

High Frequency Communications Channel Characterization

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Abstract

There are many means of wireless communications in today's society to allow people to communicate thousands of miles away. Many of these methods are expensive and require large amounts of infrastructure to work reliably. Advancements in technology have improved communication techniques and have allowed one of the oldest forms of wireless communications, high frequency communications, to be used as an inexpensive and reliable alternative for long distance communications. The purpose of this project is to help improve the performance of a modern high frequency communication system through the construction of a selectable narrow band filter bank.

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Executive Summary

One of the earliest forms of over the horizon communications was high frequency communications. High frequency signals are capable of reaching long distances because signals at these frequencies can be reflected off a part of the atmosphere called the ionosphere, These reflections are then bounced back to the surface up to thousands of kilometers from where they were transmitted. Eventually high frequency communications became overshadowed by more advance communication technologies such as satellite and cellular networks. Recent Advances have revitalized high frequency communications, allowing such systems to have higher data rates and more robust and reliable transmissions. Developing High Frequency communications is important because the increasing demand for wireless communications has made the wireless spectrum a valuable commodity. Additionally, it is important to have a system that could back up failed wireless communication systems in emergency situations. The goal of this project is to help improve the performance of a high frequency communication system by developing a filter bank in order to reduce the saturation of the received signal.

The requirements of the filter bank were that the entire frequency range dedicated to the project had to be covered, which was from about 4 MHz to around 13 MHz. The filters had to be easy to switch between since the center frequency for transmission could change frequently. The filter bank would also have to have the ability to easily interface with the rest of the communication system. The design for the filters was chosen to be a third order Butterworth filter. These filters would have no ripple in the passband, which would prevent distortion and being third order would allow these filters to have a steep transition into the stopband. A Butterworth design would also cut back on power consumption since Butterworth filters are passive due to being constructed of only inductors and capacitors. Finally, it was decided that 15 filters would be used to cover the frequency spectrum involved with this project. It was decided that the filter bank would be constructed on a printed circuit board (PCB) using surface mount components. Surface mount components are small, which allowed for minimal space for each filter. Designing the circuit for a PCB would also allow for the design to be replicated and edited latter if needed.

An online tool was used to determine what capacitor and inductor values were needed to construct each filter. The tool allowed produced what component values would produce the desired filter response based off corner frequencies, order, filter type and characteristic impedance. The tool, however gave very specific values that did not match the values of capacitors and inductors that could be purchased. To get values close to the ideal ones produced by the online filter design tool, it was

decided to use two real components in series or parallel to get as close to the ideal as possible. The figure below shows an example how the filters were designed.

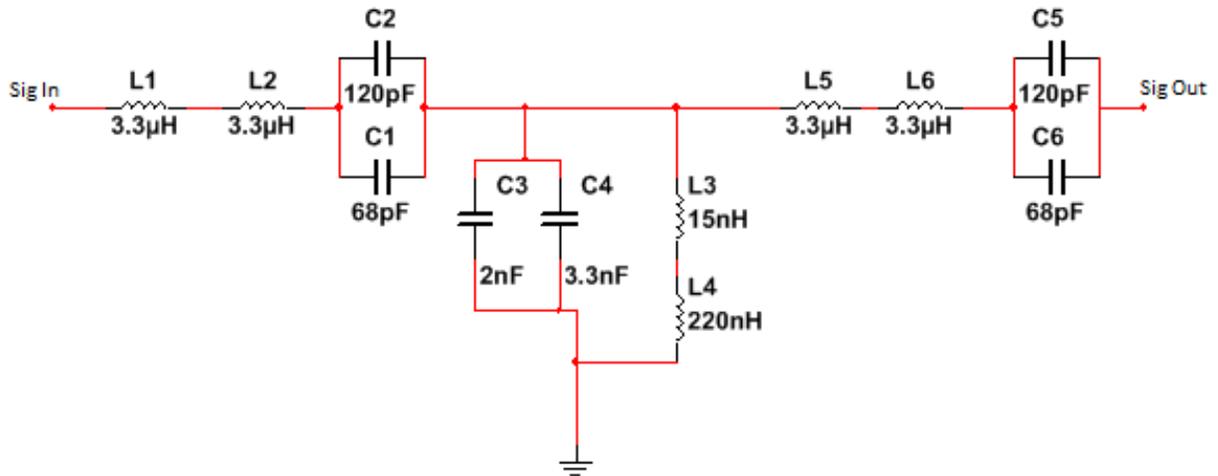


Figure i: An example of how the filters were designed. This is the first filter in the bank. Inductors were paired in series and capacitors were paired in parallel to get values close to the ideal one produce by the design tool.

Once all the parts were chosen for the filters and the PCB to house all the components was designed, the materials were ordered and assembled. The filter bank was then tested using a network analyzer to determine if the S21 characteristics of each filter were close to the ideal filter response. The tests showed that the performance of the filters went down as frequency increased. The S21 characteristics of a pass-through on the board showed that the gain decreased with frequency. The lowest gain was at 12 MHz, after which the gain of the pass-through went back up to close to 0 dB. The results of the test can be seen in the Figure 1.

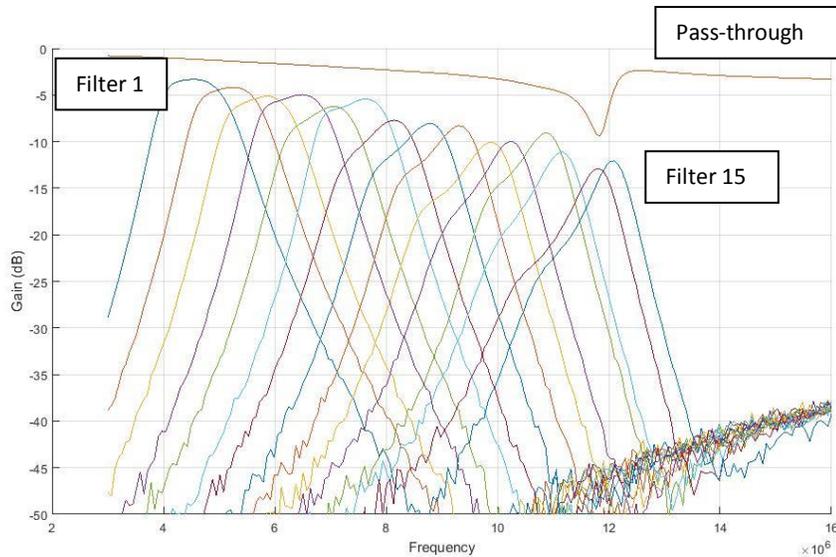


Figure ii: The results of the tests using the network analyzer. The performance tends to degrade as frequency increases and there is a resonance at 12 MHz that can be seen in the pass-through of the filter (top line). The resonance indicates that power is being lost

The resonance at 12 MHz showed that power was being lost in the filter. More tests with the network analyzer were done to locate where the power was being lost or reflected. The tests showed that there were no points in the filters that were the cause, which left the multiplexer chips as the next logical choice. The multiplexer chips were removed from the filter bank and another test was performed to see if the chips were the cause of the reflection. The results of the test can be seen in Figure 2.

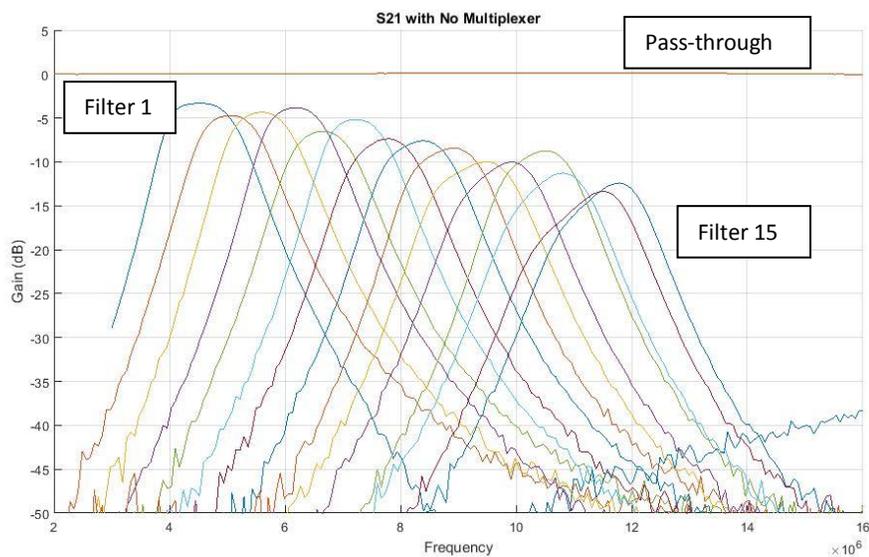


Figure iii: The results from the test with the network analyzer when the multiplexer chips were removed. The performance greatly improved and the reflection no longer was present in the system.

Removing the multiplexers did greatly improve the frequency response of the individual filters. The filters still did not perform as well as they were predicted to, possibly due to imperfect impedance matching between the design and the actual board. One area that still needs to be looked into in this project is the reflection centered around 12 MHz that is seen in the PCB caused by the multiplexers. The project team at MITRE should continue to look for a different method of switching between filters. A new design for the PCB board was made, fixing some of the design flaws, such as the trace errors in the original design. The new design also has wider traces than the original PCB, giving the new PCB a characteristic impedance of 50Ω , which the filters were designed for. There is more work that needs to be done on the design of the new boards since more research into how to switch between filters is still ongoing.

Table of Contents

Abstract	I
Acknowledgements	II
Executive Summary	III
List of Figures	IX
List of Tables	XI
Chapter 1: Introduction	1
1.1 Motivation	1
1.2 Infrastructure Based Wireless Communications	2
1.3 Over-the-Horizon Communications	4
1.4 Project Contributions	5
1.5 Project Report Organization	6
Chapter 2: Background	7
2.1 High Frequency Communications	7
2.2 Analog Filter Design	10
2.3 PCB Design	14
2.4 Chapter Summary	16
Chapter 3: Proposed Approach	17
3.1 Design Requirements	17
3.2 Filter Design	18
3.3 Physical Design	19
3.4 Logistics and Time Frame	20
3.5 Chapter Summary	21
Chapter 4: Methodology and Implementation	22
4.1: Filter Design	22
4.2 PCB Design	23
4.3 Design Testing:	24
4.4 Chapter Summary	24
Chapter 5: Experimental Results	26
5.1 Predicted Results	26
5.2 Measured Results	27
5.3 Chapter Summary	31
Chapter 6: Conclusions and Recommendations	32

6.1 Conclusions.....	32
6.2 Recommendations.....	32
V References	34
VI Appendices.....	36
Appendix A: Filter Design.....	36
Appendix B: MATLAB Code	39

List of Figures

Figure i: An example of how the filters were designed. This is the first filter in the bank. Inductors were paired in series and capacitors were paired in parallel to get values close to the ideal one produce by the design tool.	IV
Figure ii: The results of the tests using the network analyzer. The performance tends to degrade as frequency increases and there is a resonance at 12 MHz that can be seen in the pass-through of the filter (top line). The resonance indicates that power is being lost.....	V
Figure iii: The results from the test with the network analyzer when the multiplexer chips were removed. The performance greatly improved and the reflection no longer was present in the system.	V
Figure 1: An example of an uplink and a downlink between two stations on the ground and a satellite [4].	2
Figure 2: The diagram shows how a cellular network works. Each cell surrounds a base station, which takes in all the signals from the different users. The base station then relays the message to the appropriate user. A core network is used for major decision making inside the network and keeps all the cells synchronized. The Radio Network Controllers act as an intermediate step between the base stations and the Core Network [6].	3
Figure 3: A diagram of a basic WLAN network. The separate clients each separately connect to via the access point. Once connection is established, the device can communicate with each other or any other device on the network [9].	4
Figure 4: The figure shows the different layers of the ionosphere various paths that a high frequency signal could take when reflected off the ionosphere [16].	8
Figure 5: A sample ionogram showing the virtual height of the E and F layers. The double curves for each of the layers are result of the transmitted signal splitting in two, one with clockwise circular polarization, known as O-mode, and another with counterclockwise propagation. The cause of this split is the Earth's magnetic field. The two modes take different paths through the ionosphere, resulting in the two virtual heights [12]	9
Figure 6: A diagram of a filter. The passband has a gain of 0 dB, allowing frequencies that fall under it to be unaffected. The stopband has a much lower gain, so signal in that range are greatly attenuated.	11
Figure 7: The diagram show the ideal frequency response of a lowpass, a highpass, a bandpass and a bandstop filter [14].	11
Figure 8: A diagram that shows the basic components of a filter, the voltage source, the source resistance, the transfer function and the load resistance. The input voltage is measured of the source and the output voltage is measured over the load [19].	12
Figure 9: The basic layout of a LC lowpass filter and a LC highpass filter.	12
Figure 10: A design of a bandpass filter. The inductor from the lowpass design is now in series with a capacitor and the capacitor from the lowpass design is now in parallel with an inductor.	13
Figure 11: An ideal response and a real-world response of a lowpass filter. The Ideal filter has an immediate cut off between the passbands and the stopbands, while there is a transition in the practical filter. The practical filter also never reaches zero gain in the stopband, but does trend that way.	14
Figure 12: An example of a PCB. The green is the non-conductive substrate while the silver pads are where component would be soldered onto the board. The lines between pads are copper traces that connect components together [23].	15
Figure 13: A high level concept diagram of the filter system. A signal comes in and is passed through a filter based off some logic inputs from another part of the communication system. The signal is then	

passed out through a single output on the other side of the filter bank. There are 15 filters and one pass-through, allowing all frequencies to pass. 17

Figure 14: The overall layout of the transmit/receive board. The layout has two parallel systems for transmitting and receiving two oppositely polarized signals at the same time. The Receive filter banks are situated after the attenuator, and are connected to the National Instruments programmable I/O device to allow for switching. The arrows point to the filter banks that are being designed. 20

Figure 15: An example of how the filters are designed. This is the first filter in the bank, with corner frequencies at 3.9 and 5.1 MHz. The inductors are paired in series and the capacitors are paired in parallel so real components values can be used to get close approximations of the ideal values..... 23

Figure 16: The final layout of the PCB. The red lines represent traces on the top side of the board and the green lines represent traces at the bottom of the board. The bottom left part of the board is the circuit for regulating power to the multiplexers and the top left is where the logic inputs will be connected. Circled are the filters that comprise the filter bank. 25

Figure 17: The ideal response of the filters in the filter bank. Each filter has a 0dB gain for the frequency range that they cover. The ideal filters would not be able to be realized using real components..... 26

Figure 18: The figure shows the predicted S21 characteristics of the filters. The filters are not completely ideal since the inductors do have small resistances and the fact that ideal values could not be easily realized with real components. There is a decreasing trend in the gain as frequency increases..... 27

Figure 19: The measured S21 characteristics of the filter bank. Filters 3 and 9 had much lower gain compared to the filters around them. The filter response appears to get worse with frequency, and can be seen in the response by the pass-through line above the other responses. There appears to be a resonance around 12 MHz..... 28

Figure 20: The second set of tests done using the network analyzer. Filters 3 and 9 now behave much better and have behaviors comparable to the filters around them. The resonance of the board remains after the second set of test. 29

Figure 21: A comparison of the S21 and S11 characteristics of the pass-through on the board. The peak in the S11 at the same time the S21 dips shows the signal was being reflected..... 30

Figure 22: The S21 characteristics of the filters after removing the multiplexer chip from the board. The performance of the filters improved with the chips removed. 31

List of Tables

Table 1: Table of frequency characteristics of the bandpass filters.....	18
Table 2: Proposed timeline for the project.....	20
Table 3: The chosen inductor and capacitor values for the first two filters.	23

Chapter 1: Introduction

1.1 Motivation

Wireless communications has been the fastest growing segment of the communications industry ever since Guglielmo Marconi first demonstrated that radio telegraphy was possible back in 1897 when he successfully communicated with ship in the English Channel [1]. Radios quickly became the primary method for long distance communication, and after about 50 years, the use of satellites allowed people to communicate from opposite ends of the world. This explosive growth can be accredited to the convenience and mobility of wireless communications, which has become an essential part of everyday life. Cellphones, Wi-Fi, file transfer, automated highways, factories and numerous other applications would not be possible without the advancements made in wireless communications [2].

In wireless communications, part of the electromagnetic spectrum from 3 kHz to 300 GHz is used to carry information from a transmitter to a receiver. Information can be coded in a waveform using different ways, such as frequency, amplitude or phase. The way the data is coded is known as a modulation scheme. A receiver is programmed to recognize how the data is coded and decode the data based on the known modulation scheme.

The original wireless communications used radio waves to transmit short distances within visible range of each other, which is now referred to as line-of sight. In many cases, radio waves are transmitted such that they could only travel in a straight line and reach distances up to the horizon, much like how FM radio stations only have a certain range to them [2]. The desire and need to communicate across even longer distances, beyond line of sight communications was initially achieved with high frequency (HF) communications, which has existed for over 100 years. It was discovered that HF signals (3 - 30 MHz) are able to reach long distances since the signals at these frequencies can be reflected off part of the atmosphere called the ionosphere, where the signal can bounce back to the Earth's surface up to thousands of kilometers from where they were transmitted [3]. This process is known as skywave propagation [3].

Advances in various technologies have increased development of HF communications, allowing for the possibilities of higher data rates and more robust and reliable transmissions. The goal of this project is to create such a reliable beyond line of sight communication system. The system should be robust, low cost, and low infrastructure and will be accomplished through the use of high frequency communications.

1.2 Infrastructure Based Wireless Communications

Numerous wireless communication systems are available in today's society. One of the most prevalent is satellite communications, which is also known as SATCOM. Communications satellites are used for various tasks, from everyday uses in television and radio to military applications [4]. Satellite communications work by having satellites act as very tall microwave relay towers in the sky. Satellites will have antennas for both transmission and reception containing all the necessary components for being able to process received signals. The processed signal is sent through a feeding system, where an appropriate feed is selected such that the signal can be transmitted back to the surface from the correct antenna beam in order to the desired destination [4]. Figure 1 shows the architecture of a SATCOM system. The uplink and downlink signal have different center frequencies so that they do not interfere with each other during the transmission process.

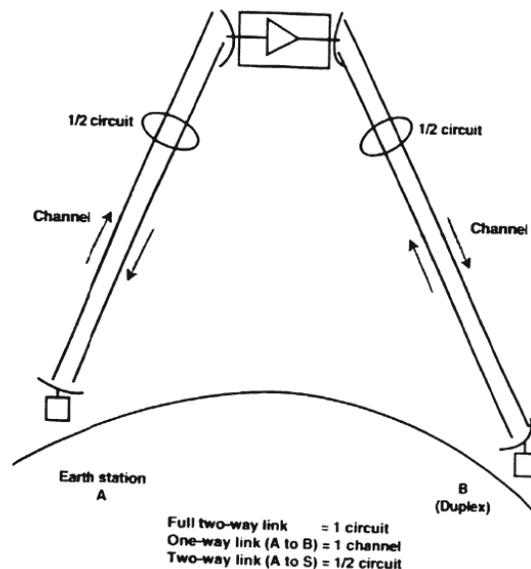


Figure 1: An example of an uplink and a downlink between two stations on the ground and a satellite [4].

Another wireless communications technology that is often used is cellular networks. In fact, billions of people use cellular networks every day for both business and personal activities. Cellular networks were designed to have high capacity coverage over a wide area. This is done by setting up base stations to create a network of cells. A cell phone will transmit its signal to a base station, which is where most of the data processing occurs [5]. The signal will then be routed to the appropriate destination, through other base stations if necessary. Transmission and reception can occur at the same time even though

cellular signals take up the entire bandwidth they are allotted. This is done by having different code sequences assigned to each data flow, which spreads a signal to fit the entire bandwidth [6]. A basic diagram of how a cellular network is set up can be observed in the Figure 2.

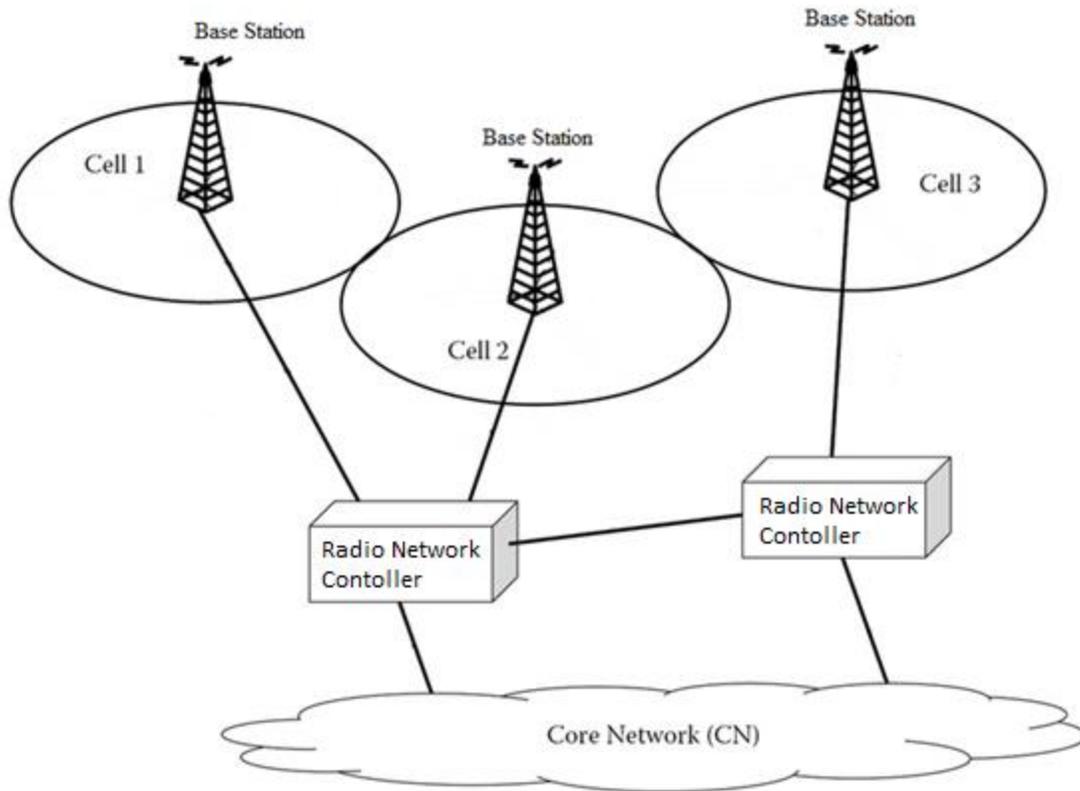


Figure 2: The diagram shows how a cellular network works. Each cell surrounds a base station, which takes in all the signals from the different users. The base station then relays the message to the appropriate user. A core network is used for major decision making inside the network and keeps all the cells synchronized. The Radio Network Controllers act as an intermediate step between the base stations and the Core Network [6].

Wi-Fi is another important wireless communication tool used in setting up a wireless local area network (WLAN). A WLAN allows devices to connect to a network via an access point, and then the device can share information with other devices connected to the network [7]. The access point is then connected to a broader network, such as the Internet, allowing long distance connectivity. WLAN have been useful for providing convenient access to the internet using Wi-Fi hotspots as seen across a variety of public spaces such as airports and coffee shops, as well as resulted in efficiency improvements in office environments by allowing flexibility in the workplace [8]. The concept of a WLAN network can be seen in Figure 3.

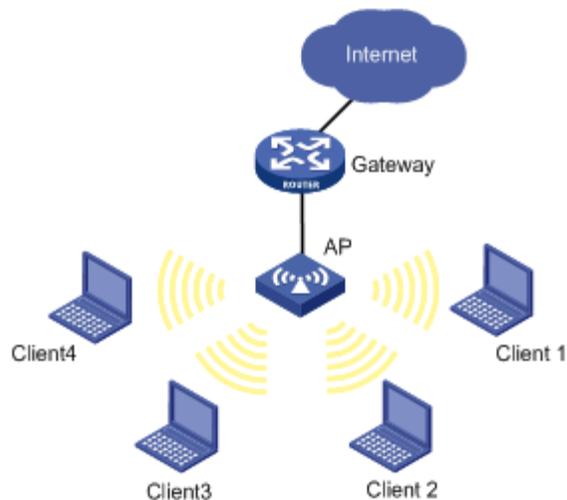


Figure 3: A diagram of a basic WLAN network. The separate clients each separately connect to via the access point. Once connection is established, the device can communicate with each other or any other device on the network [9].

The common factor between these types of systems is the large amounts of infrastructure involved with each network. All three types of networks require some sort of relay point for transmitting a signal across long distances. Large amounts of infrastructure are expensive to build and maintain, and this infrastructure could possibly become overburdened or destroyed under unfortunate circumstances such as a natural disaster. If a relay station were to go down, one of these types of communications networks would be rendered almost useless. High frequency communications are advantageous in this type of situation because they do not require relay points for beyond line of site communications. Systems like this also appeal to maritime communication applications since it is difficult to build infrastructure in the ocean. Improvements in radio hardware and signal processing have made HF communications a relevant area to explore develop.

1.3 Over-the-Horizon Communications

Over the past few years, a substantial amount of work at MITRE has been invested into developing an advanced HF communication system. Work on the development of this system has shown that low power signals, (eg 10 watts) can be transmitted successfully using skywave propagation. Research was also focused on how to increase data rates for this type of transmission. Research has shown that the ionosphere is able to support transmissions of large bandwidths, with bandwidths of 400 kHz being successfully transmitted. The research also exposed that transmitting signals using left and right handed polarization could also double the data rate of the transmission. A wave is polarized when the electric field vector of the signal rotates and changes magnitude as it propagates [10]. Left and right handed polarizations are circular polarizations, meaning the electromagnetic signal has a constant

magnitude and only changes direction in a circular manner as it propagates. These types of signals interact differently in the ionosphere with respect to reflection angle and speed, and can be separated on the reception, allowing for the data rates to be doubled without having to increase power or bandwidth [11]. In this case the communication system is considered to be multiple input-multiple output (MIMO), requiring two radios at each station to transmit and receive at both polarizations at the same time.

The high frequency band has a lot of active users as the entire spectrum is allocated out by the FCC. The spectrum becomes very crowded, especially at night when the range of usable frequencies decreases and users have to cram together in a smaller range [12]. One of the current issues in the present system in development at MITRE is that due to the large amounts of interference that the receiver picks up, the signal becomes saturated when it is passed through the low noise amplifiers (LNA) in the system. To mitigate these effects, filters are needed to remove the interference. The benchmark system used to compare with the proposed design employs filters design by Heros technology, called SCR Preselector-CAT to help reduce the impact of interference. These filters have five tunable bands from 1.8 to 30 MHz, with a 50 MHz band pass filter [13]. These filters are not narrow enough to eliminate enough noise to prevent the signal from being saturated.

1.4 Project Contributions

The objective of this project is to design a filter bank that could replace the Heros filters and improve the overall performance of the radio transmission. The new filter bank would consist of a larger number of narrower filters in order to remove interference more effectively.

The filter bank would consist of narrow band filters that would cover the entire frequency range that was allocated to this project, from about 4 to 13 MHz. The filter bank would need to be able to switch between filters remotely by being connected to the same network the radios run on. This will allow for the appropriate filter to be selected and switched to automatically once the desired center frequency for transmission is chosen.

The design would have to be low cost and possess a small form since space and money are of concern. Overall, the design would have to be an effective and inexpensive solution to the problem at hand, as creating a cheap alternative form of communication is desired.

1.5 Project Report Organization

This report documents all information pertaining to the process and development of the proposed prototype. Chapter 2 contains relevant background information, expanding on the explanation of HF communication systems as well as containing information on filter design and printed circuit board design. Chapter 3 details the proposed approach of the project, going over the different objectives in detail. Chapter 4 will discuss the methodology and the implementation of the project, outlining what steps were taken in development. The results of the research and performed test are detailed in Chapter 5. Finally, the conclusion of the report summarizes the overall project and recommendations for future work are given.

Chapter 2: Background

2.1 High Frequency Communications

The high frequency (HF) spectrum is the range of radio frequencies that fall between 3 and 30 MHz [3]. Some of the more common uses for communications in the HF spectrum include amateur radio, military and government communications and radar systems [3]. After Marconi's successful test in 1897, the development of HF radio advanced quickly and in 1901 Marconi was able to detect a signal in Canada sent all the way from Great Britain [14]. By the time World War II came around, HF radio was the primary source for long distance communications for all branches of the military [14]. The usage of HF radio decreased with the development of satellite communications, and HF was made to serve more a backup role in the military. HF radios continued to be used in applications such as amateur radio and maritime communications. However, over the last decade or so, there has been a major resurgence in HF communications, with HF radios becoming more reliable and simpler to use.

HF communications are popular due to the ability of HF radio waves to be reflected off the ionosphere, a part of the upper atmosphere that contains a high density of electrons and charged atoms, in a process known as skywave propagation [15]. There are different electron densities throughout the ionosphere, and waves are diffracted when they pass through areas possessing significant ionization gradients. Areas of high electron density affect the phase velocity of signals passing through them. This allows for an inexpensive method of long-distance, beyond line of sight communications [3]. Figure 4 shows how this type of propagation works. Transmitted signals can reflect off of different layers of the ionosphere in order to reach various distances where there is no direct line of sight with the transmit location.

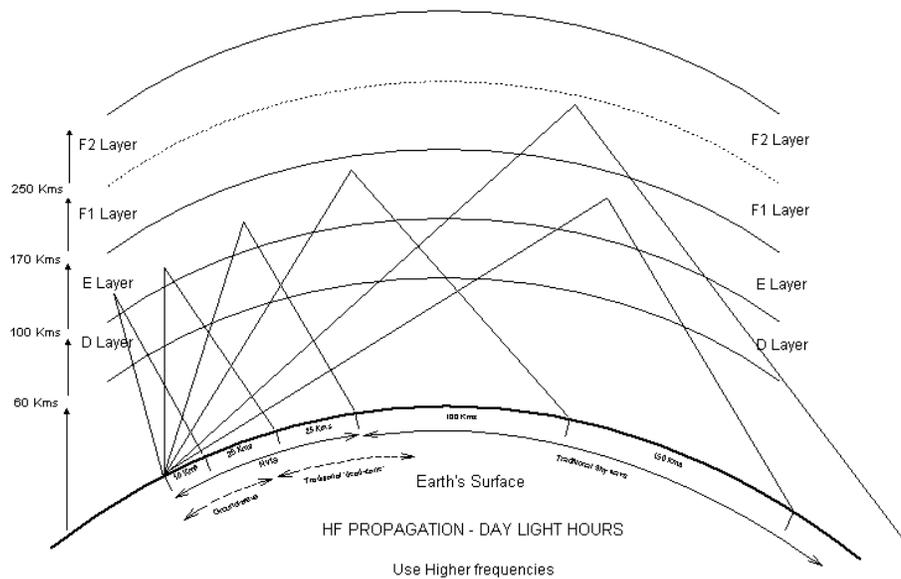


Figure 4: The figure the different layers of the ionosphere various paths that a high frequency signal could take when reflected off the ionosphere [16].

The ionosphere is formed when ultraviolet light from the sun ionizes electrons in the atmosphere, creating a layer of plasma and free electrons. As can be seen in the Figure 4, the ionosphere is comprised of different layers, each with different concentration of various ionized molecules and different concentrations of electrons. The lowest layer is the D layer, which ranges from about 60 km to 90 km above the surface of the Earth. This layer has relatively low ionization, and HF radio waves are mainly damped in this layer due to collisions with electrons and are not necessarily reflected [15]. The next layer is the E layer, which ranges from 90 km to 150 km above the surface and has a significantly higher level of ionization. The E layer can be used for HF propagation, but can only be used for ranges about 2000km or less. The highest section of the ionosphere is the F region, ranging from 150 km to 600 km [12]. The F region is comprised of two layers: F1 and F2. F1 is the lower layer, ranging from about 150 km to 250 km above the surface. The F2 layer usually ranges from 250 km to 400 km, but can get up to 600 km depending on certain conditions. These are the densest layers in the ionosphere and are responsible for most of the skywave propagation of HF radio waves [16].

One of the challenges about using the ionosphere for HF propagation is that the density of ions and free electrons in the ionosphere is constantly changing. The solar activity that determines the state of the ionosphere varies on a long-term, seasonal and even a daily basis [16]. Even the time of day has an effect on the ionosphere. During night time hours, all the layers become significantly less ionized, with the D layer becoming almost nonexistent due to the decrease in ultraviolet radiation. Furthermore,

the two F layers merge at night [15]. The seasons also affect the ionosphere in several ways. For instance, during winter when parts of the atmosphere are tipped away from the sun, solar radiation is weaker and the concentration of ions and free electrons is generally lower [3]. Furthermore, strong solar activity can cause magnetic storms the yield drastic ionospheric disturbances that might only last an hour [16]. The variability and unpredictability of the ionosphere is one of the major issues when trying to use skywave propagation techniques for long range communications.

In order to resolve this issue, HF communication systems are required to maintain a real-time ionospheric model (RTIM), which can serve as a guide for frequency selection and transmission schedules [16]. One of the common methods for modeling the ionosphere is to use a process known as an ionosonde which produces an ionogram, a plot of the virtual height of the ionosphere versus frequency for ordinary rays. The virtual height is the determined reflection heights of the signal based on the time delay between transmission to reception. The virtual height is often slightly higher than the actual height of reflection because signals will travel more slowly in the ionosphere than lower layers of the atmosphere. The signal used to complete the ionosonde is a sounder that sweeps of the desired frequency range. An example of an ionogram can be seen in Figure 7.

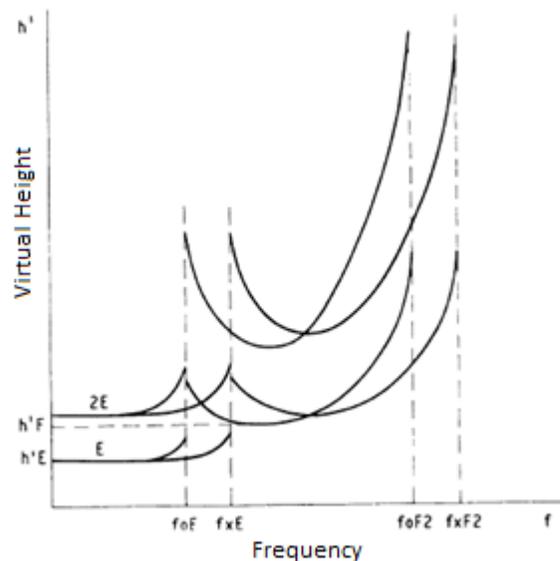


Figure 5: A sample ionogram showing the virtual height of the E and F layers. The double curves for each of the layers are result of the transmitted signal splitting in two, one with clockwise circular polarization, known as O-mode, and another with counterclockwise propagation. The cause of this split is the Earth's magnetic field. The two modes take different paths through the ionosphere, resulting in the two virtual heights [12]

It can be seen on the right side of the ionogram that the mapped virtual height curves upwards so that it is almost vertical. This is due to the frequency of the sounder getting close to the critical

frequency, the maximum frequency that a layer of the ionosphere can reflect a radio wave. The critical frequency is determined by the density of the electrons in the ionosphere. The critical frequency is given by:

$$f_0 = 9 \times 10^{-6} \sqrt{N_e} \quad (2.1)$$

where f_0 is the critical frequency in MHz and N_e is the number of electrons per cubic meter [16]. As the transmit frequency approaches the critical frequency, more of the signal will be absorbed or passed through the ionosphere at a continually greater rate until the virtual height appears infinite [12].

2.2 Analog Filter Design

Filters have been an important part of communication systems for the last century. In wireless communications, additional frequency components falling outside of the frequency band of interest can cause degraded performance of the equipment. Distortion, jamming of the received signal and poor reception are just some of the common issues that frequency components outside the signal band can cause [18]. Sources of unwanted frequencies can range from atmospheric noise to interference caused by people transmitting at close frequencies [18]. Filter circuits are added to communication systems to attenuate the unwanted bands of frequencies while passing the desired band through, improving the overall performance [18].

Filters can be thought of as a “box” which takes in a signal, processes it, and outputs the signal at the other side. The mathematical function that defines the relationship between the output voltage and the input voltage is known as a transfer function, $H(\omega)$, where ω represents radial frequency [19]. Filters are designed to allow a desired range of signal frequencies to pass through with little or no attenuation, while the signal level at other frequencies is reduced. The frequencies that are allowed to pass through with little alteration are known as the passband. The cutoff frequency, or frequencies, is the edge of the passband where the signal has 3 dB reduction. The stopband is the range of frequencies that are effectively prohibited from being passed through from large reduction [19]. An example of a filter response is shown in the Figure 6.

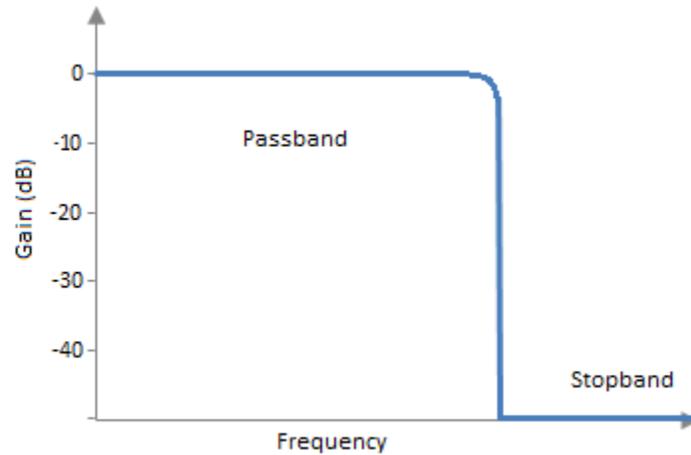


Figure 6: A diagram of a filter. The passband has a gain of 0 dB, allowing frequencies that fall under it to be unaffected. The stopband has a much lower gain, so signal in that range are greatly attenuated.

Filters are usually classified by the position of the passband within the frequency spectrum. Lowpass filters, which allow frequencies below the cutoff to pass, while highpass filters allow frequencies higher than the cutoff to pass [18]. These types of filters only have one cutoff frequency. Two other types of filters are bandpass, which allows signals to pass between an upper and lower cutoff point, and the opposite bandstop, which blocks frequencies between the two cutoff points. [18] The different types of filters are illustrated in Figure 7.

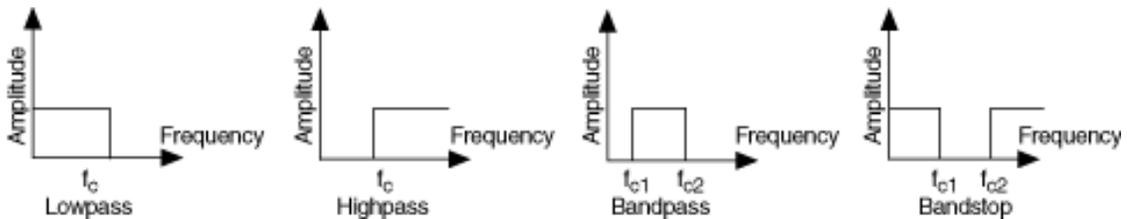


Figure 1: The diagram show the ideal frequency response of a lowpass, a highpass, a bandpass and a bandstop filter [14].

Analog filters are generally modeled as a voltage source, a source impedance a transfer function and a load impedance. The voltage output, V_{out} , is measured from the filter output and the input voltage is measured from the source. The transfer function is defined as the relationship between the input and output voltages:

$$H(\omega) = V_{out}(\omega) / V_{in}(\omega) \tag{2.2}$$

The filter response is a function of ω , or 2π multiplied by frequency, V_{out} is measure of the voltage at the output of a filter and V_{in} is the voltage measure at the signal. A basic diagram of a filter is shown in Figure 8.

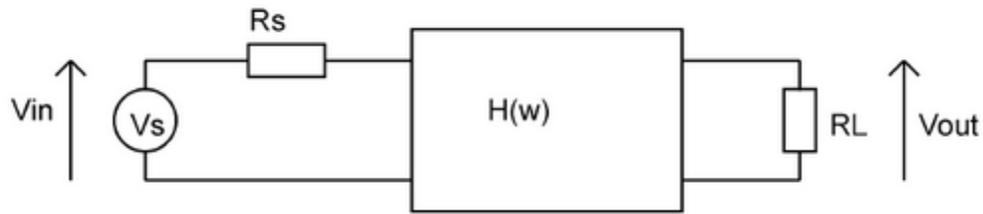


Figure 8: A diagram that shows the basic components of a filter, the voltage source, the source resistance, the transfer function and the load resistance. The input voltage is measured of the source and the output voltage is measured over the load [19].

Analog filters have two forms: Active and Passive. Passive filters only contain resistors, capacitors and inductors. Active filters contain operational amplifiers that used with resistors and capacitors to produce the desired frequency response. Passive filters tend to be used for specialized applications, such as high frequency signals and have the advantage of not consuming any power to operate [19]. To understand how filters work, we need to obtain how the impedance of capacitors and inductors are affected by frequency frequency. The impedance of a capacitor is defined by:

$$Z_c = 1/(j \omega C) \quad (2.3)$$

Where j is the square root of -1 , ω is radial frequency and C is the capacitance of the capacitor. In turn, the impedance of an inductor is defined by:

$$Z_L = j \omega L. \quad (2.4)$$

In this case, L is the inductance of the inductor. At low frequencies, inductors have low impedance and capacitors have high impedance, while the opposite is true for high frequencies. In a simple case, a voltage divider is set up with an inductor and a capacitor. In a lowpass filter, an inductor is the first component from the input and in a highpass filter the first component is a capacitor. Figure 9 shows the basic layouts of these filters.

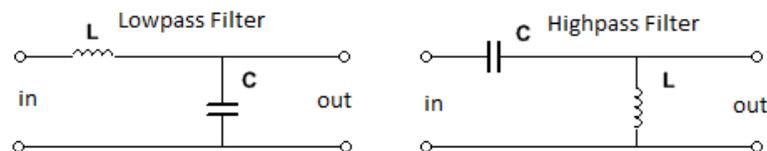


Figure 9: The basic layout of a LC lowpass filter and a LC highpass filter.

For a lowpass filter at low frequencies the capacitor's resistance is much higher than the inductor's. A majority of the voltage is seen over the capacitor and output in this instance. As the frequency increases, the inductor has a much higher resistance, and most of the voltage is lost over the inductor and not seen at the output. Similarly a highpass filter using this concept. In general, more elements can be added to a filter in a ladder type format to increase performance. The number of reactive filter components is known as the filter order [20]. Higher order filters have better frequency responses than lower order filters because of the sharper attenuation between the passband and the stopband, but tend to be more expensive because of the requirement of more components.

All passive filters are derived from a normalized lowpass model. The model has to be transformed and scaled to get the desired frequency response of a desired filter [19]. Bandpass filters are derived from a lowpass model. To get a bandpass filter, first a model lowpass filter of the desired order is scaled to have the appropriate passband bandwidth. Then all the individual inductors are turned into an inductor and capacitor in series while the capacitors are turned into a capacitor and inductor in parallel. The added inductor and capacitor values are scaled from the component they are paired with and with the resonance frequency, which is defined as:

$$F_0 = 1/(2\pi\sqrt{L_{LP}C_{LP}}) \quad (2.5)$$

The values of the added inductors are found with the equation:

$$L_{BP} = 1/(4\pi^2F_0^2C_{LP}) \quad (2.6)$$

The added capacitors are found with the equation:

$$C_{BP} = \frac{1}{4\pi^2F_0^2L_{LP}} \quad (2.7)$$

C_{LP} and L_{LP} are the capacitor and inductor values from the original lowpass filter model that was the base of the design [19]. Figure 10 shows a design of a basic bandpass filter.

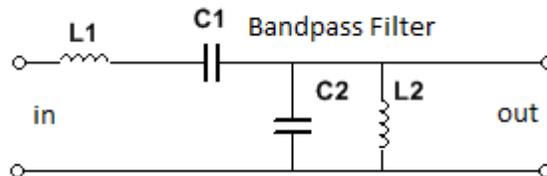


Figure 10: A design of a bandpass filter. The inductor from the lowpass design is now in series with a capacitor and the capacitor from the lowpass design is now in parallel with an inductor.

Ideal filters will allow only the desired frequency band to pass while rejecting all other signal components. Ideal filters also have no losses and a linear phase delay in reference to frequency. However, as in most cases, ideal filters cannot be realized in real life. For example, it is impossible to have a passband with zero attenuation. All components use up some sort of power, thus slightly reducing the power of the signal [18]. Figure 11 presents an example of the differences in behavior between an ideal filter and a real-world filter.

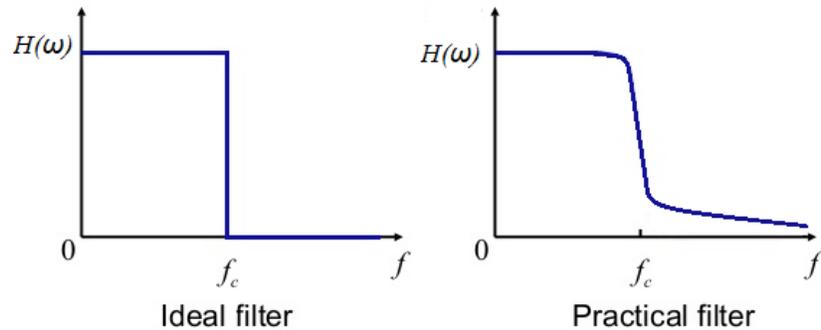


Figure 2: An ideal response and a real-world response of a lowpass filter. The Ideal filter has an immediate cut off between the passbands and the stopbands, while there is a transition in the practical filter. The practical filter also never reaches zero gain in the stopband, but does trend that way.

Instead, real filters are designed with compromise, optimizing one or more important characteristics at the expense of others [21]. In many cases, the magnitude of the transfer function will be considered more important than the phase response of the filter, but phase response might actually be of greater concern in systems that utilize complex modulation schemes [20]. It is up to the designer of the filter to determine what engineering tradeoffs to make in order to get the best performance for the filter application.

2.3 PCB Design

Printed circuit boards (PCB) electrically connect electronic components through conductive tracks and pads that have been etched out of a copper sheet and laminated onto non-conductive substrate. The substrate acts as a base that holds all the wires in place and acts as an electrical insulator [22]. Figure 12 shows what a PCB looks like.

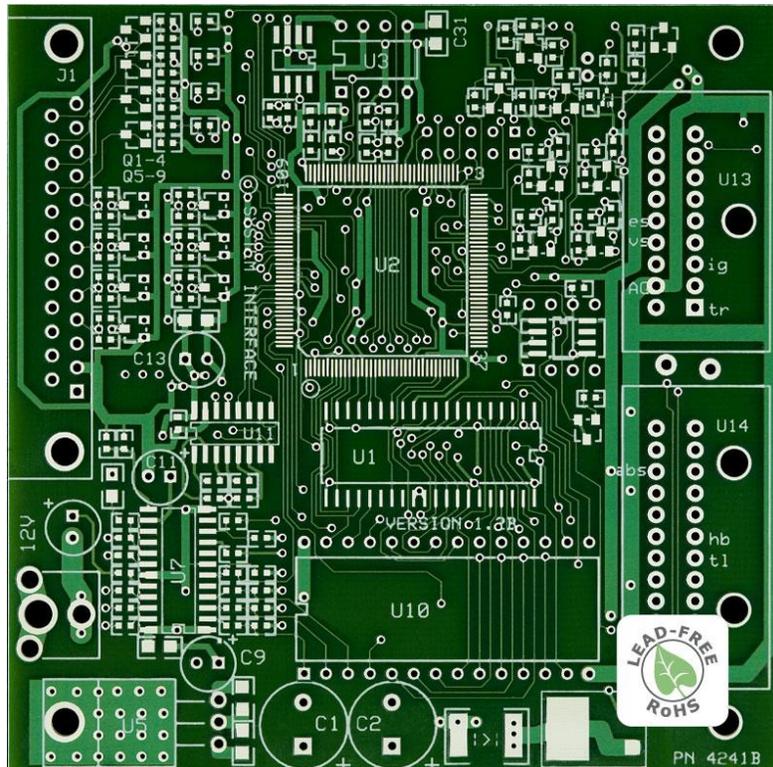


Figure 32: An example of a PCB. The green is the non-conductive substrate while the silver pads are where component would be soldered onto the board. The lines between pads are copper traces that connect components together [23].

The design of a PCB can be a difficult task because there are many of factors that need to be kept in mind based off the desired functionality of the circuit that will be constructed on the board. For example, lines have to be able to carry the required current, so power circuits generally have to have thicker than lines a circuit carrying signals [24]. Lines in RF applications should try to match the impedance of the circuit to avoid reflections [25].

The largest constraint with respect PCB design is space. In today's world there is a growing trend to keep things small and compact in order to maximize space efficiency. The PCB boards are no exception. There are a lot of issues that are associated with designing a board to fit a size requirement. Laying out the components on a board is not a simple task. Parts should have uniform spacing and be organized in a manner that maximizes board space [22]. Keeping appropriate space between components is needed as well. For one thing, there is always some margin of error in the manufacturing process, so component pads and lines placed too close together could end up in a short circuit [25]. Furthermore, another large concern is crosstalk between two lines. When a current travels down a line, an electric and a magnetic field are produced. If lines are close, the line carrying current will produce electromagnetic interference in another line, generating a current and thus inducing noise in adjacent

signal traces. Cross talk can also occur through mutual capacitance. An electrical field forms between the two lines with the space between the two lines acting as the insulating material [18]. To reduce crosstalk, lines have to be spaced apart adequately and a ground plane can be added to the board to absorb the magnetic fields [22]. Designing a PCB is delicate and time-consuming work. Tradeoffs have to be made like in all engineering processes, and it is up to the designer to determine what layout will produce the best results.

There are many tools available for designing a PCB on both a professional and amateur level. There are many CAD software packages that can be downloaded online such as KiCAD, ZenitPCB and ExpressPCB. Although there are slight differences between software, their basic concepts remain the same. The software has a schematic drawing tool that is used to get the design of the circuit for the PCB, and a CAD software is used to design the actual board layout. The software allows for the schematic and CAD design to be linked, keeping track of which components need to be connected so that the board can be wired together properly through traces.

2.4 Chapter Summary

In this chapter, background information pertaining to the project was presented. This first part of this chapter outlines important details about HF communications and how it works. It explained how HF radio waves are refracted off the ionosphere due to differences in electron densities. The ionosphere can also be mapped using radio waves creating a diagram called an ionogram. The next section outlines the process of filter design and its purpose in radio communications. There was an emphasis on passive filters and how to design a band pass filter, the filter type associated with the project. The final section outlined how to design a PCB board and what an average person can use to design their own board. Common design constraints and PCB issues, such as size and cross talk were mentioned and methods to avoid poor designs were discussed.

Chapter 3: Proposed Approach

3.1 Design Requirements

The objective was to improve the overall performance an existing high frequency communication system associated with this project through the development of a bank of narrowband filters. There are a few major design requirements include the following:

- Filters would cover frequencies from 4 to 13 MHz
- The filters would have to be passive to minimize power consumption
- The filter bank would have to easily be able to switch between filters
- The filter bank would have to be able to interface with the rest of the communication system

The bank needs to be able to take in the received signal and pass it through the appropriate filter according to the center frequency of the signal, which would require interfacing with the rest of the communication system. A simple concept diagram of the filter bank can be seen in Figure 13.

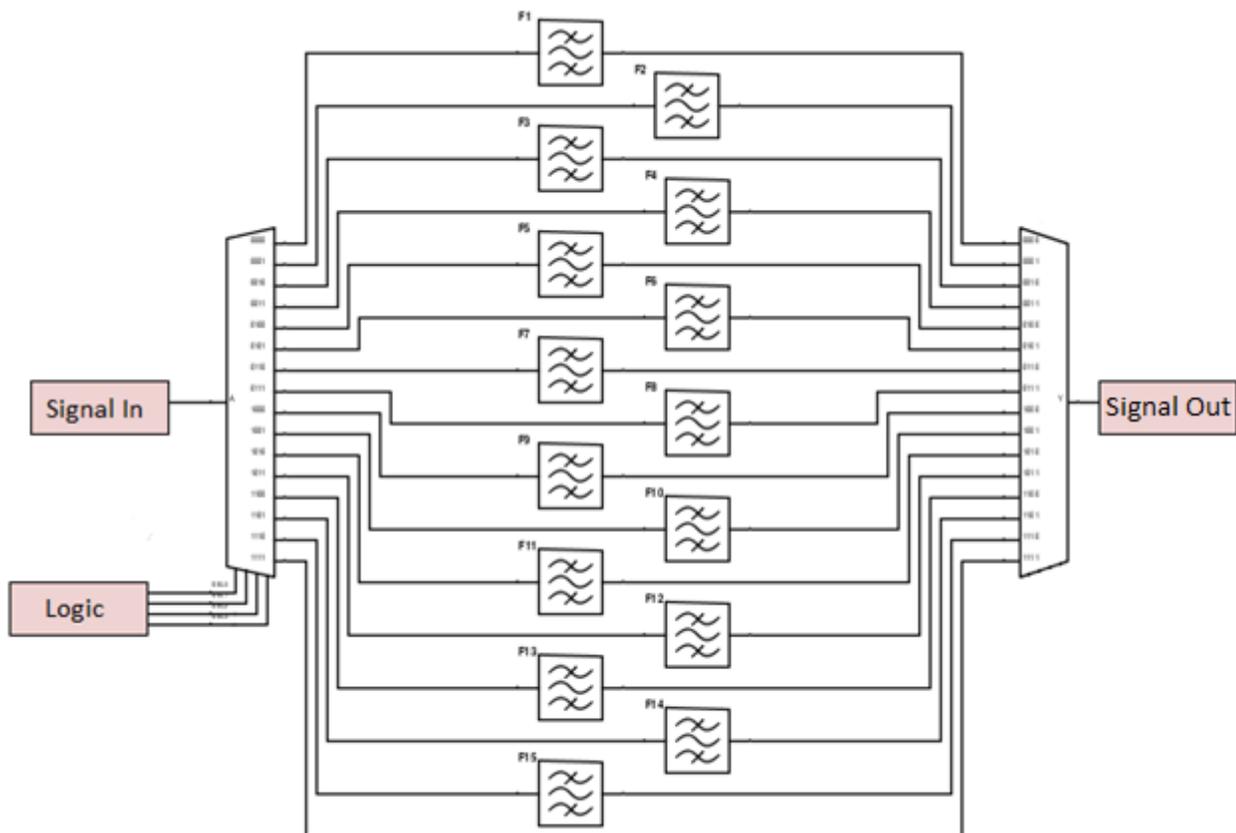


Figure 43: A high level concept diagram of the filter system. A signal comes in and is passed through a filter based off some logic inputs from another part of the communication system. The signal is then passed out through a single output on the other side of the filter bank. There are 15 filters and one pass-through, allowing all frequencies to pass.

3.2 Filter Design

In order to completely cover the entire band of frequencies relevant to this project, the filters had to be designed with some overlap in their bands. The individual frequency bands had to be wide enough to support the widest bandwidths of the transmitted signals, which in this case is 400 kHz. Additionally, knowing that the corner frequency of each filter has a 3 dB drop, the usable frequencies of each filter had to offset from the edges, as the reduction at the corners could warp the signal. Taking all of these constraints into account, Table 1 shows the characteristics of each filter.

Table 1: Table of frequency characteristics of the bandpass filters.

Filter Number	Lower Corner Frequency (MHz)	Upper Corner Frequency (MHz)	Usable Frequencies (MHz)
1	3.9	5.1	4.2 – 4.8
2	4.5	5.7	4.8 – 5.4
3	5.1	6.3	5.4 – 6.0
4	5.7	6.9	6.0 – 6.6
5	6.3	7.5	6.6 – 7.2
6	6.9	8.1	7.2 – 7.8
7	7.5	8.7	7.8 – 8.4
8	8.1	9.3	8.4 – 9.0
9	8.7	9.9	9.0 – 9.6
10	9.3	10.5	9.6 – 10.2
11	9.9	11.1	10.2 – 10.8
12	10.5	11.7	10.8 – 11.4
13	11.1	12.3	11.4 – 12.0
14	11.7	12.9	12.0 – 12.6
15	12.3	13.5	12.6 – 13.2

Each filter has a bandwidth of 1.2 MHz and overlap with half of the filter on either side of it. The usable frequencies are the center frequencies of the signal that can be used with each filter. The usable frequencies take into account the largest possible bandwidth of the signals used by the system, ie. 400 kHz, and leave a buffer so that the signal is not affected by the corner frequency of the filter.

The filters have some response requirements that needed to be addressed. The filters could not have any ripple in the passband in order to prevent signal distortion. The transition between the passband and stopband also needed to be steep in order to more effectively attenuate any unwanted noise in the receiver. The design choice for the filters was chosen to be a third order Butterworth filter. There is no ripple in the passband and stopbands of Butterworth filters, and having the design be a third order allows for a steep transition between the passband and stopband. Third order was also chosen

since although a higher order filter might have given a better response, the cost of parts and physical size of the filter had to be taken into consideration. The filters should not be too expensive to construct if multiple filters would eventually be made for systems at various locations. Size is an issue since the communication system are being constructed on boards that are already crowded with different equipment and spatial efficiency the is key for making sure all the equipment will be able to fit on one board.

3.3 Physical Design

The actual filter was constructed on a printed circuit board, using surface mount components. The circuit board was designed with a PCB design software, which involves designing a schematic and then proceeding to layout the board in an associated CAD software. The advantages behind this are that once the design is made, it can easily be adjusted or copied to make more boards. Printed circuit boards also minimize assembly errors, such as short circuits and missed connection since the machining process behind printing the board is very accurate. Components for PCBs' are very small, limiting the space required to build a circuit. Finally, PCBs are easy to inspect for errors since every component has a fixed and labeled location on the board.

The design had to incorporate a method for switching between filters. To accomplish this task, a pair of multiplexers would be used. The first multiplexer would act as a demultiplexer by taking in the signal input and passing it through the appropriate path to the desired filter. The second multiplexer would take the signal from any of the filters and pass it through a single output. The multiplexers would need digital inputs to select which path to use. A wire terminal would be attached to the board so selector bits could be sent to the multiplexers. The selector bits would come from a programmable digital I/O device, which would be connected to the computer that runs the entire communication system, allowing for the filter to be selected from logic when the center frequency is known. Figure 14 shows how the filter bank fits into the communication system.

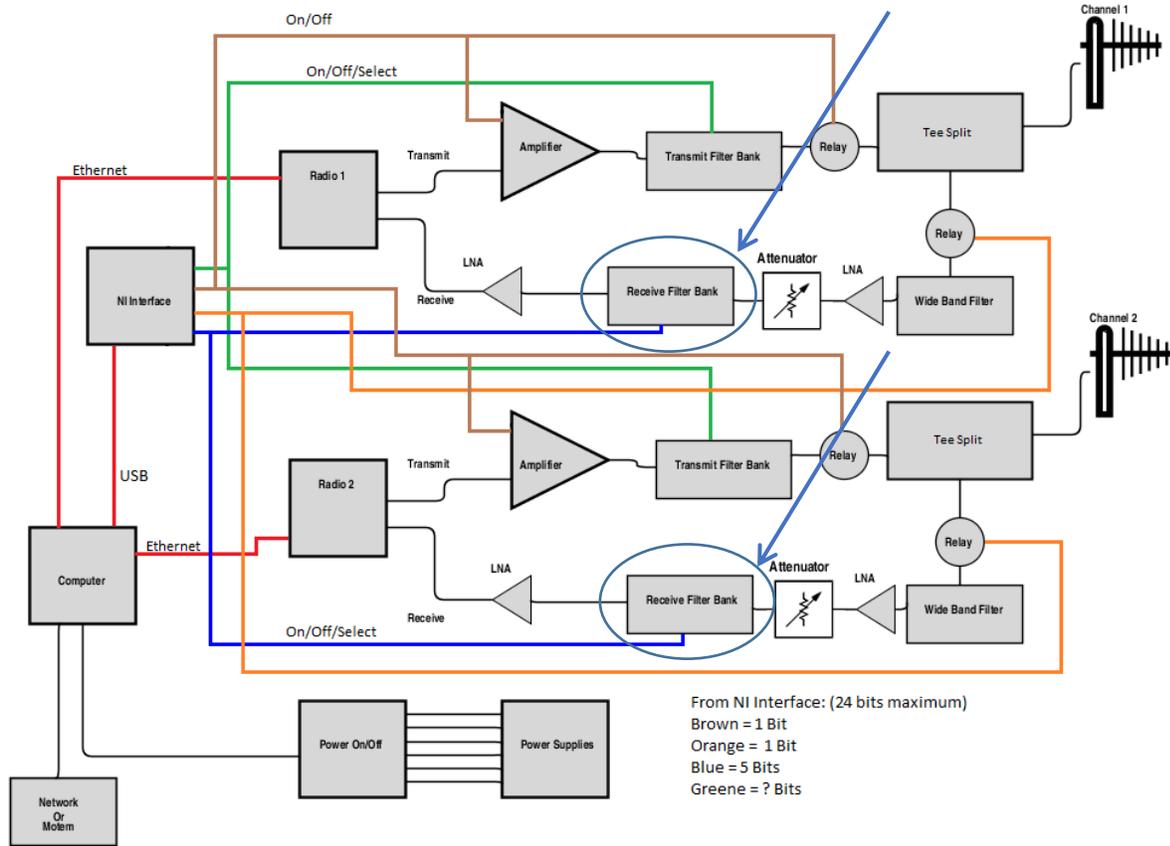


Figure 14: The overall layout of the transmit/receive board. The layout has two parallel systems for transmitting and receiving two oppositely polarized signals at the same time. The Receive filter banks are situated after the attenuator, and are connected to the National Instruments programmable I/O device to allow for switching. The arrows point to the filter banks that are being designed.

3.4 Logistics and Time Frame

There were two other major constraints for the project: time and cost. There were only seven weeks allotted to work on the project, meaning that time had to be managed efficiently. This constraint means that there would not be much of time to design and implement the filters. The design process would have to be meticulous to create a good design in short time since there would not be time for repetitious revisions and testing. Table 2 shows what steps were to be taken each week to allow for a finished project by the project deadline.

Table 2: Proposed timeline for the project

Week 1	Week 2	Week 3	Week 4	Week 5	Week 6	Week 7
Design of filter and part selection	Finish the filter design and start designing the PCB	Finish all designs and order the materials for construction	Build a prototype of the filter board	Testing and start of the debugging of the filter board	Finish debugging of the board and design revisions	Finalize all revisions and complete all reports

Cost was a major constraint because the goal of the project was to help advance a low-cost HF communication system. This constraint mainly applied to the PCB board and filter components. The cost of a PCB increase with board area, so minimizing the size was one of the goals of the design. The constraint affected what components could be used for construction. More expensive parts have lower percent tolerances, allowing for more accurate designs and builds. Tradeoffs between maximizing performance and minimizing cost needed to be made. The most ideal parts could not be used, since the cost of build a board would be greatly amplified if that was the case. The goal was to find the best value of a particular component value while keeping the percent tolerance under five percent.

3.5 Chapter Summary

In this chapter a proposed approach for achieving the goal of the project was presented. First, the goals of the project were given, stating that the filter bank needed to cover frequencies from about 4 to 13 MHz and that the board had to be able to be implemented with the rest of the system. Next, the proposed design of the filters was presented. The filters would overlap and have corner frequencies 1.2 MHz apart to cover the entire frequency band effectively. Next, the proposed approach for the printed circuit board design was given, and what parts were going to be used to create an effective filter bank. Finally, the logistics of the project were given, along with a proposed time line of when major tasks should be completed.

Chapter 4: Methodology and Implementation

4.1: Filter Design

The design of the filters was done using an online design tool developed by the University of York in the United Kingdom. The design tool allows the users to select the type of filter that they want to design, either Butterworth or various Chebyshev designs, and the type of passband there would be. The filter order could be selected, as well as the corner frequencies, the characteristic impedance of the filter and whether the filter would have a series or shunt branch design. The design tool would then output a graph of the frequency response and give a table of what values could be used to construct the desired filter.

The values that the design tool produces were very specific, giving values in scientific notation with six significant figures. Evidently, purchasable component values only have a maximum of three significant figures, so using values as close to the ideal as possible would give the best possible results. Most of the values given by the design tool were not close to any particular commercially available component values. To overcome this, pairs of capacitors and inductors were used to get as close as possible. Most of the inductors were paired in series to since values add linearly together this way. Capacitors were mostly paired in parallel since the same is true for this configuration.

The inductors and capacitors were all ordered from Digikey.com, a website where various electrical components can be purchased. Cost and tolerance were taken into account when selecting what components to use. Size was also a consideration. Components that are surface mount technology are very small, and can have dimensions that are less than one millimeter in length. It was decided that components of sizes 2012 and 2520 were used. The first two numbers of each size represent the length in millimeters and the second two numbers represent the width. For example, the size 2520 is 2.5 mm by 2.0 mm. These sizes are small enough to allow for tight spacing on the PCB board, but are not too small that they would be too difficult to handle.

One of the important constraints on the inductors was that they had to have a ferrite core. A ferrite core is non-conductive and yet has magnetic permeability, which allows for low losses at high frequencies. Ferrite cores also prevent coupling between the inductors, which could cause distortion among a signal. Table 3 shows the ideal filter values from the design tool and what values were actually used to get as close as possible for the first two filters. The full table can be seen in the appendix.

Table 3: The chosen inductor and capacitor values for the first two filters.

Filter Number	Part Type	Order Number	Ideal Value	Used Value	Part 1	Part 2
1	Inductor	1	6.63146 μ H	6.6 μ H	3.3 μ H	3.3 μ H
1	Inductor	2	235.785nH	235nH	220nH	15nH
1	Inductor	3	6.63146 μ H	6.6 μ H	3.3 μ H	3.3 μ H
1	Capacitor	1	188.628pF	188pF	120pF	68pF
1	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
1	Capacitor	3	188.628pF	188pF	120pF	68pF
2	Inductor	1	6.63146 μ H	6.6 μ H	3.3 μ H	3.3 μ H
2	Inductor	2	183.570nH	183nH	150nH	33nH
2	Inductor	3	6.63146 μ H	6.6 μ H	3.3 μ H	3.3 μ H
2	Capacitor	1	146.856pF	147pF	120pF	27pF
2	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
2	Capacitor	3	146.856pF	147pF	120pF	27pF

Figure 15 shows an example of one of the layouts for the first filter in the filter bank. All of the inductors and capacitors are paired together so that actual purchasable values can be combined to get a value close to the ideal value of the filter design.

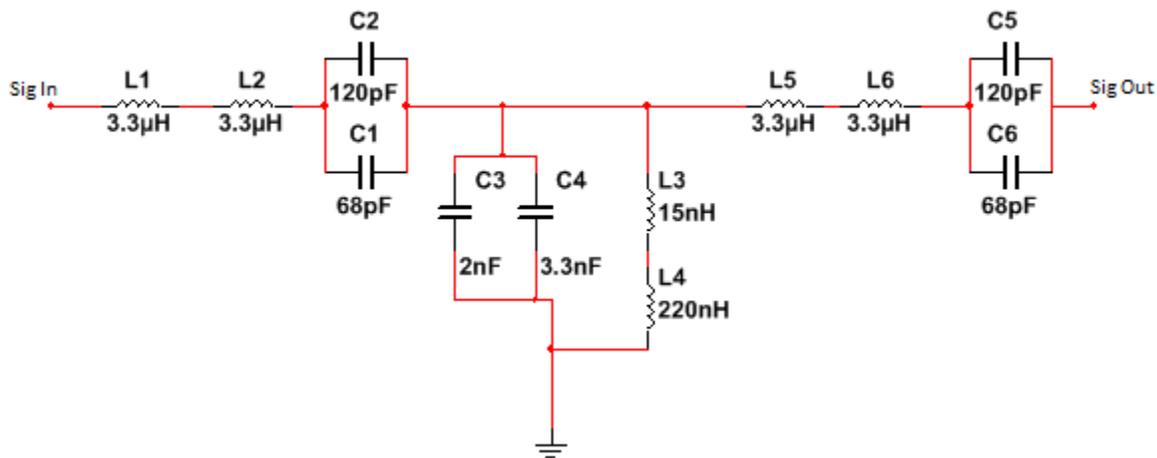


Figure 55: An example of how the filters are designed. This is the first filter in the bank, with corner frequencies at 3.9 and 5.1 MHz. The inductors are paired in series and the capacitors are paired in parallel so real components values can be used to get close approximations of the ideal values.

4.2 PCB Design

The design of the PCB layout was done in several steps. The design tool used was ExpressPCB, which uses both a schematic and CAD software to design boards. First, a schematic of the PCB was made

in the schematic tool. The schematic had to contain all the parts that would go onto the PCB board since linking the schematic with the CAD software allows the CAD software to automatically determine what parts need to be linked together.

The design process took several iterations. The design had to be rearranged a few times to reduce to board size and thus reduce the cost of the board. There were also several edits to the board that had to be made. The original schematic did not include a power regulation circuit to power the multiplexers. The multiplexers require a +2.5V and a -2.5V power input, and the regulator circuit consisting of a power supply and a positive and negative voltage regulator was added to the board to accomplish this. Another edit to the board was to use add voltage divider circuits to the input of the logic bits since the multiplexers only handle about 2.5V as a high logic and the digital I/O gave out 5V for a high logic. Figure 16 shows the final layout of the board.

4.3 Design Testing:

After the board and filters were designed, all components had to be ordered and assembled. Assembly of the board was left to an expert since the components were all surface mount technology, which requires training to solder. Tests were done on each filter using a network analyzers, testing the S21 characteristics of each filter. S21 characteristics measure the gain of a signal, comparing the output to the input over the frequency of the signal. The filters were tested from 2 MHz to 16 MHz, wider than the allocated range of frequencies that signals can be transmitted for this project. A power supply would be used to power the multiplexers and a separate 5V power supply was used to set the logic bits for filter selection. Once initial tests were completed, any debugging of the filter would have to be done. Any design flaws found would have to be corrected in a revised design.

4.4 Chapter Summary

In this chapter, the steps for designing and constructing the filter board were presented. The filters were designed by first identifying ideal component values and then selecting real component values such that they were close to the ideal as possible. The layout of the board was designed using a process of reiterations to get a finalized design. Finally each filter on the board had its S21 characteristics tested using of a network analyzer.

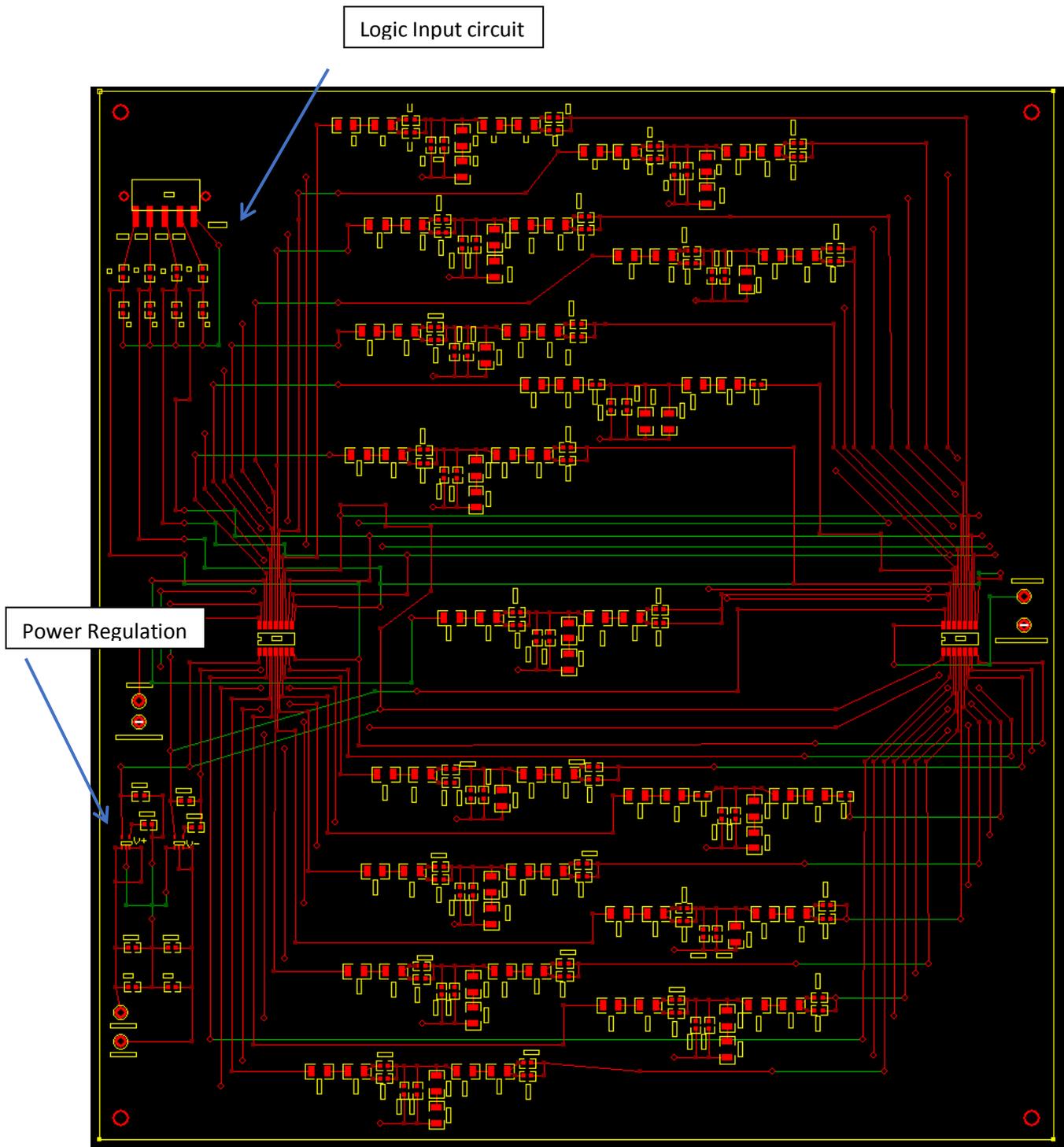


Figure 16: The final layout of the PCB. The red lines represent traces on the top side of the board and the green lines represent traces at the bottom of the board. The bottom left part of the board is the circuit for regulating power to the multiplexers and the top left is where the logic inputs will be connected. Filter 1 is at the top of the board and Filter 15 is at the bottom.

Chapter 5: Experimental Results

5.1 Predicted Results

Once the filters were designed, a model predicting the results of the filters was needed. A model could be used to serve as a base for comparisons for after the measurements were taken. Two models would be needed for comparison. One would be the ideal filter response of all the filters. The ideal filter results would not be achievable, but would act as a comparison to how well the design worked. The next model would be the predicted filter response of the filter bank. This model would take into account the imperfections in the filter components, such as the impedance that is present in inductors. The first model of the ideal filter response can be seen in Figure 17.

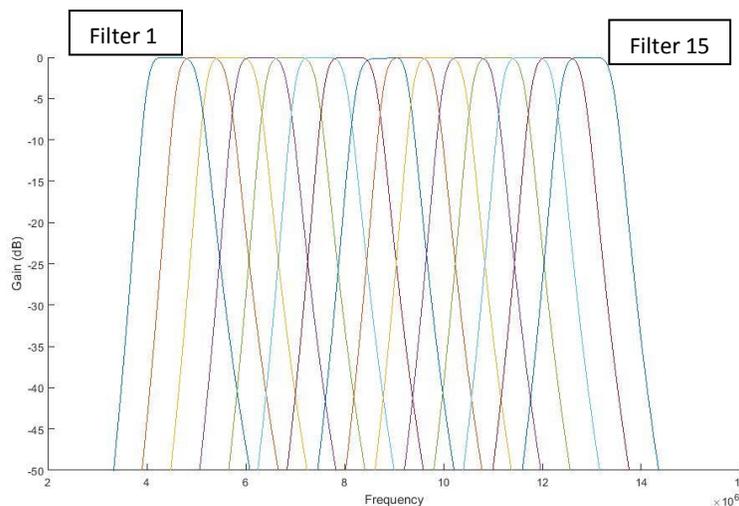


Figure 17: The ideal response of the filters in the filter bank. Each filter has a 0dB gain for the frequency range that they cover. The ideal filters would not be able to be realized using real components.

To calculate the predicted results, a MATLAB script was used to calculate the frequency response of the filters using node equations. The script took into account the imperfections in the filters parts, such as the Q factor of the inductors, which is the impedance seen in an inductor due to resistance in the materials it is made of. Calculations were done using the impedance of the inductors and the capacitors, and using equivalent circuits to find the power and current seen by each filter, and finally calculating the gain seen at the output of each filter. The full script can be seen in the appendix. The results of the model can be seen in Figure 18.

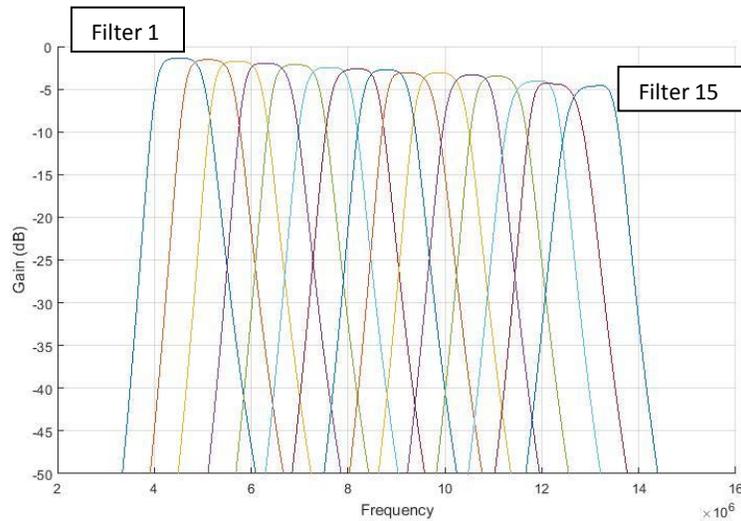


Figure 186: The figure shows the predicted S21 characteristics of the filters. The filters are not completely ideal since the inductors do have small resistances and the fact that ideal values could not be easily realized with real components. There is a decreasing trend in the gain as frequency increases.

The predicted results show that achieving a 0 dB gain is not possible due to imperfections and impedance in the components. The results also predict that the gain of the filters will decrease as frequency increases, so filter 1 will have the best response while filter 15 will have the worst response, with a gain just above -5 dB. The filters do appear to have bands at the right frequencies and good transition slopes out of the passband and into the stopband.

5.2 Measured Results

Once the all the filter parts were ordered and put together, a test of performance had to be done on the filter bank. The test would be performed using a network analyzer, so cables were soldered onto the board where the signal input and output are. A 5V power supply with a ground was connected to the terminal on the board through wires for frequency selection. The S21 characteristics of each filter had to be taken separately, so 16 tests were needed to analyze the performance of the filter. There was one test for each of the 15 filters and one test for the pass-through on the filter board. The results of the first test can be seen in Figure 19.

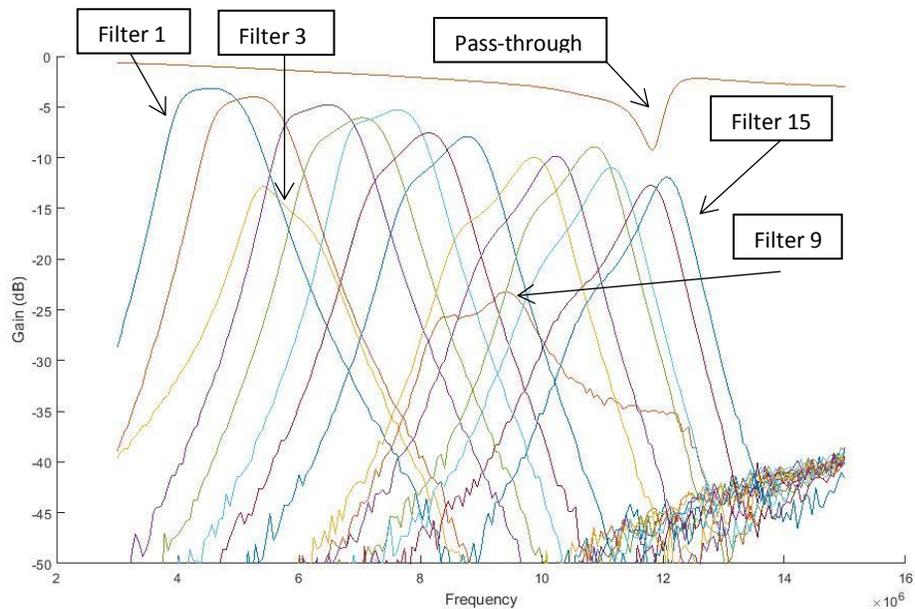


Figure 197: The measured S21 characteristics of the filter bank. Filters 3 and 9 had much lower gain compared to the filters around them. The filter response appears to get worse with frequency, and can be seen in the response by the pass-through line above the other responses. There appears to be a resonance around 12 MHz.

The results showed that the physical filter bank did not perform as well as the predicted model. The most significant result of the first test was that the board appears to have a resonance at 12 MHz, as can be seen in the behavior of the pass-through especially. The filters follow the trend of having a worse response as frequency increases, following the same pattern that the prediction model showed, with the worst filter being filter 14, where the board resonance is at a peak. Filter 15 appears to be better than the previous one, following the trend seen in the pass-through. The test results also showed that filters 3 and 9 needed to be inspected for issues, as they performed much worse than the filters surrounding them.

After checking if the correct parts were used and that the traces were correct on the board, a short over one of the capacitors in filter three was discovered and a broken trace was found in filter 9. The short in filter 3 was carefully cut using a utility knife. The broken trace in filter 9 was repaired by soldering a wire onto where the trace was supposed to connect. After the repairs were made, the process for testing the filters was repeated using the network analyzer. The results of the second set of test can be seen in the Figure 20.

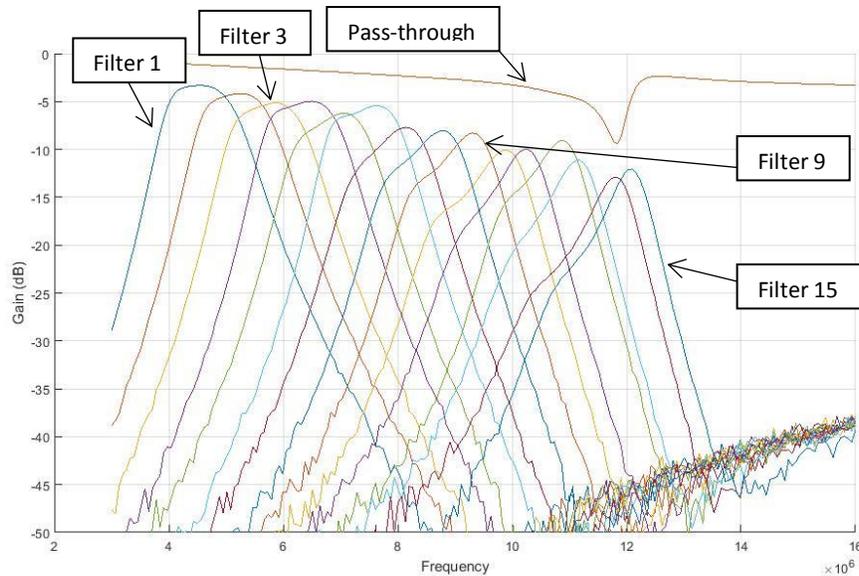


Figure 208: The second set of tests done using the network analyzer. Filters 3 and 9 now behave much better and have behaviors comparable to the filters around them. The resonance of the board remains after the second set of test.

The results show that the fixes applied to the traces on the board were able to make a large difference in the performance of filter 3 and filter 9, improving the overall performance of the filter. The filter still had resonance at 12 MHz, which can still be seen in the pass-through of the filter. The resonance is most likely the cause of the poor performance by the filters for the higher frequencies.

A lot of work went into trying to find the source of the resonance. The dip in the S21 of the pass-through indicated that some of the energy of the signal was being dissipated somehow. There are three possible options for how the power was being lost: absorbed through resistance, reflected back to the source or the board would act like an antenna and radiate some of the power out of it. The first of these could be eliminated since there were no resistors on the board. To determine if the board was reflecting or absorbing the power, the S11 characteristics of the pass-through was tested using the network analyzer. This test would see how much power was being reflected back at the input. If there was a spike in the S11 where the S21 dips, it would mean the signal was being reflected. If there was no spike, the power was being lost due to radiation. A small spike would mean that there would be a combination of reflection and radiation. Figure 21 below shows the results of the S11 test compared to the S21 of the pass-through.

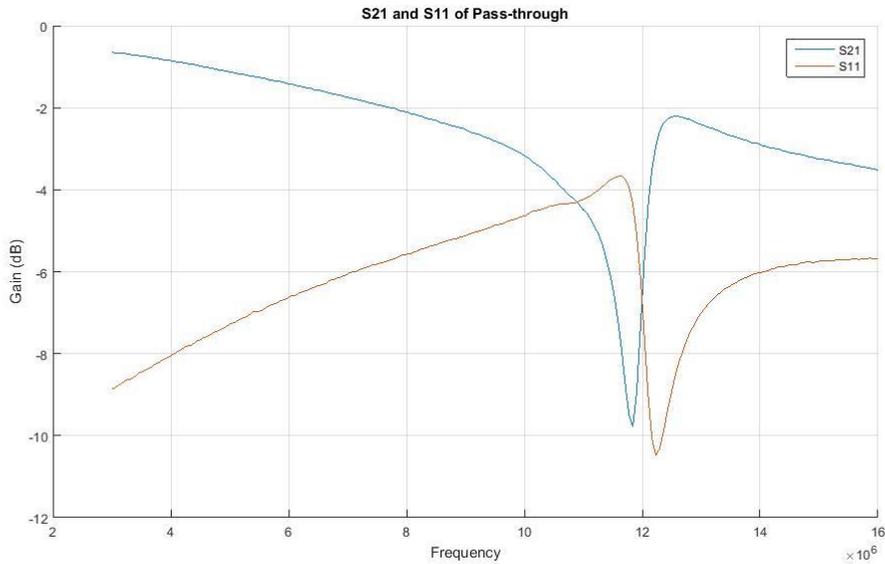


Figure 21: A comparison of the S21 and S11 characteristics of the pass-through on the board. The peak in the S11 at the same time the S21 dips shows the signal was being reflected.

The results of the test clearly showed that the signal was being reflect, not radiated. Tests were performed on the board to determine where the signal was being reflected. S11 characteristics where measured around the board and at different points along the traces, but the tests not able to find the cause of the reflection. The next option was to test to see if the multiplexer chip was the cause of the reflection. The chips were removed from the board and the filters were tested again. The results can be seen in the Figure 22.

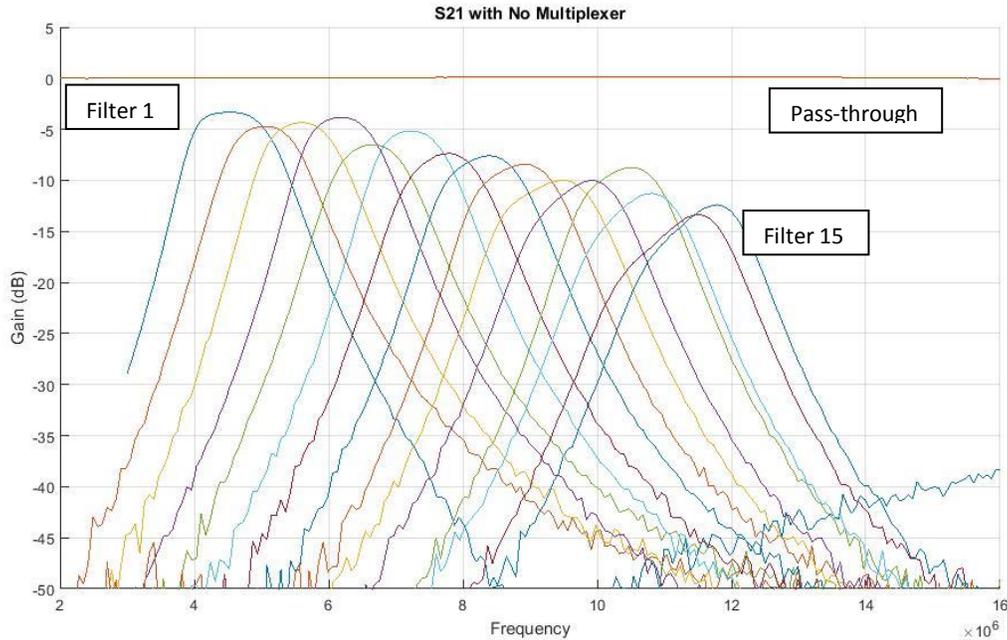


Figure 92: The S21 characteristics of the filters after removing the multiplexer chip from the board. The performance of the filters improved with the chips removed.

The results show that the performance of the filters improved when the chips were taken out. The responses of the filters were a lot more level in the pass band compared to the other tests. The pass-through had a great response, no longer showing a reflection. The filters still did not perform as well as the predicted results. This is most likely due to the fact that the characteristic impedance on the board was calculated out to be 66Ω , when the filters were designed with a 50Ω impedance in mind.

5.3 Chapter Summary

In this chapter, the various tests on the performance of the filter were looked at. The first section showed the ideal filter responses for the filter bank as well as the predicted model for the filter bank. The next section showed the results of the actual tests performed on the physical prototype. The results showed that the filter bank did not perform as well as the predicted model due to a resonance on the board at 12 MHz due reflection of the signal. It was discovered that the source of the reflection was the multiplexer chips.

Chapter 6: Conclusions and Recommendations

6.1 Conclusions

High frequency communication systems are valuable in that they provide a relatively inexpensive means of over the horizon communication due to a low requirement of infrastructure. The goal of the project was to help advance the development of a high frequency communication system through the development of a selectable filter bank. The purpose of the filter bank would be to reduce the noise seen on the receive end of the communication system and prevent the signal from being saturated, thus increasing the performance of the communication system by improving reliability and lowering the occurrence of errors. The filters would be constructed using surface mount components on a printed circuit board and all the filters would be passive to minimize the power consumption used by the filter bank.

The project was able to show that it would be possible to use a filter bank to reduce the noise in the communication system. Although the filter bank did not perform up to the standard of the predicted model, the results, especially the first few filters, showed that the concept of the filter bank could be used to reduce noise around the signal. The first few filters had responses close to their respective predicted ones. The latter filters did not perform as well. This is possibly due to the characteristic impedance of the board being different than what the filters were designed for.

There were a few other setbacks in the project besides the board causing signals of certain frequencies to be reflected due to the multiplexers. The board was not able to be tested in the actual communication system because the antennas were not up and running. It was discovered that an animal kept chewing through some of the cables that were attached to the system's antennas. Since there were no antennas up for the communication system, data was not able to be collected at the time testing of the filter banks was being performed.

6.2 Recommendations

One area that still needs to be looked into in this project is the reflection centered around 12 MHz that is seen in the PCB caused by the multiplexers. The project team at MITRE should continue to look for different multiplexer chips that could be used or even a different method of switching between filters all together. A new design for the PCB board was made, fixing some of the design flaws, such as the trace errors in the original design. The new design also has wider traces than the original PCB, giving the new PCB a characteristic impedance of 50Ω , which the filters were designed for. There is more work

that needs to be done on the design of the new boards since more research into how to switch between filters is still ongoing. Once a design is figured out, the new board should be constructed and tests to see if there is an improvement in performance should be done as well.

V References

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VI Appendices

Appendix A: Filter Design

Filter Number	Part Type	Order Number	Ideal Value	Value Used	Part 1	Part 2
1	Capacitor	1	188.28pF	188pF	120pF	68pF
1	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
1	Capacitor	3	188.28pF	188pF	120pF	68pF
1	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
1	Inductor	2	235.785nH	235nH	220nH	15nH
1	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
2	Capacitor	1	146.856pF	147pF	120pF	27pF
2	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
2	Capacitor	3	146.856pF	147pF	120pF	27pF
2	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
2	Inductor	2	183.570nH	183nH	150nH	33nH
2	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
3	Capacitor	1	117.566pF	118pF	100pF	18pF
3	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
3	Capacitor	3	117.566pF	118pF	100pF	18pF
3	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
3	Inductor	2	146.957nH	147nH	120nH	27nH
3	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
4	Capacitor	1	96.2388pF	95pF	68pF	27pF
4	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
4	Capacitor	3	96.2388pF	95pF	68pF	27pF
4	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
4	Inductor	2	120.299nH	120nH	120nH	0nH
4	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
5	Capacitor	1	80.2293pF	80pF	47pF	33pF
5	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
5	Capacitor	3	80.2293pF	80pF	47pF	33pF
5	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
5	Inductor	2	100.287nH	100nH	100nH	0nH
5	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
6	Capacitor	1	67.9061pF	68pF	68pF	0pF
6	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
6	Capacitor	3	67.9061pF	68pF	68pF	0pF
6	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
6	Inductor	2	84.8826nH	83.07nH	270nH	120nH
6	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
7	Capacitor	1	58.2185pF	59pF	39pF	20pF

7	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
7	Capacitor	3	58.2185pF	59pF	39pF	20pF
7	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
7	Inductor	2	72.7732nH	72nH	39nH	33nH
7	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
8	Capacitor	1	50.4653pF	50pF	30pF	20pF
8	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
8	Capacitor	3	50.4653pF	50pF	30pF	20pF
8	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
8	Inductor	2	62.0816nH	62nH	47nH	15nH
8	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
9	Capacitor	1	44.1637pF	44pF	22pF	22pF
9	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
9	Capacitor	3	44.1637pF	44pF	22pF	22pF
9	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
9	Inductor	2	55.2046nH	56nH	56nH	0nH
9	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
10	Capacitor	1	38.9727pF	39pF	39pF	0pF
10	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
10	Capacitor	3	38.9727pF	39pF	39pF	0pF
10	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
10	Inductor	2	48.7159nH	49nH	39nH	10nH
10	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
11	Capacitor	1	34.6460pF	35pF	20pF	15pF
11	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
11	Capacitor	3	34.6460pF	35pF	20pF	15pF
11	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
11	Inductor	2	43.3075nH	43nH	33nH	10nH
11	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
12	Capacitor	1	31.0017pF	31pF	16pF	15pF
12	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
12	Capacitor	3	31.0017pF	31pF	16pF	15pF
12	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
12	Inductor	2	38.7521nH	39nH	39nH	0nH
12	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
13	Capacitor	1	27.9036pF	28pF	18pF	10pF
13	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
13	Capacitor	3	27.9036pF	28pF	18pF	10pF
13	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
13	Inductor	2	34.8795nH	34nH	22nH	12nH
13	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH

14	Capacitor	1	25.2477pF	25pF	15pF	10pF
14	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
14	Capacitor	3	25.2477pF	25pF	15pF	10pF
14	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
14	Inductor	2	31.5596nH	32nH	22nH	10nH
14	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH
15	Capacitor	1	22.9537pF	23.1pF	18pF	5.1pF
15	Capacitor	2	5.30516nF	5.3nF	2nF	3.3nF
15	Capacitor	3	22.9537pF	23.1pF	18pF	5.1pF
15	Inductor	1	6.63146μH	6.6μH	3.3μH	3.3μH
15	Inductor	2	28.6921nH	28nH	18nH	10nH
15	Inductor	3	6.63146μH	6.6μH	3.3μH	3.3μH

Appendix B: MATLAB Code

```
S21_calc.m
%Define Frequency Values
f=[1000000:10000:16000000];
w = 2*pi*f;

%Set Q parameters
QL = 120;
QC = 1200;

%Set characteristic impedance, tolerance and initial voltage
ZLoad = 50;
Zs=50;
T = 0;
V = 1;

%Values of the components
L1s = 6.6e-06*ones(1,15);
L2s = [235 183 147 120 100 83.07 72 62 56 49 43 39 34 32 28].*(10^-9);
L3s = 6.6e-06*ones(1,15);
C1s = [188 147 118 95 80 68 59 50 44 39 35 31 28 25 23.1].*(10^-12);
C2s = 5.3e-09*ones(1,15);
C3s = [188 147 118 95 80 68 59 50 44 39 35 31 28 25 23.1].*(10^-12);

hold on

for n = 1:15

%Calculate the impedance of the inductors and capacitors
L1a = L1s(n);
L1 = L1a + T*L1a;
ZL1 = (w.*L1) ./ (QL)+1i.*w.*L1;

L2a = L2s(n);
L2 = L2a + T*L2a;
ZL2 = (w.*L2) ./ (QL)+1i.*w.*L2;

L3a = L3s(n);
L3 = L3a + T*L3a;
ZL3 = (w.*L3) ./ (QL)+1i.*w.*L3;

C1a = C1s(n);
C1 = C1a + T*C1a;
ZC1 = 1./ (QC.*w.*C1)+1./ (1i.*w.*C1);

C2a = C2s(n);
C2 = C2a + T*C2a;
ZC2 = 1./ (QC.*w.*C2)+1./ (1i.*w.*C2);

C3a = C3s(n);
C3 = C3a + T*C3a;
ZC3 = 1./ (QC.*w.*C3)+1./ (1i.*w.*C3);

%Find the equivalent impedance as seen by the input
```

```

Z1 = ZLoad+ZL3+ZC3;
Z2 = (ZL2.*ZC2)./(ZL2+ZC2);
Z3 = (Z2.*Z1)./(Z2+Z1);

Zin = Z3+ZL1+ZC1;

I50 = V/(ZLoad+Zs);
P50 = (I50^2)*Zs;

%Calculate Current
Iin = V./(Zin+Zs);

%Calcualte Current at output
Iout = (Iin.*Z2)./(Z1+Z2);

%Calculate the power at the output and S21
Pout = abs(Iout).^2.*ZLoad;

S21 = 10*log(Pout/P50);

plot(f,S21)
end

```