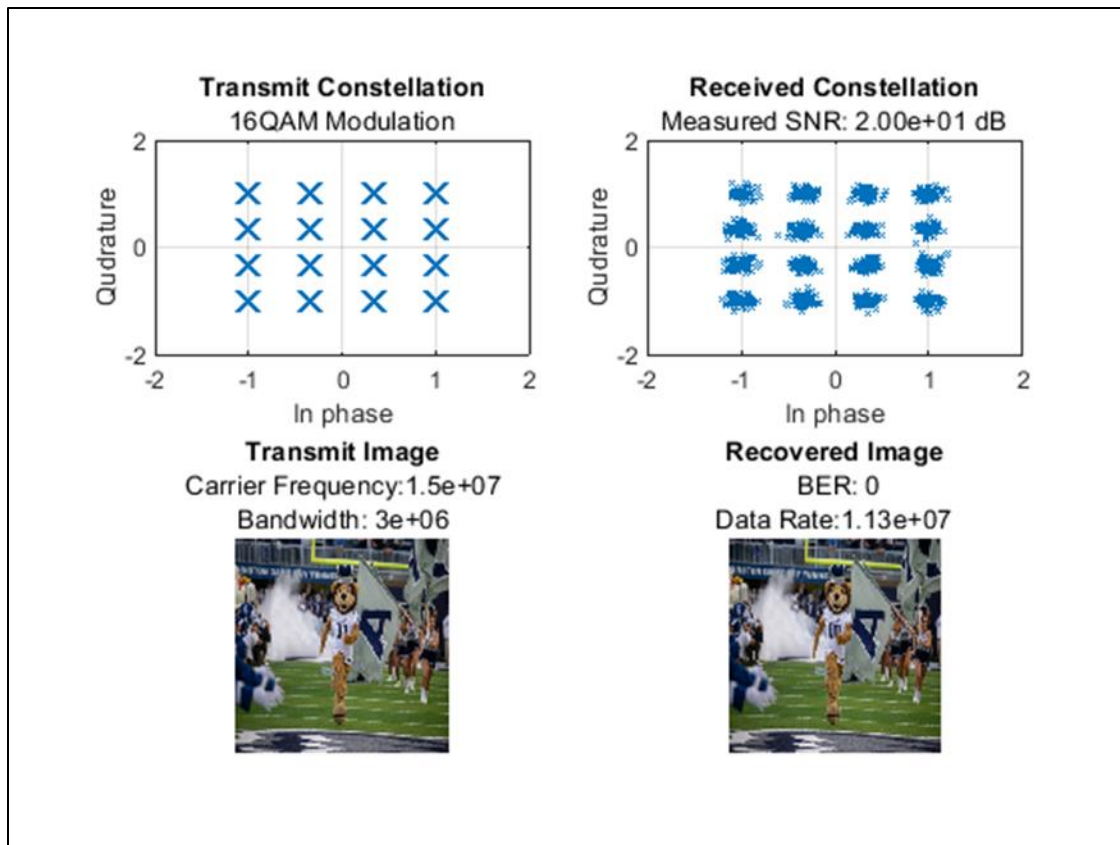


Figure 9.11: Transmitted constellation and image versus received constellation and image. 16-QAM modulation using a carrier frequency of 20 MHz, a bandwidth of 3 MHz, an image size of 256 x 256 pixels, 512 subcarriers at an SNR value of 20 dB without forward error correction. The image is recovered at an acceptable BER of zero (less than 10^{-7}) errors per bit. The constellation shows the information transmitted as one of 16 symbols, each representing four bits of data. The data that is shown is tightly congregated around the symbols, exemplifying a good data transmission