MEMS Wireless Transceiver for Use of Non-Invasive System Diagnostics

Senior Design II
Final Report

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1.0 Executive Summary

As the size of electrical components becomes smaller and smaller, the future of electronics lies not in nanotechnology, but in microtechnology. The marketability of MEMS, or microelectromechanical systems, is increasing as the field expands and new applications are developed. Most of the MEMS products developed are sensors which relate changes in capacitance, resistance, or voltage to changes in the environment. Despite the complexity of these devices, they are worthless without a method of reliably communicating with the sensor.

In this project, a transceiver will be used to communicate with a sponsor-provided MEMS sensor that is positioned on a motor a specified distance away. In this setup, the transceiver would be designed to wirelessly communicates with the sensor via a 27 MHz frequency. Although similar technology currently exists at higher frequency levels, no such designs have been found to exist for the industrial, scientific, and medical (ISM) frequency band. After the transceiver has received the amplitude, frequency, and phase data from the sensor, it filters, mixes, and amplifies or attenuates the signal as needed to obtain a clean sinusoidal wave output from the square wave input. Once a sine wave has been obtained, the information is relayed to a computer via a USB port and exported to an organized graphed function for further analysis. Signal transmission to the MEMS sensor is the most complicated aspect of the project. Because the resonant frequency of the MEMS device is changing, the transmitted signal must match the resonant frequency of the MEMS device for maximum power transfer to occur. This is accomplished by changing the transmitted frequency to match the received frequency by modulating a generated signal using a voltage-controlled oscillator. This signal is then amplified and filtered before being passed to the RF switch and propagated out by the antenna.

Beyond the frequency range limitations, the device is also limited by its power, size, transmission distance, and cost of fabrication. Design specifications limit the power consumption of the device to 10 watts and the production and equipment costs to $1,500.00. The transceiver shall be capable of transmitting and receiving at a minimum distance of 1 meter, although a wider transmission range is preferred. Additionally, the device package is of a reasonable size as well as fast and easy to set up. Project deliverables also include the microcontroller code used to communicate with the transceiver and a graphical user interface (GUI) which can be used to visualize the system response.

The ultimate objective of this design was to provide the sponsor with an accurate and completely functional transceiver that costs significantly less than the allowed $1,500.00 budget. For the device to be usable, it had to function within the ISM band at a frequency of 27 MHz. However, due to design difficulties, the operational frequency was lowered to 1 MHz. The transceiver, combined with a transponder, allowed for signal analysis and system diagnostics at a distance. Analysis may be done visually via a GUI or by extrapolating data from the microcontroller. By providing the capability to remotely monitor systems, the customer will be able to mitigate the amount of time a system is nonfunctional and thereby lessen the cost of maintenance.

2.0 Project Description

To successfully solve a problem, the underlying problem and the desired outcome (or outcomes) must be understood. By fully acknowledging the 'why's of the project, the design process becomes an easier one. The project motivators, too, must be understood, as the motivation behind the project drives the direction of the goals and objectives. Some motivators, such as reducing production costs or operating within a specific frequency band, are easy to identify but are harder to achieve. Components and subsystems are often negatively correlated so that as one design specification is improved another is negatively affected. To optimize the overall design, tradeoffs must be managed.

2.1 Project Motivation and Goals

The subjects of non-invasive testing and predictive failure of structural integrity has been of growing interest in recent years. This is primarily due to the amount of cost avoidance that can be gained by sensing a problem and correcting it before the issue can reach a point of a catastrophic failure. Additionally, non-invasive testing allows for reduced troubleshooting time. By reducing troubleshooting time, companies can reduce the amount of manpower allocated to troubleshooting and save on labor costs.

Non-invasive testing is typically accomplished by means of small sensors that are positioned within the structure or system and remain there throughout the life of the unit in question. One of the primary difficulties of implementation is the communication of the sensor with a processor and the utilization of the data obtained from the sensor. The data gathered from the sensor is used to analyze the general health of a system. The most common metrics for this analysis is the frequency and amplitude of the system's or structure's vibration. By monitoring these metrics, companies can monitor the health of rotating components by recording information about the number of rotations over a defined period. If the frequency suddenly increases or decreases, it signifies that something may be wrong with the system and that it requires attention or maintenance.

Devices like this have been designed and are currently available on the market. However, the available designs operate at frequencies far beyond the ISM band. One of the most challenging problems with devices operating at such high frequencies is signal interference. To counteract the effects of interference, the transmitter and receiver operate at slightly different frequencies and must perform modulation to communicate. Because the preexisting designs already function at high frequencies, it is undesirable to modulate these signals to even higher frequencies as this could result in encroachment on commercial or government bands. Even accidental breaches into commercial or government-regulated frequency bands poses the risk of legal action against the offender.

To avoid issues caused by operation at higher frequencies, this project set out to communicate with a sponsor-provided MEMS sensor via radio frequencies. When fully operational, the sensor would be placed on a motor so that it can monitor the changes in vibrational frequency and alert operators to potential failures.This goal is accomplished by sending a high-power radio signal to the MEMS sensor for excitation before switching to a receiving mode to gather data from the sensor. The response of the MEMS sensor is frequency variant, and this variance in frequency will be used to determine the overall health of the system. This is accomplished by taking the received frequency response of the system and applying a Fourier transform to the signal and looking for frequencies that are outside of the standard value. Once the Fouier transform has been performed on the systems microcontroller, the microcontroller relays the data to a computer where a graph is plotted to display the characteristics of the systems status.

The completed design package consists of a fully integrated system. The system was initially designed to include a printed circuit board (PCB) with embedded microcontroller that provides bidirectional communication to the sensor through the 27 MHz antenna. The PCB also include a USB port so that it is capable of interfacing with a PC. The final system consisted of two 2-layer PCB daughterboards which interfaced directly with a microcontroller development board. Additionally, the system has a launchable application on the Windows platform to provide the user with system diagnostics. The goal of this project was to create a fully functional and reliable piece of test equipment that would allow the sponsor to easily monitor the health of their systems.

2.2 Objectives

The objectives listed below are the primary functions which are incorporated within the design:

- Interfaces
  - Electrical
  - Physical
- Accept +1.9 VDC, +3.3 VDC, +3.3 VAC, +5 VDC, and -5 VDC
- Accept frequencies in the 27 MHz range
  - Updated to accept frequencies in the 1 MHz range
- Convert a square wave to a sine wave
- Provide filtering of harmonics
- Perform a Fourier transform
- Extract serial data and convert to a graphed function

- Interface with a PC via serial USB

2.3 Requirement Specifications

Requirement specifications are statements which describe the product to be designed. A quality requirement specification should identify important requirements while providing design flexibility. All requirements must be agreed upon by both the customer and designers. These specifications should be abstract enough to have multiple design approaches but unambiguous enough to be verifiable and traceable during testing and integrating. Moreover, these specifications should be clear enough to suggest intuitive methods of testing.

The specifications which have been agreed upon by the customer and designers are described below and can be split into two distinct categories: functionality and usability. The specifications related to functionality describe the basic capabilities of the system and tend to limit the hardware of the design. The specifications related to usability describe the ease of use of the system and simultaneously dictate the software and hardware.

As previously mentioned, the system was initially designed to have the ability to transmit and receive data at a relatively low FFC-approved industrial, scientific, and medical (ISM) frequency band. Transmitting within the ISM band would allow the device to be operated and tested without a license because it is for research purposes only. Because the operational frequency changed, the requirement specifications must also reflect this change. Regardless of the frequency, it is imperative that the frequency does not impose upon other frequency ranges that have been purchased by or leased to other companies or organizations. Failure to stay within this band could result in legal action against the sponsor or the students involved.

Because the MEMS sensor will be positioned on a motor, the transceiver device must be located far enough away that it does not impede the function of the motor but close enough to still receive and transmit information to the sensor. The sponsor has determined that the transceiver shall have a minimum transmission range of 1 meter. Ideally, the range of the device should be larger than 1 meter, but the range should not be so large that it interferes with other devices.

Additionally, the transceiver was designed to have a low power consumption. This reduces the heat generated within the system as well as reduces the power lost by the transceiver. Consequently, this also reduces the cost of operation. The goal power consumption is less than 10 W.

One final hardware specification restricts the operating temperature range between -40° C and 85° C (-40° F and 185° F). This constraint is not directly imposed by the customer; rather, it is the standard operating temperature range of most electronic components. The temperature range is wide enough so that this specification was easily achieved.

For the device to be useful to the customer, it is crucial that the transceiver functions with a reliable communication protocol. The loss of data during transmission or the failure to store data could result in the loss of necessary information. Therefore, only established and reliable communication protocols were used in the design of this device.

In addition to being reliable, the system must be adequately responsive. The setup and response times designed to be at a minimum so that information may be gathered and used in real time. Response time should not take more than a couple of minutes.

Further, the transceiver should be capable of storing any information which is gathered into a data analytics software. The customer has requested a storage functionality so that stored information may be used and analyzed in non-real time.

The GUI, which was designed as part of the software deliverables, provides the customer with a simple yet organized display of collected data. This interface allows the customer to easily interpret the information collected by the transceiver. The GUI shall allow operators to zoom in and out of data points, scan along the graph, and toggle between linear and logarithmic scales.

Finally, the customer has requested that a list of future improvements be included with the finished product. Because this system is the first revision of its kind, it will have areas in which the design or functionality may be improved. The customer will use this information in future revisions of the system.

Additional design constraints are dictated by the Federal Communications Commission's (FCC) requirements for transmitters and receivers. Some of the relevant standards are listed below [1]:

- Non-licensed transmitters are prohibited from causing interference to licensed transmitters and must accept any interference that they receive.
- Operators do not need a license to operate "non-licensed" transmitters.
- Low-power, non-licensed transmitters must have permanently attached antennas or detachable antennas with unique connectors
    - We will use a permanently attached antenna
- Depending on the 27.X MHz we will be using, the emission limit is either 30 μV/m (at 30 m) or 10,000 μV/m (at 3 m).
- The design should be tested for compliance with FCC standards.

2.4 House of Quality Analysis

To easily describe the relationship between the customer's requirements and the factors which affect those, a House of Quality diagram is presented in Figure 1. The House of Quality diagram shows a visual correlation between important engineering requirements and marketing requirements mandated by the customer and allows readers to easily understand the tradeoffs between these key factors. The relationship between these factors is separated into positive correlation, negative correlation, and no correlation. The strength of the correlation between the factors is denoted by an arrow for a weak correlation and two arrows for a strong correlation. The overall polarity of the related requirements can be separated into a positive polarity (denoted by a plus symbol) or a negative polarity (denoted by a negative symbol). We will use the polarities and correlations shown in this diagram to optimize our design.

			Engineering Requirements						
			Power Output	Signal Quality (SNR)	Cost	Response Time	Low Frequency	Transmission Range	g-Range
			-	-	-	-	+	+	-
Marketing Requirements	1) Citizens Band Frequency	+	↑	↑	↑	↓↓	↑↑	↑↑	↑↑
	2) Measurement Accuracy	+	↑↑	↑↑	↑↑	↓↓	↓↓	↓	↑
	3) Cost	-	↓	↓↓	↑↑	↑↑	↓↓	↑	↓↓
	4) Moderate Power Consumption	-	↑↑	↑↑	↑↑	↑	↓	↑	↓↓
	5) Transmission Range	+	↑↑	↑↑	↑↑	↓↓	↓↓	↑↑	↑
	6) Simple GUI	+	o	o	↑↑	↑	o	o	o
	Target		~10 W	10-15 dB	$1,093.50	5 secs	27 MHz	~1 m	25 g

Figure 1: House of Quality Diagram

Legend:

- ↑↑ Strong Positive Correlation
- ↑ Positive Correlation
- No Correlation
- ↓ Negative Correlation
- ↓↓ Strong Negative Correlation
- \+ Positive Polarity
- \- Negative Polarity

2.5 Block Diagrams

The block diagram, shown in Figure 2, provides a large amount of information in a single image. The broad purpose of this diagram is to visually show how the main components will interact and communicate with one another. The arrows that connect each component identifies the direction of communication as well as the inputs and output of each main component. The diagram also identifies the party responsible for the design of the components: the green blocks are to be designed by the senior design group and the blue block is to be provided by the sponsor. The block diagrams for the 27 MHz design (such as the design shown in Figure 2) and the 1 Mhz design are compared to one another below.

The diagram can be further simplified into its two main functions: signal transmission and signal reception. Many of the blocks within the design are multipurpose and are utilized in the transmission and reception stages.

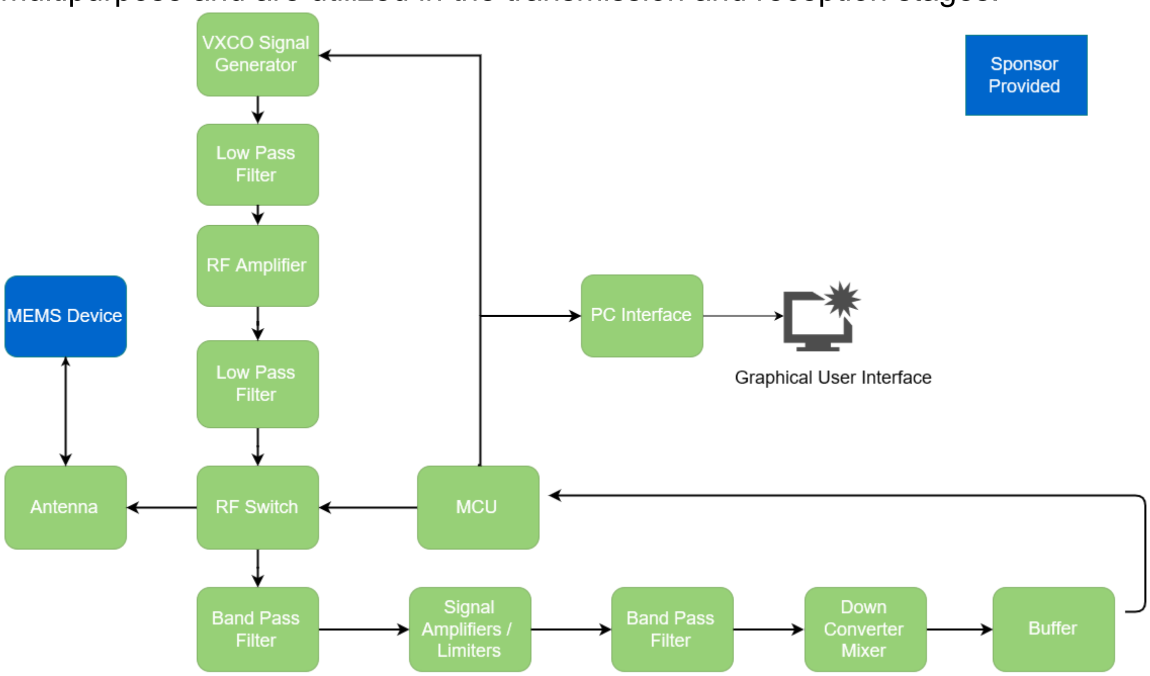


Figure 2: Overall Block Diagram for 27 MHz

The overall design for the 1 MHz system is shown in Figure 3 below. Many of the components, namely the RF switch, crystal generator, downconverter mixer, and redundant filters, were changed or removed entirely from the updated design.

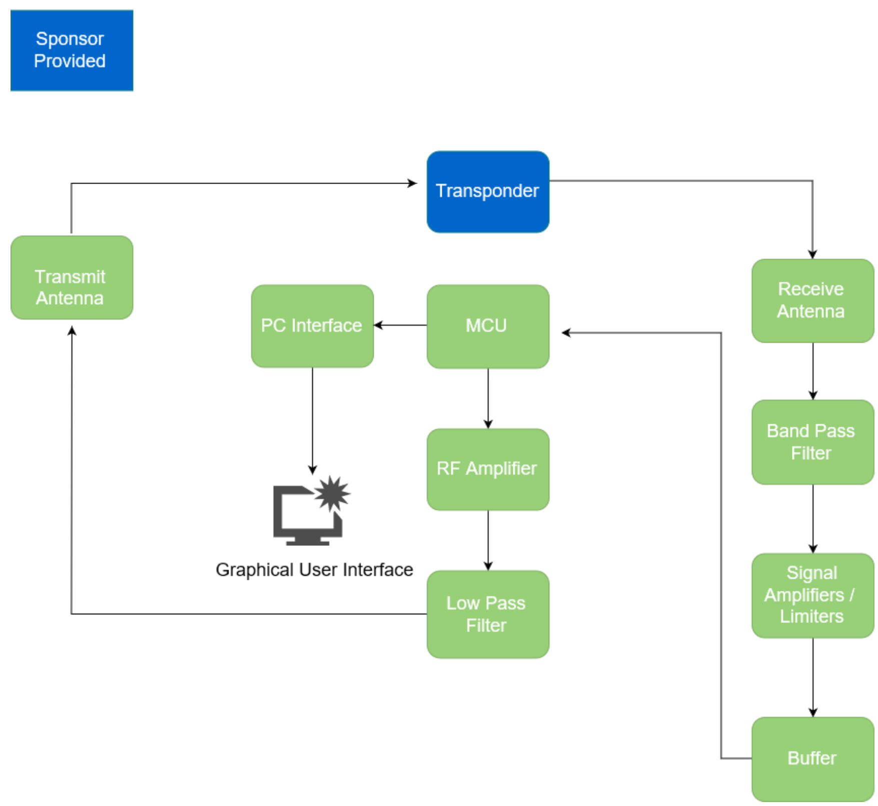


Figure 3: Overall Block Diagram for 1 MHz

Figure 4 below identifies the blocks which will be utilized in signal transmission. Most of the components used during signal transmission are the components connected to the signal generator and RF switch. As such, the filtering and PC stages are not utilized during transmission.

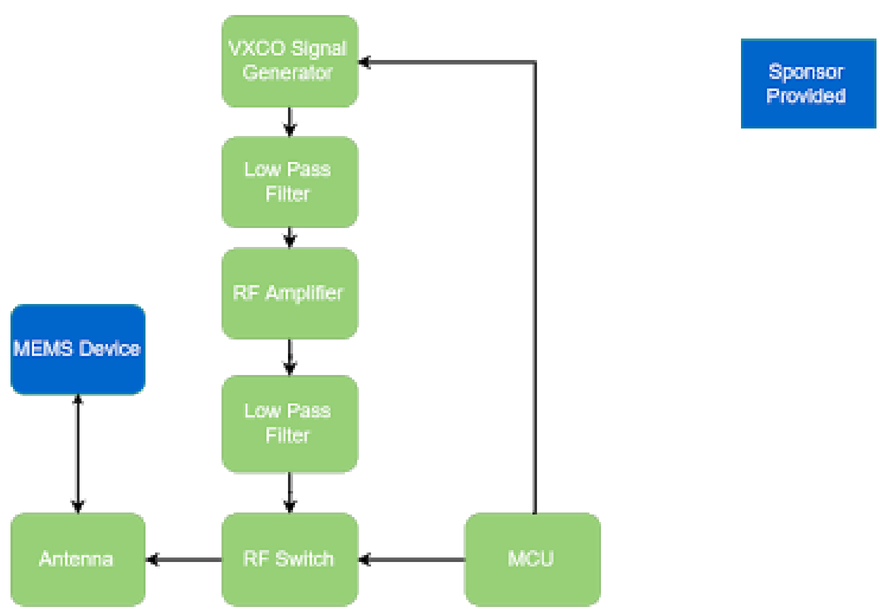


Figure 4: Signal Transmission Block Diagram for 27 MHz

Similarly, the updated block diagram for the system transmission scheme for the 1 MHz system is shown in Figure 5 below:

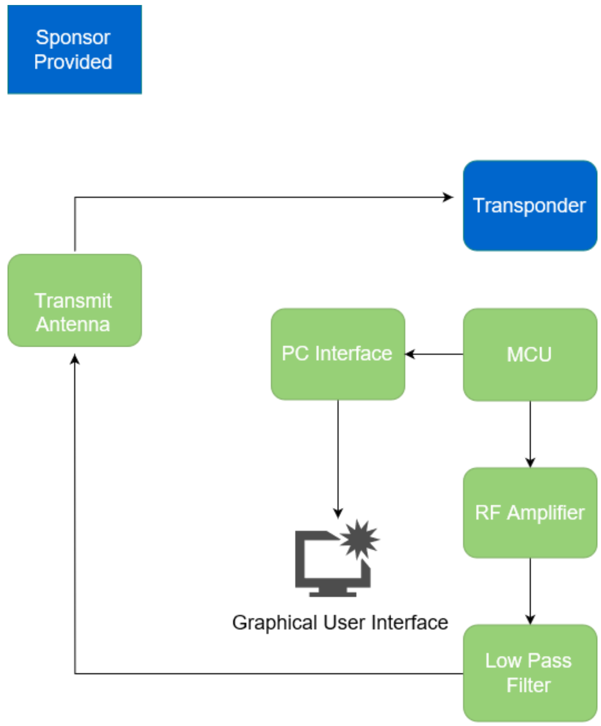


Figure 5: Signal Transmission Block Diagram for 1 MHz

The final block diagram identifies the components which will be used during the signal reception phase. Many of these stages serve to filter and convert the incoming signal into usable information that can be analyzed after they have been received. Figure 6 below shows the signal reception block diagram as designed for the 27 MHz frequency band.

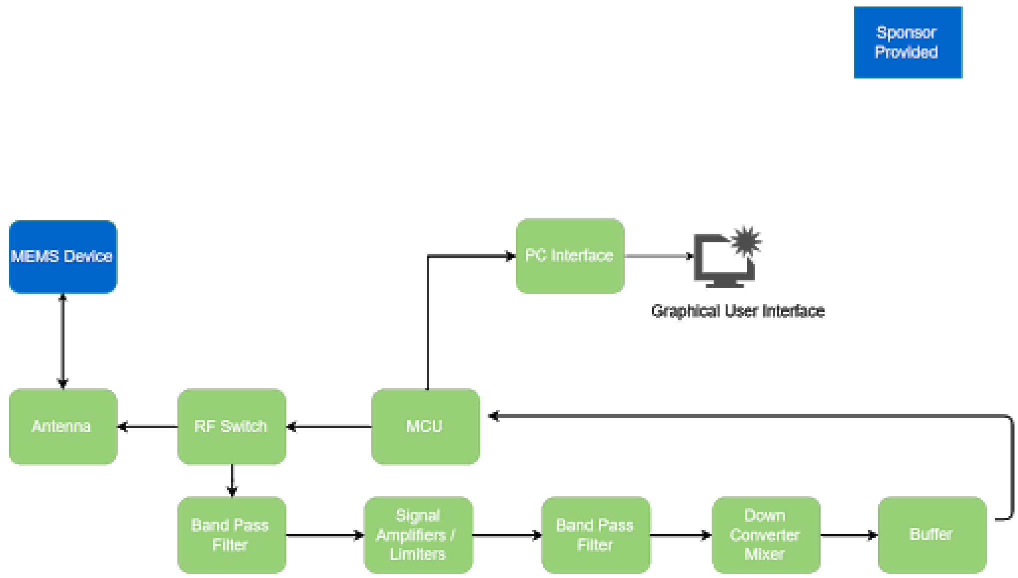


Figure 6: Signal Reception Block Diagram for 27 MHz

Similarly, the updated block diagram for the system transmission scheme for the 1 MHz system is shown in Figure 7 below:

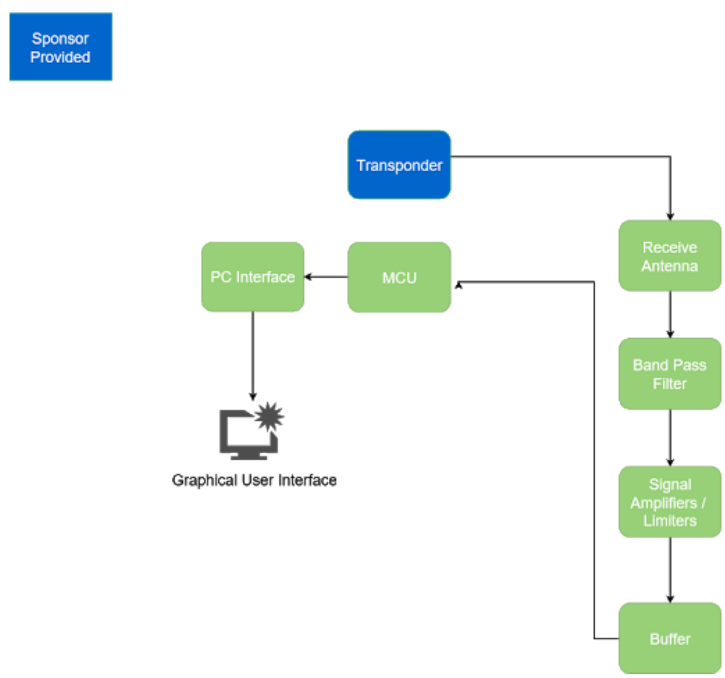


Figure 7: Signal Reception Block Diagram for 1 MHz

3.0 Research Related to Project Definition

An integral part of the design process is researching what technology is currently available and what designs already exist. In the case of application engineering, where a customer has a problem and needs a solution, research solidifies your understanding of the customer's needs and directs product development.

Research of preexisting technology is especially important in the realm of application engineering. Care should be taken to verify that the proposed solution to a customer's problem has not already been designed or patented. If a similar solution already exists, the proposed solution should be sufficiently different from preexisting ones so that no patent or copyright infringements occur.

3.1 Predictive Maintenance Technologies

The use of predictive maintenance (PdM) has become increasingly common in electrical and mechanical systems. The goal of predictive maintenance "is first to predict which equipment failure might occur, and secondly, to prevent the occurrence of the failure by performing maintenance" [2]. It is used to prevent disruptive maintenance work on a system and reduce the costs associated with operating a system.

A variety of predictive maintenance technologies are currently in use and the type of technology used depends on the application. The technologies used for the monitoring of electric motors such as infrared thermography, ultrasonic noise detection, and vibration analysis will be discussed in depth here [3].

Infrared thermography uses temperature as a metric to perform machine health diagnostics [3]. Because heat is usually a key indicator for machine and equipment malfunctions, manufacturing plants can track the temperature of equipment with temperature profiles. These profiles allow technicians to identify unusual readings and apply predictive maintenance. However, infrared thermography does have some key shortcomings. For example, not all machine equipment is suitable for infrared measurement and therefore not all equipment can be diagnosed if only infrared thermography is used. Additionally, to use thermal thermography, someone must carry a portable thermal imager from one machine to another to check for unusual temperature readings. In larger manufacturing plants with a lot of equipment it may require multiple technicians or an entire team to complete the job. While this method of system diagnostics may decrease costly maintenance, the use of manual human labor increases the cost of operation.

Ultrasonic noise detection is simpler and less expensive than other predictive maintenance technologies [3]. The ultrasonic method utilizes microphones to record sounds of different machine components. Like the frequency analysis technologies, ultrasonic analysis detects changes in ultrasonic wave emissions to diagnose the health of the system. Ultrasonic vibration profiles allow diagnoses to be performed across multiple devices because different failures will cause unique vibrations profiles.

Vibration analysis is a technique which will be used throughout this project. Like ultrasonic noise detection, vibration analysis operates by detecting changes in the oscillation and vibration of the system [3]. This method of predictive maintenance is typically used to detect unbalance, misalignment, resonance problems, and mechanical looseness or weakness.

3.2 Existing Similar Projects and Products

As discussed in the paragraphs above, the concept of non-invasive structural analysis is not a novel idea. For instance, Analog Devices currently manufactures vibration analysis systems for wireless measurements to obtain data on the structures health [4]. The device is very similar to ours in its functional topology, but this MEMS wireless vibration system operates at a frequency range of 862-928 MHz. Due to the higher frequency, it is not optimized for the application that ours will be intended for. Additionally, the Analog Devices design is now obsolete and so it is no longer available.

Another company, Valmet, does still produce wireless MEMS sensors and transceivers for vibration analysis. The package by Valmet is similar in its functionality in that the major components of the systems consist of a MEMS sensor, a wireless transceiver with antenna, and signal processing units to interpret the response of the MEMS device [5]. However, their device is designed to operate at a significantly lower frequency (in the kHz range) and therefore is not capable of operating in the desired ISM band.

3.2 Relevant Technologies

The use of preexisting technologies and design procedures will ease the design process. Some topics, such as RFID, will be discussed to show how the transceiver design differs from current technology. Most technologies presented will be discussed in depth to compare the applications and variations of each concept. The technologies presented here will be used to implement or inspire the design of the transceiver package.

3.2.1 RFID

Radio-frequency identification, more commonly known as RFID, works in the way of transmitting a signal to electromagnetically excite a device via “interrogating” radio waves [6]. This interrogating radio wave is typically set to the 13.56 MHz range. After exciting the RFID tag, the reader receives an RF response which is used to determine the ID of the tagged device. Unlike other identification technologies, RFID does not require the tag to be within sight of the reader.

This project is similar in the transmission portion of RFID because a signal will be used to excite the MEMS sensor. Unlike RFID, the exciting RF signal be sent at a different frequency. A second notable difference occurs when the RFID receives the response as a single constant value. This is different from the transceiver system in that it will have a varying frequency that will need to be analyzed. This frequency variance is the key to the vibrational information which the device will be monitoring.

3.2.2 Spectrum Analyzers

There are two main types of spectrum analyzers. The first, known as a swept-tuned analyzer, operates by down-converting the signal to a center frequency [7]. Next, it “sweeps” through this down-conversion with a voltage-controlled oscillator through a bandpass filter to obtain a plot of magnitude and frequency.

The second type of spectrum analyzer is based on analog-to-digital converter technology [7]. This type of analyzer samples the incoming frequency using analog to-digital-converters. The Fourier transform analyzer computes the Fourier transform using an analog-to-digital converter to obtain the information for the transform computation.

The goal of the design is to view the signal in the same way a spectrum analyzer would view it but on board the system. Through this analysis, the vibrational information of the system can be determined. The system will operate as a hybrid of the two spectrum analysis methods. First, the signal will be down-converted. This will be performed prior to processing for the sake of alleviating the constraints on the ADC. Since the amount of down-conversion required is known, the onboard microprocessing unit will be used to back calculate the actual frequency of the signal for the use of the customer. Additionally, the microprocessor will be used to modulate the voltage-controlled oscillator for a tuned transmission of the device for efficient sensor excitation. The system will still use a bandpass filter to refine the signal because it is within a known range, but the signal will be processed digitally.

3.2.3 Limiters

In signal processing, limiters are circuits which attenuate (or limit) the strength of signals above a certain threshold while allowing signals below this threshold to pass unaffected [8]. In most cases, limiting is done as a safety measure. If a signal is too powerful, it can damage the equipment that it is passing into. However, limiting may also be performed to protect the integrity of the signal that is being processed and to ensure that the next stage is provided with a constant level of signal. If a signal is not limited, it could introduce undesired distortion.

The circuit design will employ a series of limiters to help process the signal. Since the signal being received is constantly decaying, the amplitude must be normalized to process all the available information. This normalization is completed using operational amplifiers in conjunction with the limiters. By using operational amplifiers, the largest and smallest part of the signal being transmitted will be amplified by the same amount. However, if the waveform is then limited by a diode-based voltage limiter, the peak and trough of the waveform will both be normalized to the same voltage. With each amplification stage, the slope leading to the cutoff point of the voltage level is increased in its steepness. This means that the wave will resemble that of a square wave. A square wave filter, or any filter that removes the upper harmonics of the wave, will be enough to convert this signal back to the center frequency sine wave at the same height across the time spectrum of amplitude decay.

The accuracy of a fast Fourier transform is directly based on the number of samples taken of the signal in question. By implementing limiters in the design, the decaying signal can be amplified and limited to the point where the entire signal resembles something like a square wave. After transforming the amplified signal to a square wave, it is then converted to a sine wave by filtering the signal prior to the down-conversion.

3.2.4 Filters

Circuit designs which have a frequency components typically require the use of filters. Filters are electronic circuits that have been designed to remove unwanted frequencies from a signal [9]. Filters are comprised of resistors, inductors, and capacitors, and the combination of these three elements allows for the formation of a variety of filters. Filters are typically divided into two categories: passive filters and active filters. Passive filters are designed using only resistors, inductors, capacitors, or a combination of these components. Active filters are also made with resistors, inductors, and capacitors, but also include active components such as transistors or amplifiers.

The filter types which are relevant to the transceiver design are the low-pass filters and bandpass filters. Low-pass filters are a type of filter that allows low frequency signals to pass while attenuating signals which have a frequency higher than a selected threshold (called the “cutoff frequency”) [9]. A bandpass filter operates in a similar manner by allowing a certain range of frequencies to pass and attenuating any signals which have frequencies outside of this passband.

There are several common filter types that are typically used in designs. One of these filters is the Butterworth filter (also known as the maximally flat magnitude filter) [19]. This nickname is due to absence of ripples in the frequency response. Rather than display a ripple, the frequency response will instead roll off towards negative infinity as the frequency leaves the passband. Another advantage of this filter type is that the Butterworth filter has a very high degree of linearity in the phase response.

A second important filter design is the type one Chebyshev filter. One advantage to the type one Chebyshev filter is that the filter has a very steep roll off which is preceded by a ripple [20]. The drawback to this design is that the design procedure is more difficult than that of the Butterworth filter.

Unlike the type one, the type two Chebyshev filter lacks the ripple effect and it does not roll off to negative infinity as the frequency leaves the passband [20]. However, it does feature a ripple in the stop band which is undesirable for this design.

The final main filter type is the elliptic filter. The elliptic filter has an incredibly steep roll off in the frequency response, but the design is far more complicated and requires more components than the Chebyshev filters or the Butterworth filter [21]. The response is like a combination of Chebyshev type 1 and Chebyshev type 2 filters because it has a ripple prior to the roll off and then bounces instead of approaching infinity. This filter is beyond the requirements of our project and significantly increases the complexity of design, so this filter design will not be implemented.

Figure 8 shows the general architecture demonstrating the complexity of the layout and components required of each filter type. It is important to note that the Chebyshev filter shown is a modified version and therefore slightly different than the type one and type two. The Chebyshev filter shares the same architecture as the Butterworth filter, but the components calculated would have different values. The selected Butterworth filter with calculated values and its corresponding simulation is discussed in further detail in section 5.

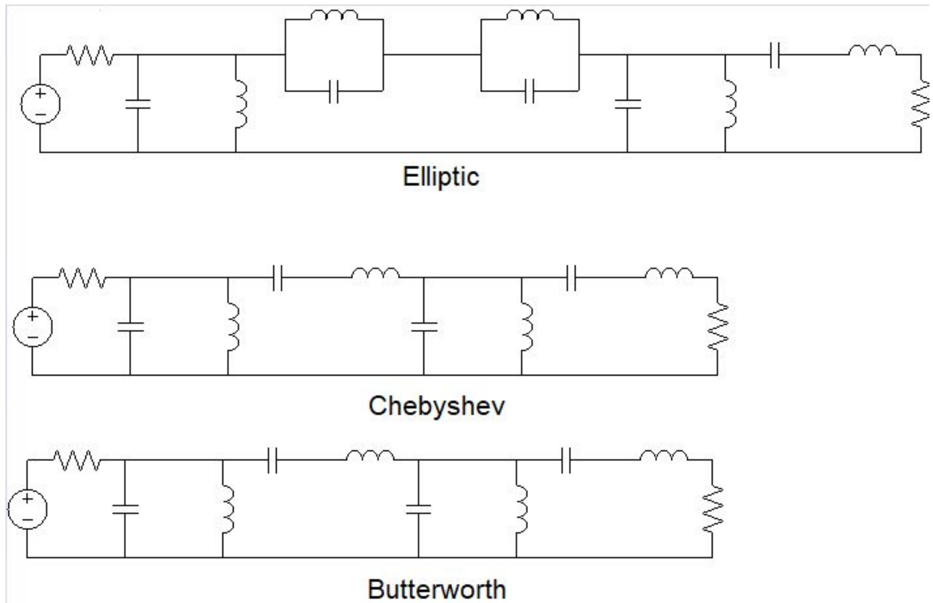


Figure 8: The Architecture of the Elliptic, Chebyshev, and Butterworth Filters

The next figure (Figure 9) compares the graph of the frequency response of the Butterworth, Chebyshev, and elliptic filter types.

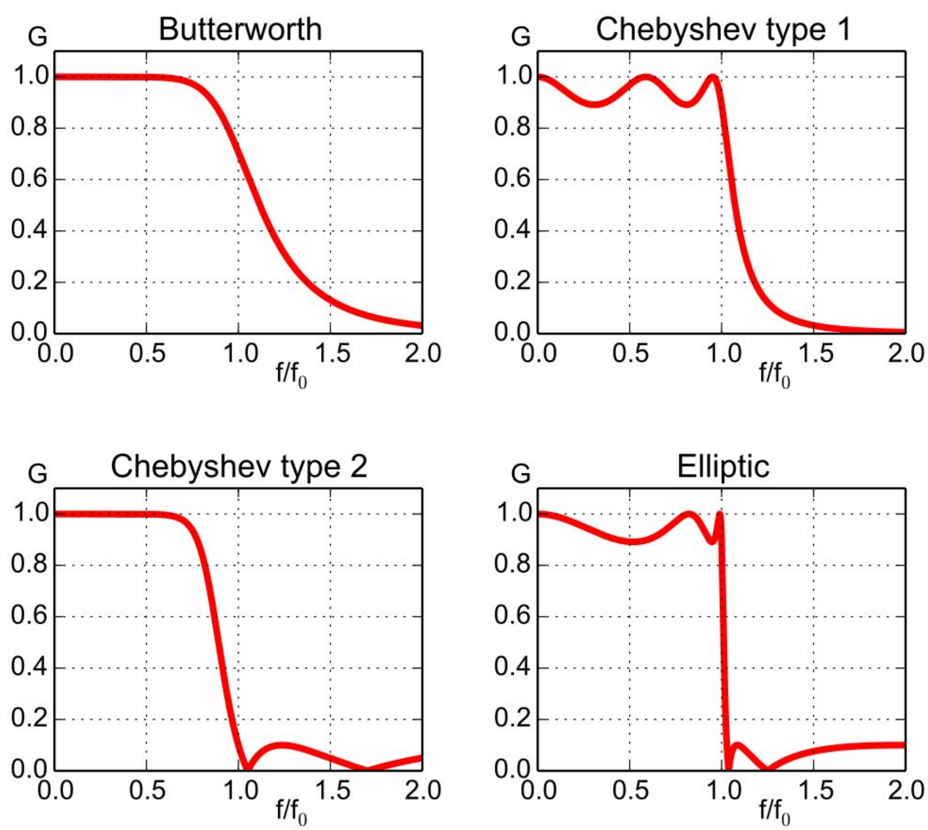


Figure 9: Frequency Response of Selected Filter Types

Passive filters will be employed in the design to filter the signal. Active filters will not be used due to the high frequency nature of the design. The signal will be filtered passively and amplified separately. Passive filtering has been chosen over actively filtering the signal because active filtering would require operational amplifiers with gain bandwidth products above 10 GHz and operational amplifiers with this gain bandwidth product are unattainable.

3.2.5 Operational Amplifiers

Amplifiers are used to amplify both the output and input signal. To achieve the high output current needed, multiple operational amplifiers were used in a driver-and-slave configuration.

The gain stages on the receiving side of the signal employs operational amplifiers placed in series. This configuration will achieve large signal gains without being affected by the gain bandwidth constraints. To prevent distortion of the signal, only operational amplifiers with very low slew rates will be considered for the design.

3.2.6 Frequency Mixers

Radio frequency mixers (RF mixers) are devices which change the frequency of an electromagnetic signal by modulating or demodulating the signal. Mixers have three ports: an RF input port, local oscillator (LO) input port, and intermediate frequency (IF) output port. Depending on the type of mixer, it alters the frequency of an electromagnetic signal by adding or subtracting the frequencies of the inputs [10].

Downconverting mixers are mixers that subtract one input frequency from the other to achieve a smaller desired frequency [11]. Downconverters can be further categorized as low-side downconverters and high-side downconverters. The distinction between these is that the LO frequency is subtracted from the RF frequency in low-side downconverters and the RF frequency is subtracted from the LO frequency in the high-side downconverter. Rather than subtracting input frequencies, upconverting mixers add the intermediate frequencies of the inputs together to obtain the desired radio frequency.

There are four important parameters to be considered when choosing mixers:

1. Conversion loss or gain - this measurement quantifies the conversion loss of a passive mixer or conversion gain of an active mixer.
2. Input intercept point - this is the point at which the output power of the undesired intermodulation product is equal to the desired intermediate frequency output.
3. Noise figure - this parameter defines the level of noise generated by the mixer.

4. Dynamic range - this value is the range over which the mixer can operate as expected.

3.2.8 Microcontroller Architectures

There are two main categories of microcontroller architecture: the Von Neumann architecture and the Harvard architecture [22]. The Von Neumann architecture, developed by a Princeton physicist and mathematician, is a digital computer architecture comprising of five major components:

- Memory for data and instruction storage
- Processing unit containing registers and the arithmetic logic unit (ALU)
- Input and output
- External data storage.
- Control unit (program counter and instruction registers)

The Von Neumann architecture operates on the stored-program principle. In the stored-program design, both program instructions and data are stored in the same manner [23]. This allows program instructions to be rewritten within the computer's memory. This was a significant advancement of computer technology and has remained the most widely used computer architecture in the world since its invention.

Variations of this architecture have been invented to overcome shortcomings of the Von Neumann architecture and to optimize computer performance. One shortcoming that must be overcome is the structuring of this architecture. Von Neumann architecture is structured such that an instruction to fetch data and the actual transmission of data cannot happen simultaneously. One instruction needs to occur before or after the other. This effectively bottlenecks the system performance. However, the use of a CPU cache helps to increase computer speed via advanced statistical and engineering methods [22].

Unlike the Von Neumann architecture, the Harvard computer architecture operates by physically isolating the instructions and data from one other [22]. This is achieved in part by separating the data addresses from the instruction addresses. This effectively overcomes the bottleneck present in the Von Neumann architecture. The Harvard architecture improves system speed as the buses dedicated to data transmission and instruction storage are separated.

Variations of the Harvard architecture also exist. One such variation, called the Modified Harvard architecture, lightens the rule of separation between the instruction storage and data storage [22]. While still retaining the general Von Neumann architecture for the CPU-memory interface, it uses the Harvard architecture for the cache. The Modified Harvard architecture allows direct access between the CPU and external memory. This can be achieved without having to copy the data into the actual computer memory. This saves precious computer memory as well as time. Due to these advantages over a traditional Von Neumann architecture, the Modified Harvard architecture is increasingly being adopted in newer microcontrollers, processors, and computers.

3.2.9 Fixed-Point and Floating-Point Digital Signal Processors

Another key component that was considered in the MCU is the fixed-point vs. floating-point digital signal processors. A fixed-point processor uses 16 bits to express more than 65 thousand possible numbers [18]. Similarly, the floating-point processor uses 32 bits and can express more than 4 billion possible patterns. As such, a fixed-point processor with a uniform decimal point placement can only represent a relatively limited array of decimal values when compared with the floating-point. These two categories of DSPs must be selected based on the application. The kind of processor selected has a direct impact on the dynamic range as the dynamic range is defined as the largest and smallest values that can be represented. In cases where dynamic range and resolution are key design specifications, floating-point processors are the better option.

In addition to affecting the range and resolution, the type of processor used has a direct impact on the precision of the device. Smaller gaps between the numbers, a key advantage of floating-point processors over fixed point processors, means that the device is more precise. This is due to the decimal numbers not being truncated so that the approximations more accurate.

3.3 Strategic Components and Part Selections

When choosing components for our designs, we focused on a few general qualities to narrow our search.

First, the functionality of each part was considered, and the datasheets of each component being considered was carefully read. If the component was unable to function within the desired frequency, voltage, current, power, gain restrictions, or had too few pins, the part was rejected.

Second, the cost for a single component was considered. Most of the parts chosen for our design are less than a couple of dollars to keep the production cost at a minimum. Some of the major components, particularly the frequency sensitive components, were more expensive. If the available parts are more than a few dollars, the part will be selected using the other criteria.

Third, the availability and lead time of the component was considered. To keep the project moving at a reasonable pace, we opted to select parts with short lead times or large availabilities when possible. This allowed us to quickly replace parts when a component broke or did not function as expected.

Fourth, we considered where the component was within its product lifecycle. Since the customer hopes to manufacture the design in the future, it was important to choose components that had not reached the obsolescence stage. Therefore, we chose products that are readily available and suggested for new designs.

Finally, we considered the physical footprint of the component. Whenever possible, we chose a part that was large enough to be handled or soldered as needed yet small enough to minimize the size of the PCB. When possible, the selected components fell between 1206 and 1218 imperial size. However, when components within this size range were unavailable, compromises were made.

Another factor that helped limit the part selection process is Restriction of Hazardous Substances (RoHS) compliance. This directive, which restricts the amount of hazardous materials allowed in a single device, is mandatory for countries in the European Union but is not required for manufacturers within the United States of America [13]. However, since most electronic components available are already RoHS compliant, we attempted to choose only RoHS compliant components.

3.3.1 Downconverter Mixer Selection

Finding mixers that operate at the frequency of the incoming signal and able to down-convert that signal to a lower frequency for digital signal processing is highly crucial to the design of this project. According to the Nyquist criterion, in order for the ADC to faithfully reproduce a signal, the sampling frequency of the ADC/MCU must be at least twice the highest frequency component in the baseband signal [14]. For an incoming signal around 27 MHz, an ADC would require a sampling frequency of 54 MHz to satisfy the Nyquist criterion. However, this is impractical. As such, a downconverter is required to shift the baseband signal to a lower frequency for it to be digitally processed.

When selecting the downconverter frequency mixer for the project, a few general and engineering specific parameters were considered. The general parameters include cost, lead time, manufacturer credibility, compatibility, ease of use, and low power. The engineering specific parameters can be broken down into six categories:

- Conversion Loss
- Input Intercept Point
- Noise Figure
- Dynamic Range

- Isolation
- Spurious Interference

Conversion Loss: This parameter relates to the gain of the mixer. It is a measure of the ratio of the output frequency power to the input frequency power at a specified local oscillator frequency [45]. For the given frequency range, it was important that a flat conversion loss profile was maintained to avoid/minimize distortion in the output.

Input Intercept Point: This parameter relates to the measure of linearity of the mixer [46]. For devices with nonlinear transfer function such as a mixer, it was imperative that the selected device must have a high enough IP3 (linearity) in the frequency range of operation of the mixer. Linearity of the device is important because non linearities in the *V=IR* general model of the device leads to instabilities and specification deviations.

Noise Figure: This relates to how well the device can process signals in the presence of noise [47]. It was an incredibly important parameter as it is an overall measure of noise in the system. As such, it was important that mixers with low noise figures be selected to maintain signal integrity.

Dynamic Range: This is the ratio of the highest input signal level to the lowest input signal level [48]. The highest input signal level is determined by several factors such as the IP3 point.

Isolation: This parameter relates to the measure of leakage, interference or feedthrough from different ports of the mixer [49]. It was important to ensure that the device selected has high port isolation to avoid unwanted power loss or signal distortion because of intermodulation which can be incredibly difficult to filter out thereby compromising signal integrity and resulting in wrong measurements.

Spurious Interference: This is a measure of the range of frequencies that may come into the system and be down-converted to the IF band thus creating an unwanted signal interference or noise [50]. Any nonlinear device is susceptible to this phenomenon and great care must be taken to ensure that the mixer selected is not significantly affected by spurs.

Table 1 shows the various devices that were considered, and all the specifications listed above. Although this device was removed from the 1 MHz system design, the subsequent paragraph after the table discusses why the LT5560 Analog Devices mixer was selected as the mixer that best suited our needs for the 27 MHz design.

Table 1: Comparison of Downconverter Mixers

Device	**LT5560**	LT5526	LT5521	CSM4T17	SA 605
Manufacturer	Analog Devices	Analog Devices	Analog Devices	MACOM	NXP USA
Operating Frequency Range	100kHz-4 GHz	20MHz-2 GHz	10 MHz-3.75 GHz	1 MHz-3.4 GHz	0-500 MHz
Conversion gain (dB)	2.4	0.6	0.5	9	13
IIP3 (dBm)	9	16.5	24.2	25	10
Noise Figure (dB)	9.3	11	12.5	1	4.6
Isolation(dB)	52	52	40	35	
Max Power(dBm)	18.26	21.86	20	20	17.16
Size (mm)^2	9	16	16	117.03	19.36
Operating Temperature. (C)	-40 to +85	-40 to +85	-40 to +85	-40 to +85	-40 to +85
Cost	$1.61	$3.40	$4.95	$59.26	$2.96
Lead Time	Available	Available	Available	Available	Available

Two of the biggest factors in the selection of the LT5560 mixer from Analog Devices was the size and cost. Unlike the other mixers listed, the LT5560 is less than 10 mm and will minimize the overall size of the PCB. Additionally, the isolation of the device is higher than most of the other mixers and therefore will be less prone to signal and power loss.

3.3.2 RF Switch Selection

The RF switch specifications differs slightly from normal engineering specifications. One major difference is bandwidth definition. For RF switches, bandwidth is defined as the maximum frequency component that can be routed by the switch without sacrificing key performance metrics [51]. This definition of bandwidth is different from the regular definition which is just an approximation of -3dB points of the frequency range. To ensure that the signal being transmitted did not suffer significant attenuation by the RF switch, the switch was selected such that its bandwidth was higher than the highest frequency component of the transmitted signal. The relationship between the -3dB cutoff point and the rise time of the RF switch is given as:

$0.35/\tau$ = (3dB Point)

Where τ is the rise time of the RF switch. The rise time of the RF switch has a direct impact on the overall response time of the device. As such, it was important to select an RF switch with a relatively short rise time while also considering other factors such as cost, lead time, etc.

Other specifications that are relevant to the RF switch selection include

- Insertion Loss
- Frequency Range
- Isolation
- Power Handling
- Operating Life
- Settling Time

Insertion Loss and Isolation: Like the RF mixers, insertion loss (also called isolation) is the loss of signal power due to a device being inserted in a transmission line [52].

Frequency Range: This is the range of frequencies that the RF switch can operate in with acceptable performance [53].

Power Handling: Power handling refers to the maximum amount of power that a switch can withstand [54]. If the RF power entering the switch exceeds the rated power handling, the switch will be damaged and may experience failure.

Operating Life: The operating life of a switch is the number of cycles that switch will complete before it begins to fail. This life cycle refers only to the electrical life and accuracy of the RF properties; a RF switch may continue to mechanically work long after the switch becomes inaccurate. For our device to be functional for as long as possible, a long operating life is desirable. A typical operating lifetime of an RF switch is one million cycles.

Settling Time: The settling time is the amount of time that it takes for a device to reach and stay within a desired error range of the final value [55]. A small setting time means the system reaches the desired value quickly, and so a small settling time is preferable.

Table 2 below shows the different RF switches that were purposefully considered in congruence with the design specifications. The subsequent paragraph explains why the HMC199AMS8/199AMS8E RF switch was selected.

Table 2: Comparison of RF Switches

Part	HMC284AMS8GE	F2912	**HMC199AMS8 / 199AMS8E**
Manufacturer	Analog Devices	IDT	Analog Devices
Switching time	5 ns	1.1 us	20 ns
Insertion Loss	0.5 dB	0.4 dB	0.3 dB
Isolation	45 dB	71 dB at 1GHz	25 dB
Operating Frequency Range	DC - 3.5 GHz	300 kHz - 8 GHz	DC - 2.5 GHz
Cost	$3.46	$4.75	$2.54
Lead Time	15 weeks; can ship immediately	20 weeks; can ship immediately	7 weeks; can ship immediately

The HMC199AMS8/199AMS8E from Analog Devices was ultimately chosen due to its comparatively low insertion loss and it had the lowest cost and shortest lead time of the devices considered.

3.3.3 MCU Selection

The microcontroller selection was one of the most important in the parts selection process. Due to the centrality of the MCU in the functionality of the device, selecting an MCU that can perform excellently without sacrificing any of the design specifications is important. Before proceeding to select the MCU, there were some general factors that had to be considered.

First, a list was made of hardware interfaces that the microcontroller would need to support. The hardware interfaces can be broadly classified into two categories: communication interface and digital inputs and outputs (such as the ADCs, PWM, etc.). Ultimately, the communication interface that was best suited our needs was selected following intensive research, design comparisons, and consultation of the design specifications.

Three communication interface options were available for the MCU: Serial Peripheral Interface (SPI), Inter-Integrated Circuit (I2C) and UART. Because the design specifications give a required response time, the speed of communication has a direct effect on the overall response time. As such, ensuring that a relatively fast but reliable communication protocol (or hardware in case of UART) is chosen.

The I2C communication protocol, while powerful, does not suit the requirements of this project. I2C communication is more suited for multiple devices sharing the same bus, which does not apply to the project design [16]. SPI, while faster than other protocols, does not allow for error checking [17]. The UART communication system is a relatively simple one that uses two pins (full duplex) for communication between the MCU and a local computer via USB [15]. This allows for code to be written directly on the local computer and then serially transmitted to the MCU through an onboard USB-serial converter. This option suits the design requirements. Since only one microcontroller is being used, it does not make sense to use communication protocols that apply to communication between multiple microcontrollers. As such, the UART-USB communication interface is the best option.

After determining the appropriate communication protocol, the general software architecture is considered. The software architecture plays a key factor in the type of microcontroller to be used. This MCU must have good processing capabilities to perform the required Fourier transform and to do this relatively quickly. The processing power of the MCU is one of the major components that determines which microcontroller is selected.

Third, the hardware architecture is to be considered. Some important considerations include selecting an 8-bit processor vs a 16-bit or 32-bit ARM. The central issue in this process involves looking at processors that can perform Fourier transforms relatively quickly to reduce the response time.

Fourth, the memory needs of the microcontroller are to be analyzed. This includes both flash memory and random-access memory (RAM). Given that there are multiple other devices to be controlled by the MCU (such as switches, mixers, and transmitters), it is important that the MCU selected can store enough variables and working memory (RAM) required for computational purposes and multiple device control.

Fifth, in the design of this project, ensuring excellent resolution, precision and dynamic range is very important because accurate and precise measurements must be taken. Due to these reasons, the decision was made to use a digital signal processor with a floating-point unit.

It should be mentioned that there was an intentional design decision to use an actual DSP as opposed to a regular microcontroller or a microcontroller in conjunction with a computer. This is because the DSPs have been optimized to execute key digital signal processing algorithms (Fourier transform, Infinite Impulse Response Filter, Finite Impulse Response Filter, etc.). An example of this is a simple sum of products (SOP) algorithm executed on a PC vs on a generic digital signal processor microcontroller. The SOP is a simple algorithm that calculates a new value, x, that is the sum of partial products of two data arrays. The products of the data arrays are added together. This can be a fixed-point operation or a floating-point operation. In a standard PC configuration, this algorithm must execute the for loop almost forty times assuming a step size of 4 and two data arrays of 4 integer elements. This is due to the sequential nature of instruction execution. Under the same conditions, a DSP can perform the same algorithm in three steps. This is a significant reduction in number of executed instructions. As such, less computing is required. Also using a DSP instead of a PC contributes to a faster response time for the device while consuming less power.

Finally, the general considerations that goes into parts selection such as cost, part availability (lead time), power, and ease of use (coding and compilation) is discussed. We decided to select a microcontroller that supported analog-to-digital functionalities and can perform Fourier transform computations on a single chip while still maintaining high performance. Choosing a single device capable of these functionalities (instead of purchasing individual components) makes the design process less cumbersome.

The table below (Table 3) shows the different digital signal processors that were considered and lists out the performance specifications of each device. The subsequent paragraph discusses why the Texas Instruments F28335 microcontroller was selected as the best choice that suited the given design specifications.

. *Table 3: Comparison of MCUs*

Device	**TMS 320F28335**	TMS 320F28332	TMS 320F28234	TMS 320F28232
Frequency (MHz)	150	100	150	100
Floating Point Unit	Yes	Yes	No	No
On-chip Flash Memory (kB)	512	64	128	64
RAM (kB)	34	26	34	26
ADC (bits)	12	12	12	12
# of Direct Memory Access Channels	6	6	6	6
Timers-32 bit	3	3	3	3
Multichannel Buffered Serial Port	2	1	2	1
# of GPIO pins	88	88	88	88
External Interrupts	8	8	8	8
Instruction Cycle (ns)	6.67	10	6.67	10
PWM channels	6	6	6	6
ADC Conversion Time (ns)	80	80	80	80
Cost	$25.98	$17.60	$24.37	$20.81
Lead Time	Available	Available	Available	Available

Considering the options available, the TMS320F28335 was selected as it best suited the control and computational needs. Although it is slightly more expensive than the other available options, the financial constraint had to be overlooked. The F28335 microcontroller has a faster processing time compared to the other options except the F28234 microcontroller. However, the F28234 controller does not have a floating-point unit (a key requirement for obtaining precise measurements). Furthermore, the selected microcontroller (TMS320F28335), it has both fixed-point and floating-point units thus allowing us the flexibility to maximize the benefits of both architectures. The F28234 was also rejected because it operates at a lower frequency than the F28335 and has a much lower flash memory capacity. Furthermore, it costs about the same price as the selected microcontroller. The decision was to select the F28335 out of the other options as it had better performance metrics and cost roughly the same price as the others, especially the ones closer to the performance specifications of the selected MCU.

In order to ease the testing process and begin the programming earlier, a development board was acquired for the TMS320F28335 microcontroller. The board is designed to be used during prototyping so it included additional features such as header pins and a USB port [59].

3.3.4 Diode Selection

During the diode selection process, the two key parameters that were considered were the price and recovery time. These parameters were selected as most important given the device response time specified by the customer and financial constraints. Table 4 below shows the different diode options that were considered and the one that was eventually selected.

Table 4: Comparison of Diodes

Diode	Recovery Time	Vf - Forward Voltage	Vr - Reverse Voltage:	Size	Manufacturer	Price
1SS309 (TE85L, F)	4 ns	1.2V	80V	2.9 mm x1.6 mm	Toshiba	$0.48
PMBD9 14,235	4 ns	1.25V	100 V	2.1mm x 2.1mm	Vishay	$0.12
BAV21	50ns	1.25	250 V	2.85 mm x1.2 mm	Micro Commercial	$8.13

W-TP					Components	

Because the forward voltages and dimensions of the selected diodes were similar, these parameters did not contribute to the selection process. The 1SS309(TE85L, F) diode was consequently selected due to low price and a fast recovery time. Additionally, the lower reverse voltage better suits our needs.

3.3.5 Power Amplifier Selection

For this stage, a power amplifier is needed for the transmitter to meet the 10-watt specification required for the MEMS sensor as dictated by the customer. However, finding an RF power amplifier to deliver that much power at the required frequency is not an easy task. A comparison of various types of amplifiers was generated and is shown in Table 5 below for the component selection.

Table 5: Comparison of Operational Amplifiers

Amplifier Type	Op Amp Chain	Wide Band Amplifier	RF Amplifier
Size	Small and PCB Mountable	Usually Large and Standalone Parts	PCB Mountable
Frequency Range	Wide Band	Wide Band	Narrow RF Band of Operation
Power Output	When chained together approximately 1 Watt	Can be obtained up to 5 watts or more	Typically, less than 1 Watt
Price	Under $30	Approximately more than $30	Approximately more than $30

Due to the above analysis, the chosen amplification method will be operational amplifier based. This will ensure that all components can be cheaply integrated onto our board, fit our desired operation frequency, and fall within our power requirements.

Because operational amplifiers are available in a wide range of functionalities, several key features will limit the options: gain bandwidth product, slew rate, current output, voltage supply, number of channels, and size. These important considerations, as well as the manufacturer and cost, are described in Table 6.

Table 6: Comparison of Operational Amplifiers

Operational Amplifier	**LMH6703MAX/NOPB**	LM7171	LTC6268IS8-10#PBF	LTC6253IMS-7#PBF	LTC6253HMS-7#PBF	LTC6268HS6-10#TRPBF
Gain Bandwidth Product	1.8Ghz	-	4GHz	2GHZ	2GHZ	4GHz
Slew Rate	4.2KV/us	950V/us	1500V/us	500V/us	500V/us	1500V/us
Current Output	90 mA	100mA	80ma	90ma	90ma	80ma
Voltage Supply	+/-6V	+/- 5V	5.25	5.25	5.25	5.25
Channels	1	1	1	2	2	1
Size	4.9 mm x 3.9 mm	4.9 mm x 3.9 mm	3mm X 3mm	3mm X 3mm	3mm X 3mm	3mm X 3mm
Manufacturer	TI	TI	Analog Devices	Analog Devices	Analog Devices	Analog Devices
Price	$3.78	$3.21	$8.13	$6.70	$7.23	$7.23

The LMH6703MAX/NOPB operational amplifier from Linear Technologies was selected due to the superior slew rate. Since the operational amplifier will be used in the master-slave configuration (as shown in the power amplifier design section), the slew rate must be extremely large to avoid (or at least minimize) signal distortion. Although the gain bandwidth product is lower compared to the other operational amplifiers, it is sufficiently large enough for our purposes. Finally, the size of this device is slightly larger than the dimensions of the other op amps. However, the dimensions are still relatively small, and the size can be compromised for a superior slew rate. These features, combined with the lower cost per unit, led to the selection of this component.

However, when this device was chosen, the amount of gain achievable by this amplifier was overlooked. In the inverting configuration, the feedback resistor is suggested to be a minimum of 200 Ω for a gain of 10 [40]. Decreasing the value of the feedback resistor would increase the gain closer to the desired value, but also introduced noise in the form of peak overshoot and ringing. As such, a different operational amplifier had to be substituted for the LMH6703MAX/NOPB. The amplifier which was chosen was Texas Instruments LM7171. Like the LMH6703 amplifier, it was designed for high frequency use and could support a 1 MHz frequency [58].

3.3.6 Filters Selection

All filters used in the project will be designed subsystems. There are two major filter types that will be employed: the bandpass filter and the low pass filter. The function of the low pass filter is to cut off harmonics of the central frequency and preserve the signal as a sine wave. The bandpass filter will function to limit noise in the system as well as remove higher harmonics of the signal and keep the frequency as a sine wave.

The order of the filter helps determine the accuracy of the filtering procedure. The low pass filter was decided to be third order and the bandpass filter was determined to be fourth order. The use of a third order filter to limit transmitted harmonics is standard in industry designs. The fourth order filter was increased used in lieu of a third order because the amplification of that step was very large, and the noise would become too great and would disrupt the signal.

The filter type selected for this project is decided to be the Butterworth filter. This is due to several reasons: the Butterworth filter type required fewer components, our group was already familiar with the design process of the Butterworth, the Butterworth filter rolls off to negative infinity in the frequency response, and the response leading up to the cut off frequency is maximally flat. Any disadvantage of roll off rate with the Butterworth filter can easily be compensated by increasing the order of the filter.

3.3.7 Inductor and Capacitor Selection

The passive inductors and capacitors used in the project were selected so that the self-resonance frequency was at least ten times greater than the frequency of operation. If the frequency of operation were to ever reach the self-resonance of a component, then the component would act as a band stop filter and reject the signal that we are trying to pass [38]. If the self-resonance value is surpassed, the capacitor would be dominated by its parasitic inductance and the inductor would be dominated by the parasitic capacitance. To keep the product suitably close to the design calculations, the self-resonance of the component is selected to be at least 10 times greater than the frequency of operation. In most cases, the self-resonance of the selected component was significantly greater than 270 MHz.

This effect is shown in further detail in the below figure. The figure shows a low pass filter that has been simulated in Multisim. An AC sweep has been performed to demonstrate the actual characteristics of circuits operating at high frequencies.

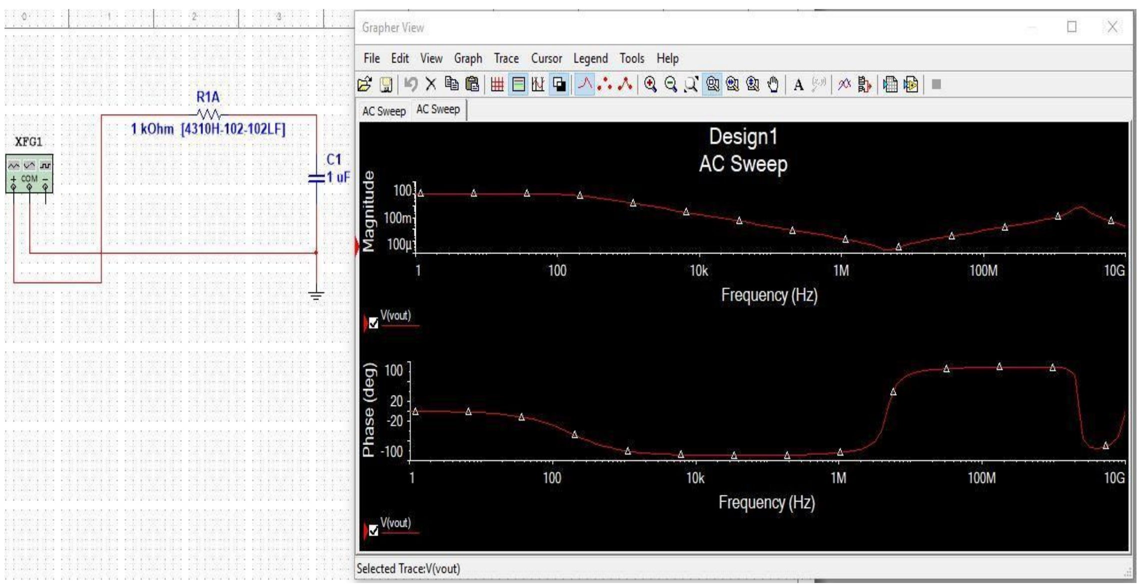


Figure 10: Parasitic Effects on Passive Components Simulated in a Filter

As seen in what a low pass filter would normally be, the effect of self-resonance of that component gives a second rise in output magnitude across the capacitor. This is because the capacitance becomes negligible and the self-inductance of the capacitor opposes the rapid change in current yielding a different effect than the one desired in the creation of the circuit. This effect is more indicative of a wide notch filter than the original low pass desired.

3.4 Market Analysis

This section of the report briefly delves into the market research for devices like ours to ensure that the device is financially viable in the marketplace. This is an important component of the project and, although more emphasis is being placed on the actual design of the device, it is also very important to consider the market prospects. The factors considered in this market analysis are the potential customers, maintenance considerations that manufacturing companies are adopting, competition, and the current challenges faced by competitors.

Preventative maintenance is work that is performed while the equipment is still in use [26]. It is performed to ensure that the equipment does not break down while in use and to extend the life cycle of the equipment. Premature breakdown of manufacturing equipment can disrupt production, lead to workplace injuries, and result in a loss in profits. Therefore, preventative maintenance is highly important.

Preventative maintenance can be divided into two categories. Time-based preventive maintenance is one in which maintenance of the equipment is performed at regularly scheduled time intervals [26]. Conversely usage-based maintenance is one in which the maintenance of the equipment is performed after a certain threshold of usage to prevent breakdown. A good example of this is when preventive maintenance is performed on a car after it has driven 10,000 miles. Our device was designed to perform both time-based and usage-based preventive maintenance by regularly providing vibration data and continuously monitoring changes and unusual readings. This method is advantageous as manufacturers can track equipment health relatively easily and quickly.

Vibration analysis is one of the more common methods of preventative maintenance. Just in Florida alone, there are over twenty-four companies that offer vibration analysis services of equipment [31]. This means that introducing this device into the market would be met with stiff competition and it is important to ensure that our device is able to positively compete in the free market. To achieve this, the design must offer significantly better performance metrics and competitive prices when compared to the competitors. Moreover, other consumer considerations (such as reliability, ease of use of the device, and ease of access to data), must also be comparable to the competition.

Regulations concerning preventative maintenance and equipment diagnostics must be considered in determining the market viability of the device. Environmental regulations, taxes, marketing and advertising regulations, and employment regulations are all important considerations. Each of these regulations factor into cost considerations that ultimately determine the price, profitability, and marketability of the device. To ensure optimal performance of the device, the decision was made to adopt credible design standards and methods. Standards from reputable organizations such as the Institute of Electrical and Electronic Engineers (IEEE) and the American National Standards Institute (ANSI). Section 4 of this report extensively discusses engineering regulations that pertain to our device.

4.0 Related Standards and Realistic Design Constraints

Without regulatory standards, many engineering designs would be incompatible with each other, be wildly varied in their designs, or be hazardous to the public or environment. The establishment of engineering standards and design constraints, typically by associates like the Institute of Electrical and Electronics Engineers (IEEE) and the American National Standards Association (ANSI), ensures that engineers have a common and sound approach to designing. The standards and constraints which have the most bearing on our projects are discussed in the sections below.

4.1 Standards

Standards are documents which establish specifications and specific procedures [27]. They are written to regulate the reliability of materials and products and establish guidelines for procedures and services. Standards include various protocols, rules and guidelines that ensure that products are usable, safe for consumers and in many cases able to work well with other devices which also adhere to the same standards. This helps to establish device compatibility. Without widespread standards, manufacturers would make their own versions of products that lack compatibility. These standards help ensure that product development is efficient as it lays down protocols that are universal and generally adopted. Through the general adoption of these standards, device compatibility is greatly improved. With the adoption of more international standards, international trade is facilitated, and product marketability and credibility are also greatly improved.

Compatibility is a major concern in designs where subcomponents from different manufacturers are used in conjunction with each other. Standards from reputable organizations (such as IEEE and ANSI) ensure compatibility between devices. Additionally, rules and guidelines provided in these standards ensure that the device is fit for consumer use and that it is marketable within the framework of regulations put out by the FCC and other relevant regulatory commissions. Many of the standards established by these organizations have been adopted by the FCC and as such can be considered extremely reliable. In many cases, government bodies will voluntary adopt industry standards.

In wireless communications, adherence to relevant standards is very important. A vast number of our ubiquitous electronic devices all use some form of electromagnetic energy. As such, ensuring consumer safety is paramount. Safety standards from several organizations approved by the Federal Communications Commission, such as the American National Standards Institute (ANSI), the

Institute of Electrical and Electronics Engineers (IEEE), and the National Council on Radiation Protection and Measurements (NCRP) all seek to ensure that the effect of human exposure to these kinds of emissions (electromagnetic fields) is not harmful.

4.2 Related Standards

The American National Standards Institute (ANSI) and the Institute of Electrical and Electronics Engineers (IEEE) are comprised of a variety of individuals and organizations from involves various technical backgrounds. These groups collaborate to develop standards. Thousands of these standards are published, reviewed and updated frequently. They cover a broad range of categories involved in the design of consumer electronics to help ensure that the end products are marketable, compatible with other devices (universal), and ultimately safe.

In our design, many of the standards related to antennas, hardware, software, communication protocols were complied with. Because the device is entirely an electronic device, IEEE standards were mostly used. For each aspect of our device, the relevant IEEE standard was complied with to ensure that the device was properly designed. Marketability, an incredibly important factor to our customer, is increased by the added credibility that comes with compliance with these standards and regulations.

4.2.1 IEEE Standard 1149.1-2001: IEEE Standard Test Access Port and Boundary-Scan Architecture

This standard relates to the maintenance, testing and support of assembled printed circuit boards (PCB) and the testing of internal circuits [28]. A standard interface must be selected so that instructions can be communicated through it. One of the test features dictated by this standard is the boundary-scan register. The boundary scan register is a testing method which ensures that the device can respond to a set of instructions designed to test the components of the printed circuit board (PCB).

4.2.1.1 Design Impact

To ensure that the PCB works as expected, a series of tests were designed to check the functionality of the circuit. JTAG enabled devices, through a series of tests are specifically designed to check that the connections on the printed circuit board match that of the actual design. This step of checking the connections on the PCB through these specially designed tests help to ensure that circuit works as expected. This is an important step as it verifies the correctness of the design of the device and ensures proper functionality of the circuit. If the PCB design fails these tests, it must be redesigned and retested.

4.2.2 IEEE Standard: Microcontroller System Serial Control Bus

This standard relates to the interconnection of microcontrollers and other devices with limited programmability via serial bus [29]. The standard lays out rules and guidelines that apply to the interconnection of independent devices and ensure safe and reliable communication between these devices.

4.2.2.1 Design Impact

The microcontroller module of the device controls the receiver, transmitter, analog-to-digital converter, RF switch, and other important modules of the device. As such, it is one of the most important parts of the design. Given the microcontroller is at the center of the operation of the device, it is imperative that it has excellent functionality. The communication between the microcontroller and the other devices must be reliable to ensure that the device works properly. As such, reliable communication protocols for serial communication for microcontrollers (such as UART, USB, and SPI) were used and follow the IEEE standard.

4.2.3 IEEE 3003 Standards: Power Systems Grounding

The IEEE standard practice for grounding and bonding of equipment in industrial and commercial power systems is discussed in the IEEE 3000 standards [30]. These standards cover the interconnection and grounding of the non-electrical metallic elements of a system. Additionally, they provide guidelines on equipment bonding, grounding, current handling capability for ground faults and overcurrent protection. Adherence to these standards significantly reduces electrocution hazards to product designers and consumers. The standard also covers the fundamentals of planning, designing, maintaining, and installing electrical systems. The IEEE lists four regulatory requirements for equipment bonding and grounding:

a) Conductive materials which enclose or form a part of electrical conductors or equipment should be connected to earth to limit the voltage-to-ground on these materials. Where the electrical system is required to be grounded, these materials should be bonded together to form part of the grounding system and should be bonded to the supply system neutral conductor at the source and/or the main service panel.

b) Where the electrical system is not solidly grounded, these materials should be bonded together in a manner that establishes an effective means of limiting the voltage potential between the conductive materials or ground.

c) Electrically conductive materials that are likely to become energized should be bonded to the supply system grounded conductor at the source. They should be grounded in a manner that establishes an effective path for fault current.

d) The earth should not be used as the sole protective conductor or fault current path.

Electrocution is a result of contact with energized metallic components of a circuit. The risk of electrocution can be significantly reduced by ensuring effective grounding and bonding practices. Another factor that can result in electrocution is a breakdown of insulating components. If insulating components breakdown, it can result in a contact between the energized metallic component of the circuit and the metal encasing of the device. This then causes the voltage of the metallic encasement to rise to the voltage of the energized metallic components of the circuit resulting in an electric shock when touched. To avoid this, the IEEE standards dictates that there must be safety considerations in the bonding and grounding process. The safest designs form a low-impedance path from the fault back to the source.

The standard also includes the thermal capacity of the grounding conductor. The grounding conductor should be able to conduct ground fault current for a sustained duration of time without resulting in excessively high temperatures or arcing. To ensure this, all the fault lines in the device circuitry must have a high current capacity and a relatively large cross-section grounding. Circuits that have a large cross-section grounding have an increased current sinking capability. Adherence to these guidelines reduces the risk of fire hazards and other catastrophic failures.

4.2.3.1 Design Impact

The IEEE standard in the previous section was particularly pertinent to the PCB design of our device. All the proper safety regulations, guidelines and recommendations will be complied with to ensure that the risks of fire, overheating, and electrocution are greatly reduced.

4.2.4 IEEE Standard for Standard SystemC® Language Reference Manual

Due to the nature of the design of this project, a programming language that can interface software and hardware components is vital. SystemC provides a mechanism for modeling hardware and software with several layers of abstraction in such a way that traditional HDL languages do not [32]. The SystemC provides a C++ based standard that effectively interfaces hardware and software components of the design. The code was written in accordance with IEEE guidelines to ensure readability and reusability if need be. Names of functions, pointers, variable type declarations, and loops will be written to comply with IEEE standards.

4.2.4.1 Design Impact

The code format will be in strict concordance with IEEE guidelines for proper programming practice. Proper commenting will be made to ensure that the code is understandable to third parties and reusable. Variables will be properly named and initialized, and functions and structures are named in compliance with IEEE guidelines.

4.2.5 IEEE Standard for Safety Levels with Respect to Human Exposure to Radio Frequency Electromagnetic Fields, 3 kHz to 300 GHz

The IEEE standard for safety defines the safe levels of human exposure to radio frequency electromagnetic fields [33]. These recommendations ensure that the public is protected from the adverse effects of exposure to electromagnetic fields in the radio frequency range of 3 kHz to 300 GHz. The recommendations are broken down into two sections: basic restrictions (BR) and maximum permissible exposure values (MPE). The purpose of this standard, as described by the IEEE, is to significantly limit the effect of electromagnetic field (EMF) energy on human health.

The basic restrictions can be further subdivided into three categories: internal fields, specific absorption rate (SAR), and current density. Internal fields are defined as emission of electrons because of an electrostatic field. Specific absorption rate is defined as the rate of absorption of radio frequency electromagnetic energy by a body. According to FCC regulations, SAR is tested by using the highest power level in all the frequency bands and testing their effects on models of different human tissues. Finally, current density emission relates the thermal energy to current.

For radio frequency transmissions within the frequency range of 3kHz to 5 MHz, the major health concern is painful electrostimulation. Electrostimulation is defined as stimulation of bodily tissues using electricity. For frequency transmissions within the frequency range of 100 kHz to 300 GHz, the IEEE regulations focus on minimizing adverse health effects that are associated with heating. Because the device is designed to work at 1 MHz, it falls within the 100 kHz to 300 GHz range. It should be mentioned that the IEEE standard does not consider the sensation of heating as adverse. However, the heating of body tissues is an adverse side effect. As such, rules and guidelines pertaining to type of waveforms, duty factor, and transmission time must be established.

4.2.5.1 Design Impact

The SAR limit as averaged over the whole body according to FCC regulations is approximately 1.6 W/kg. The maximum power received by the device from the transmitting antenna is approximately 1 W. This means that for a SAR limit beyond that recommended by the FCC, the mass of the transmitting device must be at least 0.625 kg. This limitation will provide a design parameter so that the device follows the FCC mandated specific absorption rate.

4.2.6 FCC 15.221 Operation In The 525-1705 kHz Band

This standard states that 1 MHz devices which emit radio frequency energy may operate on a college or university campus as long as the radiator complies to the following:

(1) The field strength is less than 24000/F(kHz) and cannot be measured at a distance greater than 30 meters.
(2) At the campus perimeter, the field strength is less than 24000/F(kHz) and cannot be measured at a distance greater than 30 meters.
(3) If it is designed to connect to the public utility (AC) power line, it shall not have a conducted limit quasi-peak greater than 56 dBμV or an average conducted limit of 46 dBμV [60].

4.2.6.1 Design Impact

To comply with this standard, the signal being transmitted by the system must be weak enough to fall within the 24000/F(kHz) range and not be capable of being received beyond 30 meters. Because the signal transmitted by the design, it is easy to fall within the desired range.

4.3 Realistic Design Constraints

There are several design constraints that factored into the design of the device. Some of these constraints were because of regulatory compliance, customer specifications listed in the House of Quality diagram, and ultimately, time. These design constraints have been further categorized into various subsections which will consequently be discussed in detail in the upcoming paragraphs. These categories are:

- Economic and time constraints
- Ethical constraints
- Health and Safety constraints
- Manufacturability
- Sustainability
- Social and political Constraints

The device, as specified by the customer, was to transmit and receive signals (data) at a frequency of 27 MHz. This was a major design constraint as existing technologies of the sort are usually designed at much higher frequencies and finding appropriate parts to design the system at this specific frequency was quite tasking. In some cases, components had to be designed from scratch because parts could not be purchased because of the frequency constraint. Because this constraint was so difficult to design around, the operational frequency was decreased to 1 MHz.

Additionally, budgetary constraints necessitated that we select devices that were within our budgetary limits but also had good functionality. This step involved rigorous research as we needed to ensure maximal functionality of the device while staying within the financial limit.

4.3.1 Economic and Time Constraints

The old idiom “time is money” holds true for any design project. Long and unexpected delays often result in huge amounts of additional manpower. Conversely, too strict of a budget can result in insufficient time to complete a design; even if a project is completed on a strict budget, it may not be fully functional or may have subpar performance. In an ideal case, a project would have enough funds, manpower, and funding to design the best possible product. However, this is rarely the case and project planners must identify economic and time constraints and create a strategy to minimize the effects of these limitations.

4.3.1.1 Economic Constraints

The economic constraints for the project limit the total cost for manufacturing to under $1,500 dollars. The primary goal of the customer is to be able to manufacture and sell this product in the future. Therefore, although our tolerance for budget is $1,500 dollars, it is in the customers best interest if the budget per unit is minimized where possible for higher profit margin in future sales. It is also our intent to limit the total cost of the device to a total price of $300 dollars for total manufacturing price. This manufacturing price does not include trial and error and cost of integration and development, but only the cost necessary for the reproduction of the design.

One method of minimizing the cost of operation is to keep the power consumption of the device to a minimum. Our marketing requirements restricted the power usage to 10 watts of power or less.

Since the funding has already been awarded to the sponsoring customer, for our purposes, budget concerns are not so much as an obstacle as they are a parameter to be optimized. To achieve this, we first designed a functional circuit that was robust enough to accomplish our needs, and then once the design was created, the components were selected with budget in mind.

4.3.1.2 Time Constraints

The goal is to work as quickly as possible and stay ahead. The customer had a hard deadline relating to their contract that occurred in late August 2019 which is within our senior design timeline. However, it was in the customers best interest if the product is completed prior to the end of August to allow time for data collection and compilation. For this reason, it was our intent to conclude the device fabrication and debugging by July 19th to allow ample time for the customer to collect data to be used in the future.

The biggest time constraints are long lead times and unforeseen problems which cause long delays. To minimize these issues, we selected parts with short lead times and attempted to mitigate any design complications before they could cause issues. Unfortunately, some key details were overlooked in component datasheets, and caused delays during the prototyping phase.

4.3.2 Social Constraints

In the design process, environmental, social, and political constraints are very important factors to consider. The end goal of the project was to ensure that the device brought about a positive social impact. The device was to be used for non-invasive diagnosis of mechanical systems through spectral analysis of the vibration profiles of these machines. As such, it has the potential to help companies save money through predictive maintenance. Manufacturing companies that utilize industrial machinery can save money, energy, and other resources through effective predictive maintenance. According to the Mckinsey Global Institute report, predictive maintenance has the potential to save up to six hundred and thirty billion dollars by the year 2025 in manufacturing costs [34]. The money-saving features of this device makes it positively socially impactful. Additionally, the device could potentially help to prevent the breakdown of the manufacturing process, thus ensuring that companies do not lose revenue due to an interrupted production process or an inability to manufacture.

4.3.3 Environmental and Political Constraints

Another key factor in the product design were environmental factors. Given the current state of our climate, it has become imperative for engineers to design devices that contribute to making the planet more conducive for habitation. This includes being more environmentally conscious when making design decisions.

Our machine health diagnosis device helps to reduce the amount of energy and resources required to maintain industrial machinery as it could potentially help extend the life cycle of the machine through proper predictive maintenance. Additionally, it can potentially save companies a lot of money by reducing the need to purchase new machinery. This device helps contribute to the green initiative due to the reasons stated in the preceding paragraphs.

4.3.4 Health and Safety Constraints

The safety of humans is always a consideration in any engineering design project. Technology should never intentionally or unintentionally cause harm to individuals. To avoid injury and negative health effects, the overall design must be considered and thoroughly examined to determine potential hazards. Typical hazards include high voltage, hazardous or restricted materials, and electromagnetic radiation.

Health and safety constraints are particularly important for devices that transmit and receive electromagnetic energy. It was incredibly important that the device follows safety standards associated with EMF radiation. The electromagnetic spectrum (as shown in Figure 11 below) is classified by frequency range and ionization [35]. At the lowest end of the spectrum are radio waves with long wavelengths and low frequency and at the highest end of the spectrum are gamma and X-rays which have high frequencies and low wavelengths. In between are infrared, visible light, microwaves, and ultraviolet light.

Our device operates within the radio frequency range which encompasses the bandwidth between 3 kHZ to 300 GHz. Furthermore, as stated above, the electromagnetic spectrum can also be classified between ionizing and non-ionizing frequency. The radio frequencies fall within the range of non-ionizing radiation, which makes it relatively safe for public use. The energy of radio frequency signals is not high enough to cause ionization (alteration of the atomic structure). As such, the harmful effects associated with ionizing electromagnetic radiation were not a major concern in the design of the device.

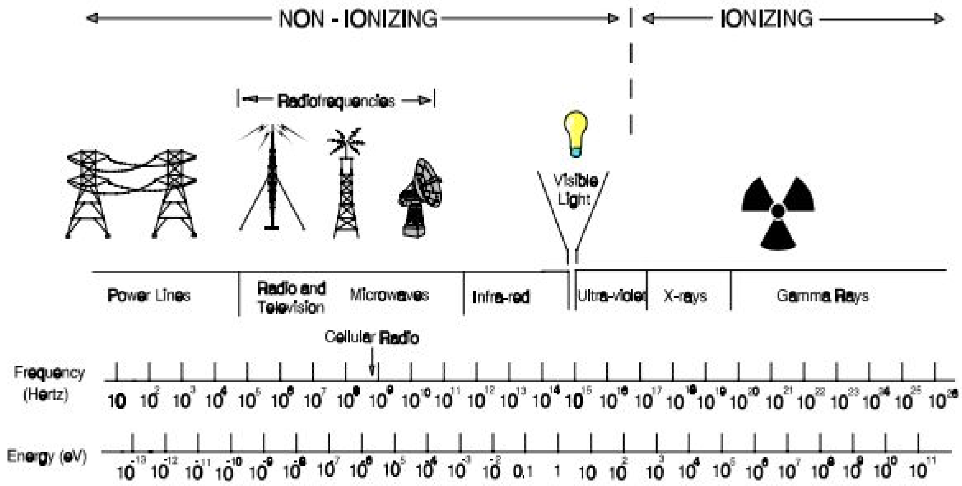


Figure 11: The Electromagnetic Spectrum

The main health concern associated with our device is the risk of electrocution. Electrocution is a risk when high voltage or current is being used, when sources of power are improperly handled, or when the device is grounded incorrectly. To minimize the risk of electrocution, the product was grounded per the IEEE standards found in section 4.1.2.

4.3.5 Ethical Constraints

The significance of engineering ethics covers two aspects of the design process. The first is in the design specifications and requirements and the second aspect is the process of making decisions based off tradeoffs (or what is being sacrificed to optimize another parameter). In the design, the specifications provided by the customer were reviewed carefully to ensure that there were no breaches of design ethics. Ethically relevant choices were made to ensure that the device did not violate the IEEE code of conduct. The first IEEE code of conduct states that the safety, health, and welfare of the public is to be held paramount and that engineers should strive to comply with ethical design practices and to disclose factors that endanger the public [36]. As can be observed from the design specifications in previous sections, this code of conduct was strictly complied with.

By operating at a relatively low frequency (1 MHz), the device avoids interference found in higher frequency bands and it also drastically reduces the level of energy absorbed by humans. This is in keeping with the IEEE code of ethics of prioritizing consumer safety [36].

The second code of ethics states that conflict of interests should be avoided wherever possible and relevant parties should be informed in case a conflict does exist [36]. The entire design process involved in the design of this device is void of any conflict of interests in concordance with IEEE code of ethics.

The third IEEE code of ethics states that the engineer should be honest and realistic in stating claims or estimates based on the available data [36]. In the design process, extensive research was done to ensure that the design specifications were feasible and practical. This included looking at existing technology to see if the design specification was practical and consulting textbooks and other credible sources to ascertain the viability of the design specifications, requirements, and relevant tradeoffs.

Another pertinent IEEE code of ethics in our design process states that full disclosure of technological qualifications, experience, and training should be made known [36]. The customer is fully aware of our qualifications and experience and each team member has been assigned tasks based on his or her qualifications. This ensures that all parties are in accordance with IEEE code of ethics.

As discussed earlier, engineering ethics also applies to the process of making appropriate tradeoffs. In our design, not all the design specifications could be met or optimized simultaneously. This necessitated the need for initially making tradeoffs and then consequently leveraging our technical skills and knowledge and consulting textbooks or other resources to determine ways to best satisfy all the design specifications.

4.3.6 Manufacturability and Sustainability Constraints

To fulfill our customer’s requirement for a device which can be reproduced on a larger scale, we must design with manufacturability and sustainability in mind. Important considerations are fabrication, assembly, and testing practices. Our design must be capable of interfacing and communicating with a provided transmitter. The remaining components in the design will be sourced from third-party vendors.

One hazard of sourcing materials from outside vendors is the limitations imposed by the lifecycle of the components we choose. Parts naturally have a period where they are readily available before they are eventually phased out by newer components and become obsolete. While we were designing and choosing parts, we actively avoided any parts that are within the obsolescence stage of their lifecycle. Choosing newer parts assisted in our sustainability efforts and ensured that parts were easier to acquire.

The selection of available parts will also allow for easier maintenance should the design need rework. If readily available parts are implemented, it will minimize the time, cost, and frustration associated with maintenance. One final sustainability consideration is the environment that the device will operate in. Currently, it is expected that the device will be operated indoors and will not be exposed to temperature or humidity extremes.

5.0 Project Hardware and Software Design Details

Once the components of the design have been selected, the design process can proceed in more detail. The sections below summarize the parts selected and provide more detail about the design.

5.1 Parts Selection Summary

The sections below provide a summary of the main components within the design. The main components will each be defined, and the key factors will be explained. Additionally, these sections will explain how the component will function within the design.

5.1.1 FT2232D

The FT2232D is a 48-pin dual USB to serial UART/FIFO integrated circuit designed by Future Technology Devices International Ltd (FTDI) [37]. This device was selected because it provides our design with the capability to connect and communicate with a PC via a 2.0 USB port. The entire USB protocol is handled on the chip and the manufacturer provides users with a free driver that eliminates the need to develop USB drivers. When operating at full capability, it can support a transfer data rate of 300 to 3 Mbaud (where baud rate represents the number of pulses per second in the transmission medium).

This device was removed from the 1 MHz system due to the F28335 experimenter board having an on-board USB interface.

5.1.2 Low-Pass Filter

A low-pass filter was constructed with capacitors and resistors to create a fourth order ladder filter to remove all harmonics of the signals being transmitted. Filtering these harmonics ensures that we are within the desired band of transmission. The circuit was built as shown below in Figure 12 where the load resistor is 50 ohms, the inductors are 12 nH, and the capacitor is 12.75 nF (for a 27 MHz operational frequency). This design is shown in Figure 7 below.

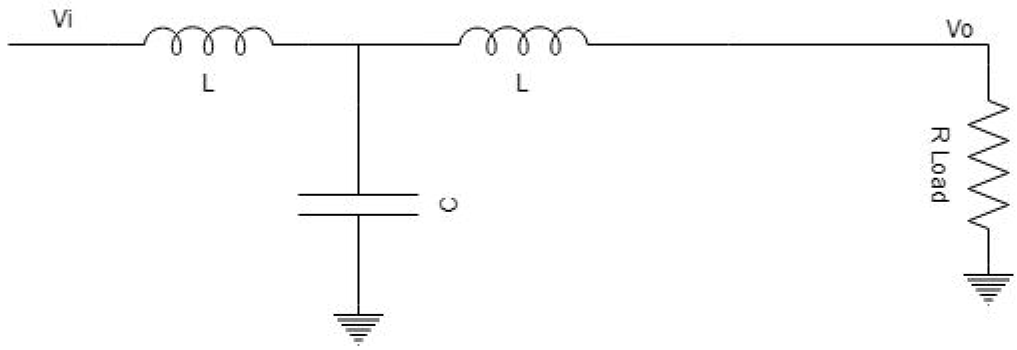


Figure 12: Low-Pass Filter Design

5.1.3 Passive Bandpass Filter

The following filter shown in Figure 13 is the bandpass filter (designed for the 27 MHz system) that was used to reduce signal noise and preserve the received signal. The filter was designed with realistic component values. The passive filter was chosen for its relative simplicity, fourth order nature, and functionality at high frequency.

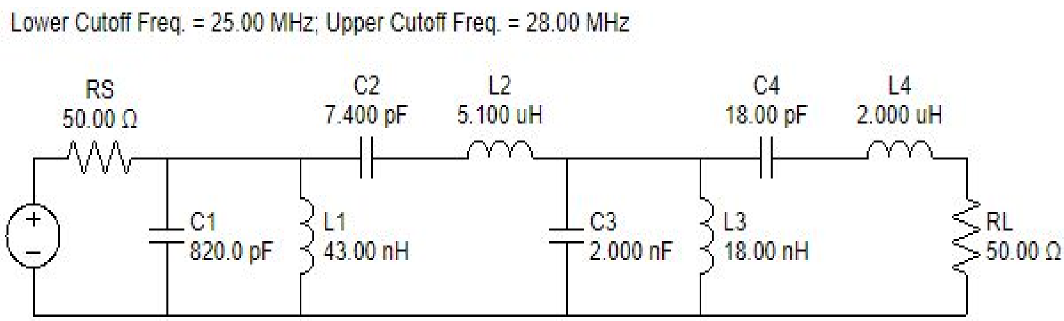


Figure 13: Fourth Order Passive Bandpass Filter

The above filter was simulated and demonstrated the following result:

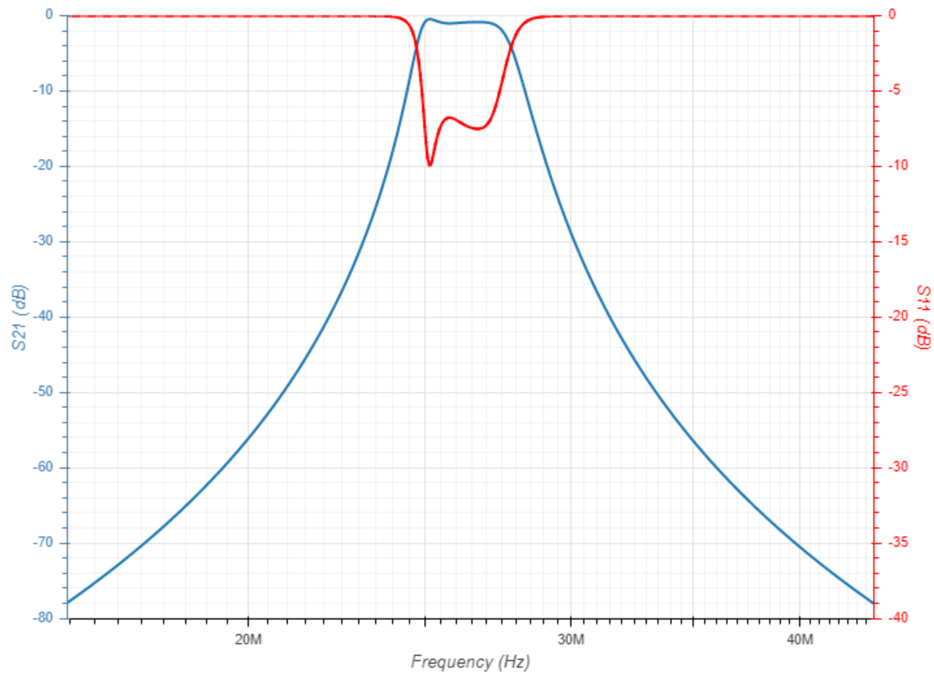


Figure 14: Simulation of the Fourth Order Passive Bandpass Filter

As seen in the graph in Figure 14, the simulation shows a near perfect transmission between 25 and 28 MHz. These cut off frequencies were chosen to allow some tolerance for our clients MEMS device response. If our clients first model demonstrates outside of the targeted frequency domain, our device should still function properly. The figure shown is based on a model containing only standard value passive components. To increase the functionality of the filter and ensure that the actual filter response closely resembles the simulation all standard components to be selected for this part of the design are within 1 percent tolerance.

5.1.3 Power Amplifier

Since we were unable to find a suitable packaged power amplifier, one must be designed. The power amplifier consists of multiple operational amplifiers that are joined together to increase the current output of the device. To preserve the quality of the signal, the operational amplifiers selected are very fast relative to the output signal. The part number of the selected operational amplifier is LMH6703MAX/NOPB. This part was selected for its high frequency operation up to 1.2 GHZ and its fast slew rate of 4.2kV/us [39]. The design of the power amplifier is shown in Figure 15.

As previously mentioned, the LMH6703MAX/NOPB was replaced by the LM7171 operational amplifier during the testing and integrating phase due to peak overshoot and ringing caused by the LMH6703.

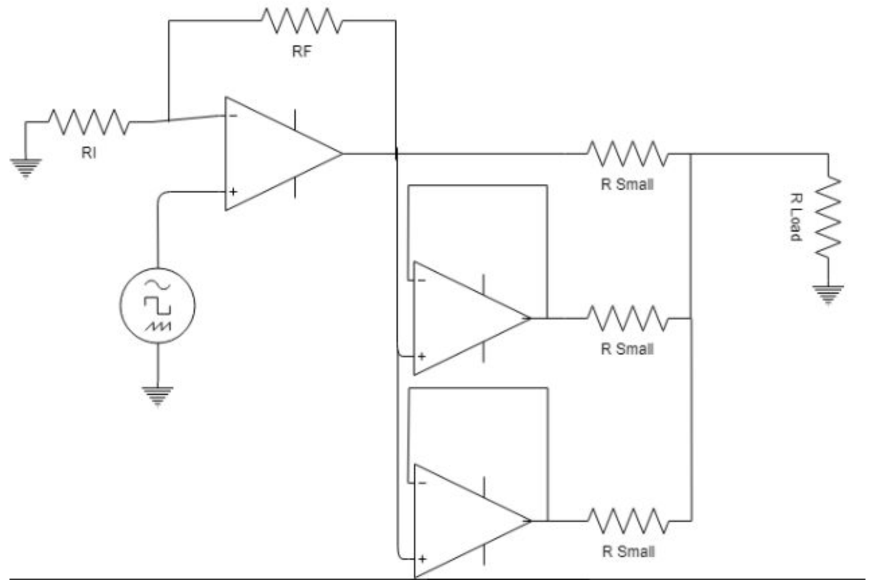


Figure 15: Power Amplifier Design

The above amplifier design was selected because no high-power RF amplifiers existed in the 27 MHZ range. The solution that we came to was to use consecutive operational amplifiers by this design we can increase the current output going to the antenna.

There were several other ideas explored for the RF amplifiers. The issue with many of the RF amplifiers was the range of operation. Our operational frequency of 27 MHz was above low frequency amplifiers such as audio amplifiers but the signal was below the functional range of RF amplifiers such as the types used for Wi-Fi and other high-frequency radio.

The other type of amplifier explored were wide band amplifiers. Wide band amplifiers were very large and not chip based but rather large packages that could not be integrated into a PCB. They also proved to be more expensive than the other methods.

5.1.4 Downconverter Mixer

The downconverter mixer that was ultimately decided on is the LT5560. The LT5560 is a low power active mixer produced by Linear Technology that can support frequencies between 0.01MHz to 4GHz [40]. This component was chosen because it features a sample test circuit which can be externally matched for the desired frequency by selecting and solving for resistor, inductor, and capacitor values. Additional advantages of this part are its small footprint (it comes in a 3mm x 3mm package) and it operates within our desired temperature range.

When designing circuit components for relatively high frequency signals, it is incredibly important that power loss be minimized to the fullest extent possible. One significant source of power loss is wave reflection back to the power source. When designing the circuital components accompanying the LT5560 device, impedance matching techniques were used to ensure that the device was matched at all its ports to avoid power loss. Although the input design at 27 MHz (operating frequency of the device) was not explicitly stated, it was approximated through extrapolation of the data supplied in the data sheet. Using Microsoft Excel, a graph was plotted and the complex input impedance at 27 MHz was approximated to 28.4 + j0.5. Figures 16 and 17 show the relationship between the real and imaginary parts of the input impedance and the frequency of the incoming signal.

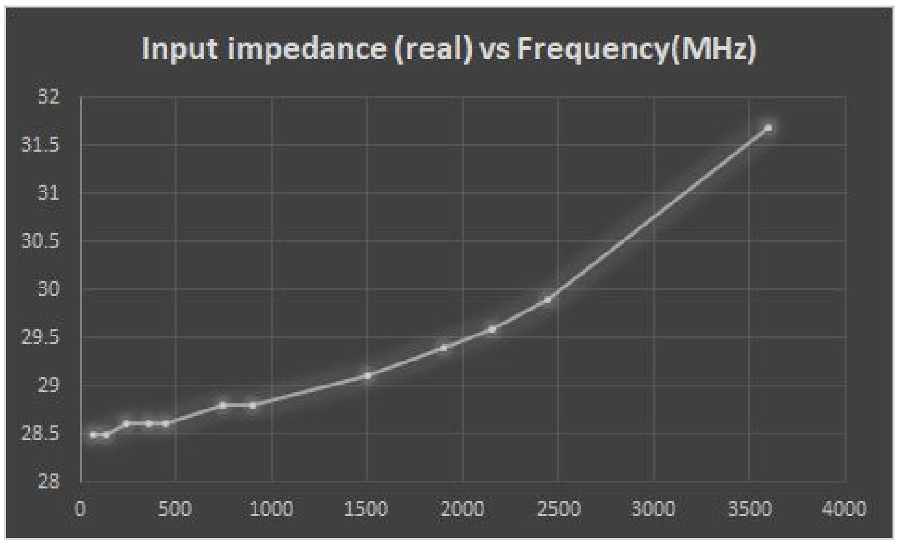


Figure 16: Real Input Impedance vs. Frequency

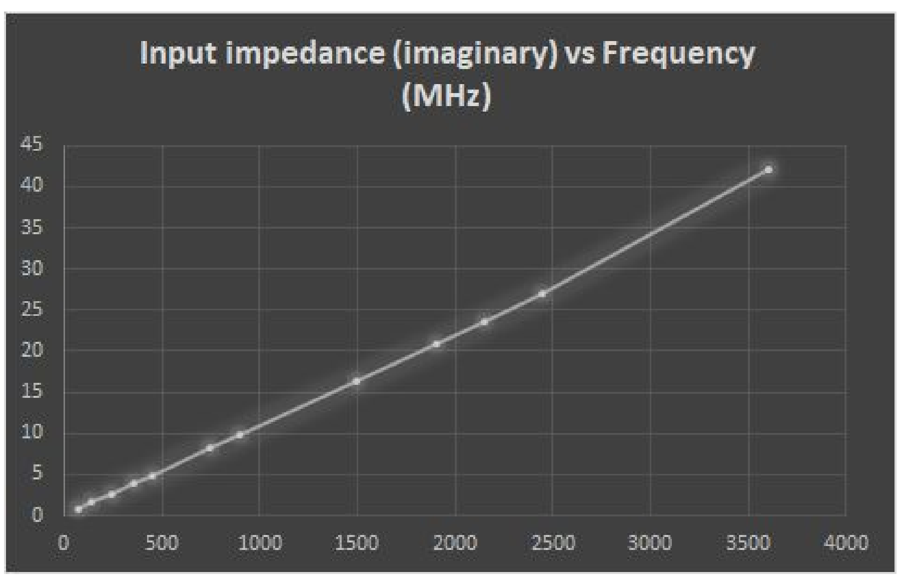


Figure 17: Imaginary Input Impedance vs. Frequency

The downconverter mixer was removed from the 1 MHz design because a mixer was no longer required or optimized for this frequency and because the incorrect footprint was used during PCB fabrication.

5.1.5 Frequency Oscillator

All oscillators in the design are crystal based. This is selected because of the high precision and sinusoidal output. These oscillators are employed for transmitted frequencies, clock oscillators, and mixed signal oscillators.

Frequency oscillators were removed from the 1 MHz design. Instead, the F28335 development board and a function generator was used to supply the PCB with test frequencies.

5.1.6 Limiter

The limiter, shown in Figure 18, is created out of a diode clipping circuit to trim the tops of the waveform to the desired height.

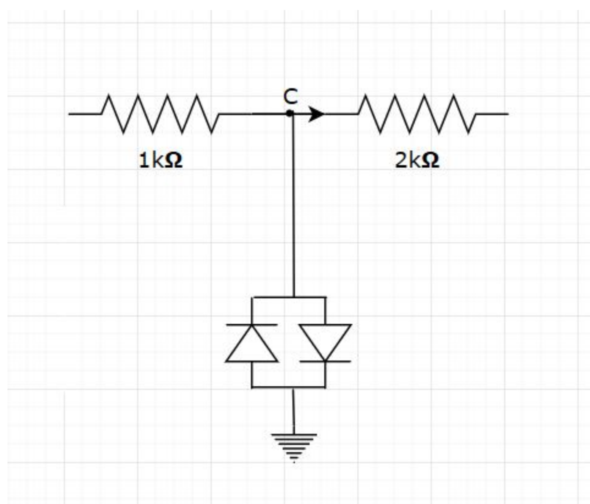


Figure 18: Limiter Design

The diodes were selected based on switching speed, forward voltage, and maximum current. The resistors are placed on either side of the diode node to allow for a voltage drop when the diode turns on. The voltage drop that occurs across the diodes essentially clip the waveform. The reason that the second resistor differs from the first is that the second resistor is used as part of the gain of the operational amplifier that it is connected to.

5.1.7 Microcontroller Unit

The microprocessing unit that was selected is the TMS320F28335. The unit is a highly integrated digital signal controller (DSC) microcontroller unit [41]. The unit was selected for its high processing power capable of 150 million instructions per second, integrated on board ADC capable of 80 ns conversion rate with a resolution of 12 bits, and low number of peripheral components that must be added to our board design.

As previously mentioned, the TMS320F28335 was replaced by the TMDSDOCK28335 experimenter kit. It functioned as the F28335 on the PCB would have functioned, but it included header pins and a UCB board to ease the testing process.

5.2 Architecture and Related Diagrams

To simplify the designing process, the architecture was first modeled as a series of block diagrams. The design was broken down into diagrams related to signal transmission, signal reception, and signal processing at the microcontroller. Blocks were used to identify individual subcomponents and relate subcomponents to one another using directional arrows.

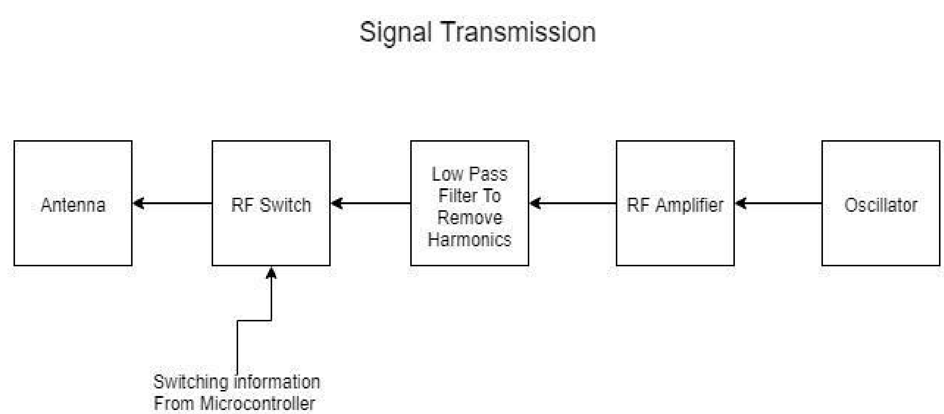


Figure 19: 27 MHz Signal Transmission Block Diagram

The functional block diagram shown in Figure 19 above demonstrates how the signal is manipulated from its generation to its transmission in the 27 MHz system. The signal starts with an oscillator chip that creates the frequency to be sent. This generated frequency is then be passed on to an amplifier which provides the power necessary for the transmission of the signal. Prior to transmission, the signal passes through a low-pass filter to provide a sinusoidal output and to prevent harmonics of the frequency from being transmitted. If this filter were not in place the transmitted harmonics would break FCC code as they would fall outside of the industrial scientific and medical RF spectrum. The signal is then passed through the RF switch block which is in place to switch between transmit and receive. In this case during the transmission the switch will not affect the signal. Lastly, the signal travels out the antenna for the sensor excitation.

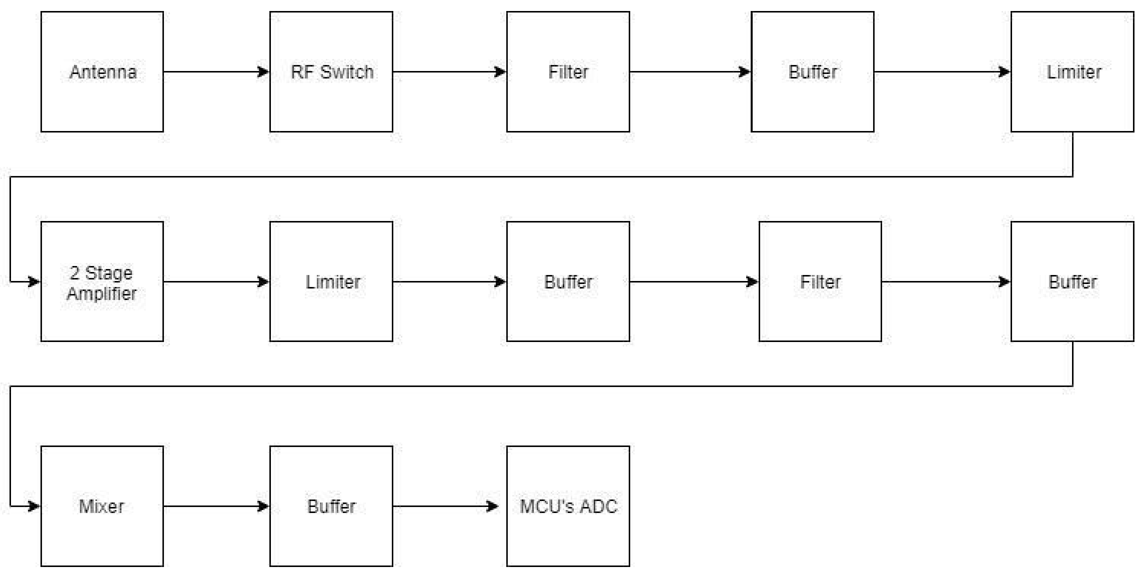


Figure 20: 27 MHz Signal Reception Block Diagram

The block diagram shown in Figure 15 above displays the signal path from its initial reception at the antenna to the final processing at the MCU for the 27 MHz system . Once the signal is received it passes through the RF switch which acts as a short while the signal is being received. The signal then passes through a filter to remove anything outside of our frequency range. The buffer immediately afterwards is to prevent any loading effect from altering the filters response. Next, the signal passes through a diode-based limiter. The purpose of this is to protect the circuit from large high voltage spikes originating at the antenna. The 2 stage amplifiers used in the circuit are two consecutive operational amplifiers. This was done to obtain very large gains while circumventing the limitations imposed by the innate gain bandwidth product of the operational amplifier. The last buffer also functions as an offset to allow the ADC to properly interpret the data.

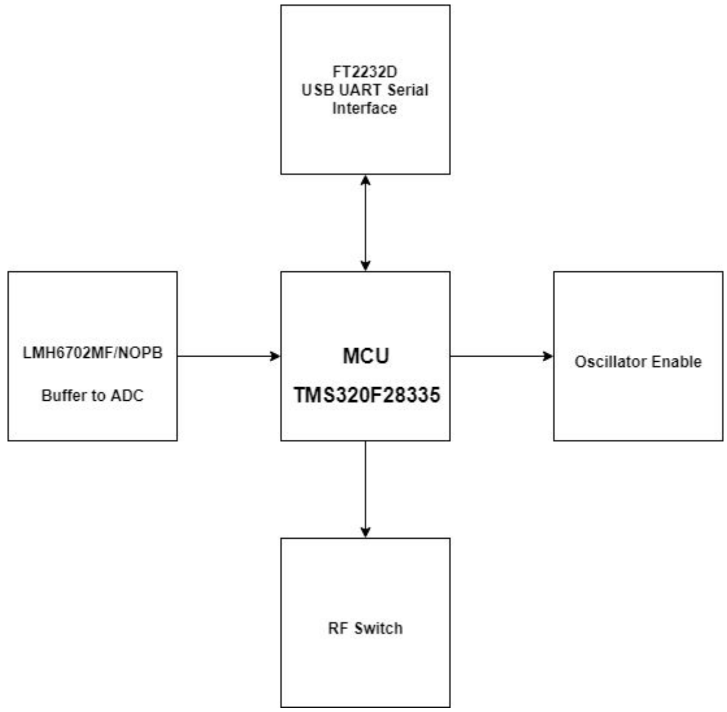


Figure 21: Microcontroller Unit

The above figure demonstrates the interactions of the microprocessor unit. The controller interfaces bidirectionally through the USB UART interface. This interface is in place to deliver and receive data via a computer interface. Through this we are able to program and plot our obtained data to the microcontroller. The buffer passes on the data and shift the dc bias of the alternating incoming signal once the signal has been down-converted to reduce the requirement of the ADC for processing. The serial output of the MCU drives the RF switch to turn from transmit and receive. This functionality is in place in place so that the same antenna can be utilized for both functions and the signal be interfered with between the transmitting excitation and the reception of the actual data. For testing purposes this control over the RF switch is useful when only transmitting or receiving. Lastly, the MCU provides the logic levels to turn on and off the oscillators. All oscillators selected require a logic enable to begin functioning. We always expect to keep the oscillators functioning that the device is on to avoid any transient states generated when initially powering on the oscillator. However, one reason why we may need to control the oscillators activation is noise interference. This is especially a concern because both oscillators are within the range of the frequency spectrum that we are transmitting and receiving. This means that any noise generated passes through all filters that are in place on the circuit. from each other as possible within the circuit. A mitigation strategy that is in place is that we separate the sources of noise by space on the PCB layout. This ensures that the lines will be as separated as possible.

5.3.1 Initial Architecture Design and Related Diagrams

The initial schematic of our design is presented in the images below. All schematics have been created in Altium Designer and the designs (unless otherwise marked) are original designs. Some schematic pages utilize test circuits or schematics designed by the manufacturer and requests to use these designs have been submitted to the appropriate individuals. These copyright requests and approvals are documented in Appendix A.

The schematic designs developed in these sections were used to produce the printed circuit board. To ease the conversion process, the components used in the design have been identified by their part number. By associating each part with the manufacturer's part number, Altium Designer is able to export the 2D footprint and 3D model of the components to the PCB layout.

The schematic shown in Figure 22 is the overall schematic design for the 27 MHz system. Because components are difficult to see and decipher at this scale, the schematic will be broken down into smaller subsystems in the following figures.

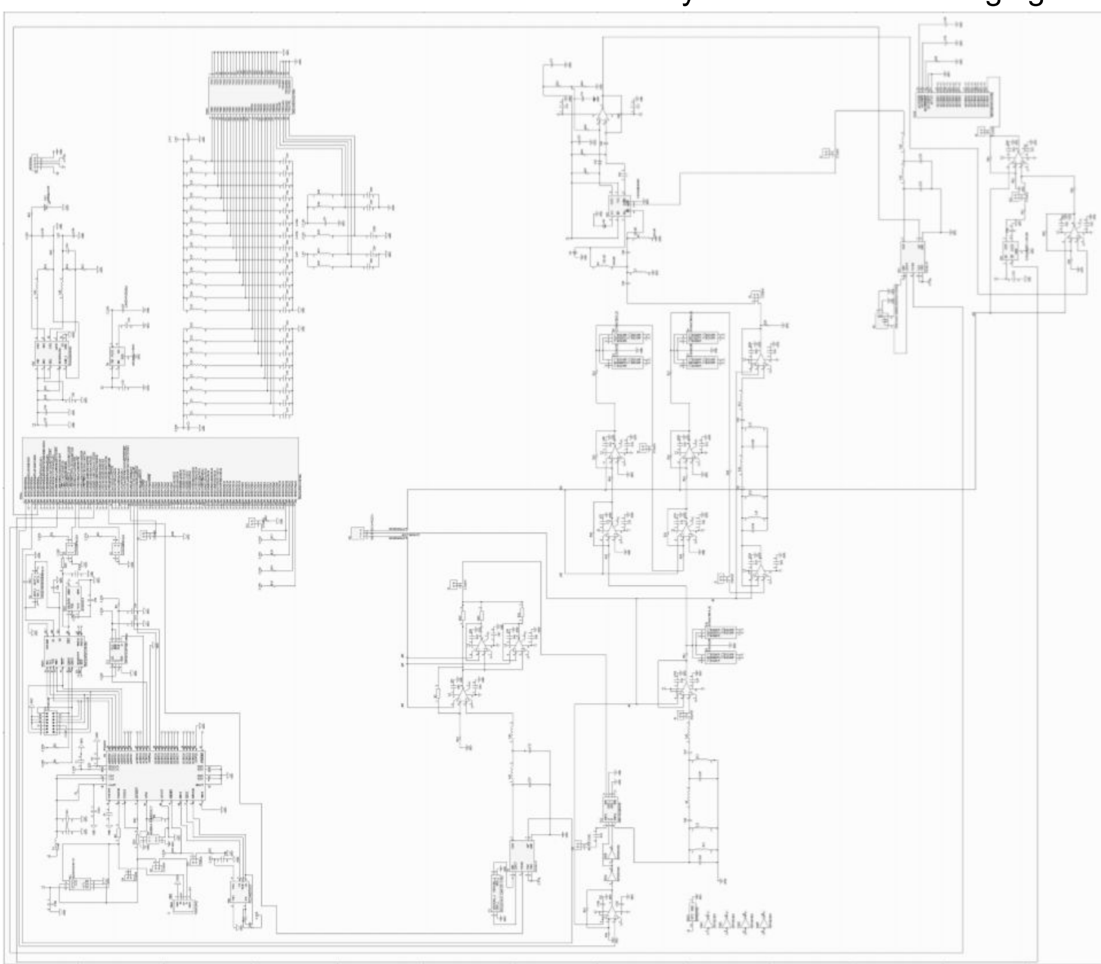


Figure 22: Overall Schematic Design for the 27 MHz System

The first sheet, shown in Figure 23, shows the schematic for the FT2232D interface (courtesy Texas Instruments). This component was designed to interface with the microcontroller and allow for bidirectional communication through the receiving and transmission pins. This component is mostly a “plug-and-play” device that requires little to no changes to be functional with our design.

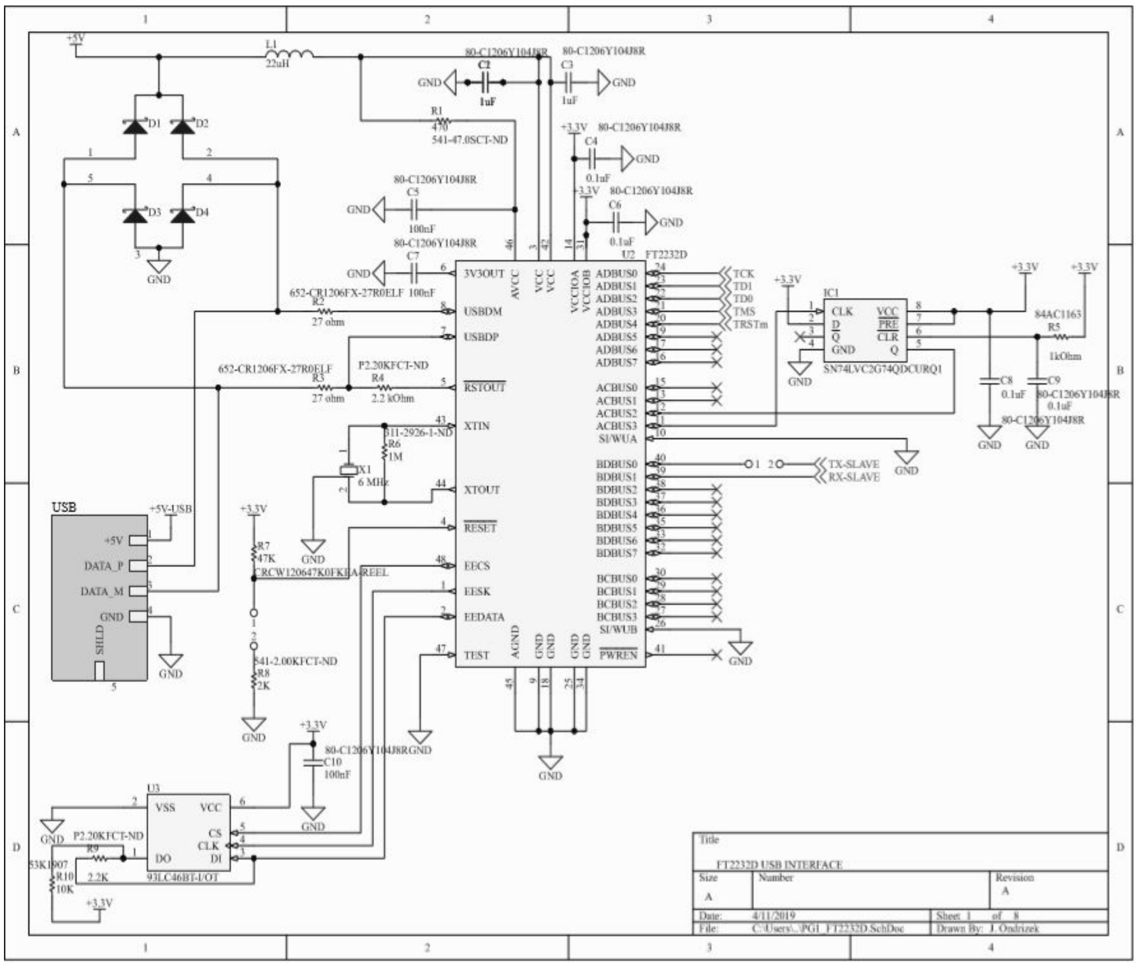


Figure 23: FT2232D Interface (Courtesy Texas Instruments)

The second page of the schematic, shown in Figure 24, serves as a midpoint for other stages in the schematic. Here, the RF switch (part number HMC199AMS8 / 199AMS8E) and antenna (not shown) would connect to the power amplifier stage (identified by the incoming off-page connector RF_SWITCH) and some of the filtering stages (identified by an outgoing off-page connector FILTERS). The RF stage also functions bidirectionally and allows for transmissions to be sent out or received depending on which mode the RF switch is in.

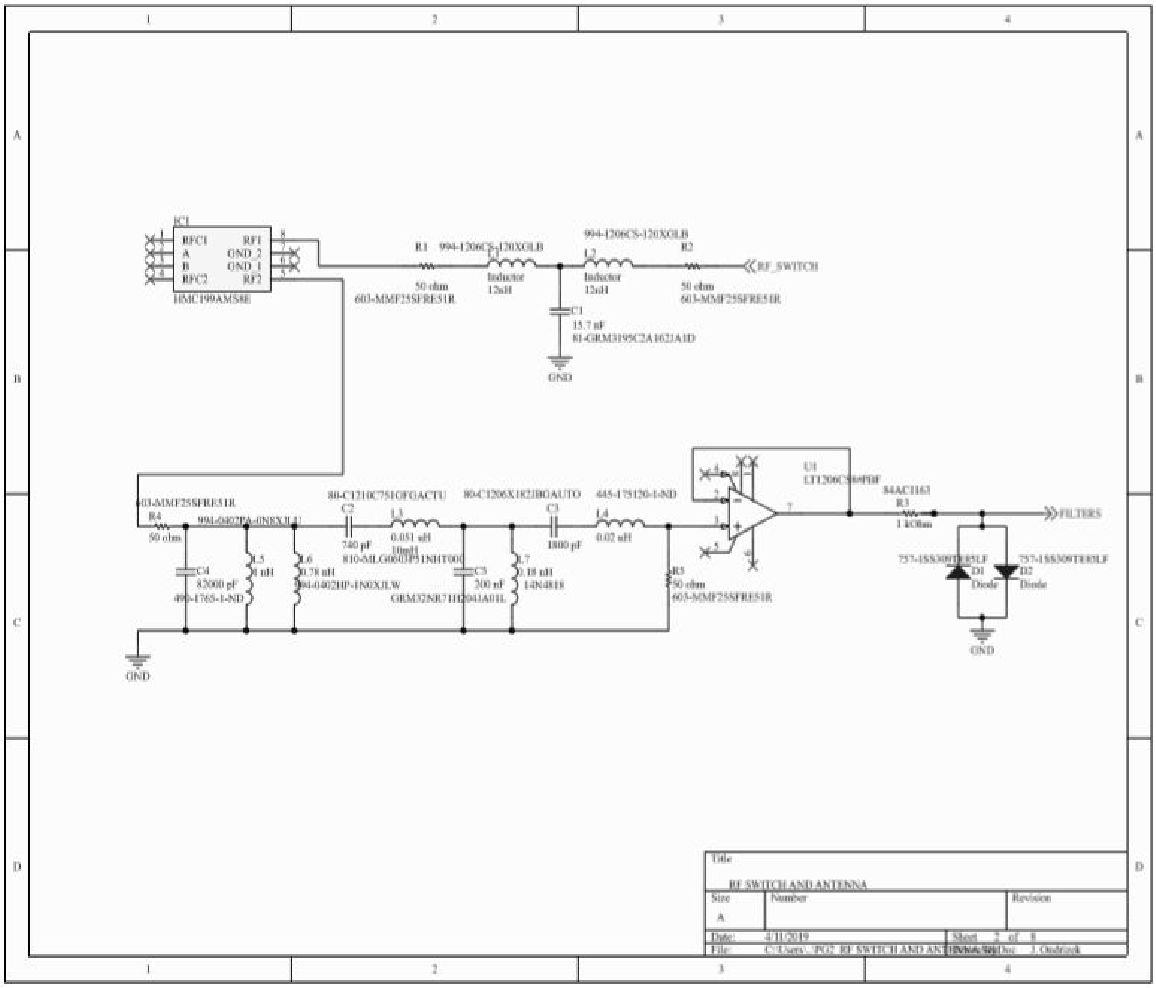


Figure 24: RF Switch and Antenna Stage

The first of the stages connected to the RF switch is the power amplifier and frequency oscillator stage, as shown in Figure 25. A single MEMs crystal oscillator (part number DSC1001CI2-026.8000T) would be used to generate the frequency required at this stage. This signal passes through a protective buffer stage and low pass filter before entering the operational amplifiers which comprise the power amplifier. A potentiometer is used in the driver operational amplifier to ensure that the frequency being amplified and transmitted to the RF switch is within an acceptable range. As previously discussed, we were unable to find a packaged amplifier that suited our needs. Therefore, a power amplifier has been designed by connecting four operational amplifiers in a driver and slave configuration. The signal that passes through the power amplifier is then passed through the low-pass filter and into the RF switch, as seen in the previous image.

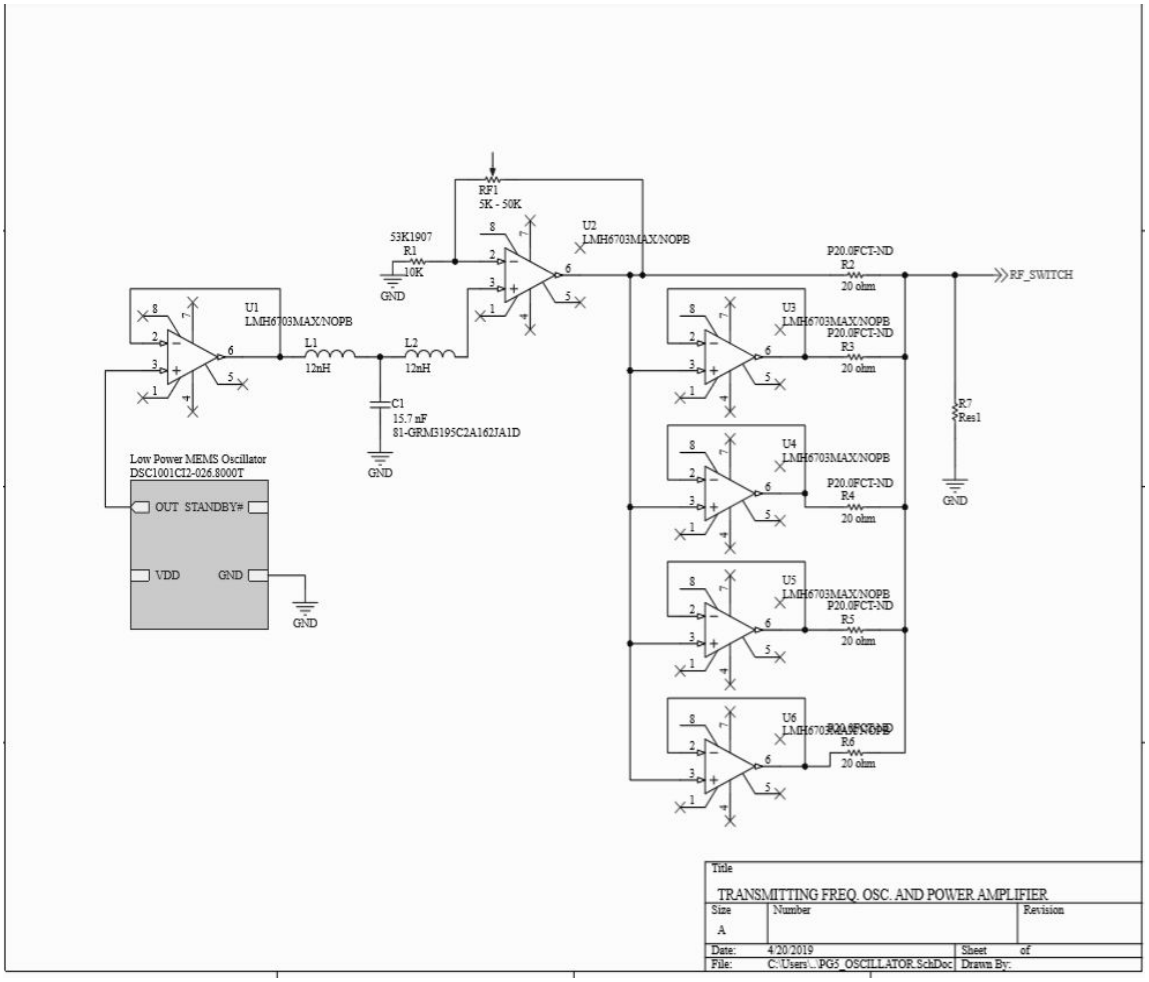


Figure 25: Transmitting Frequency Oscillator and Power Amplifier

The second stage connected to the RF switch is the filtering and limiting stages. This stage performs signal filtering and amplification on the received signals. These stages are performed in the fourth page of the schematic (Figure 26). The signal from the antenna and RF switch is first passed through a fourth order Butterworth bandpass filter. This filtering will ensure that the signal's frequency lies within the desired range. Next, the signal passes through a buffer which protects the circuit. After the buffer, the signal travels through a limiter which clips the waveform to a desired height. This stage protects the rest of the circuit from dangerously high voltages transmitted by the antenna. The two amplifiers positioned after the limiter amplify the signal by 60 (per amplifier) before the signal is clipped by a limiter again. This amplification and clipping process is repeated by a second set of amplifiers before the signal is passed to another buffer.

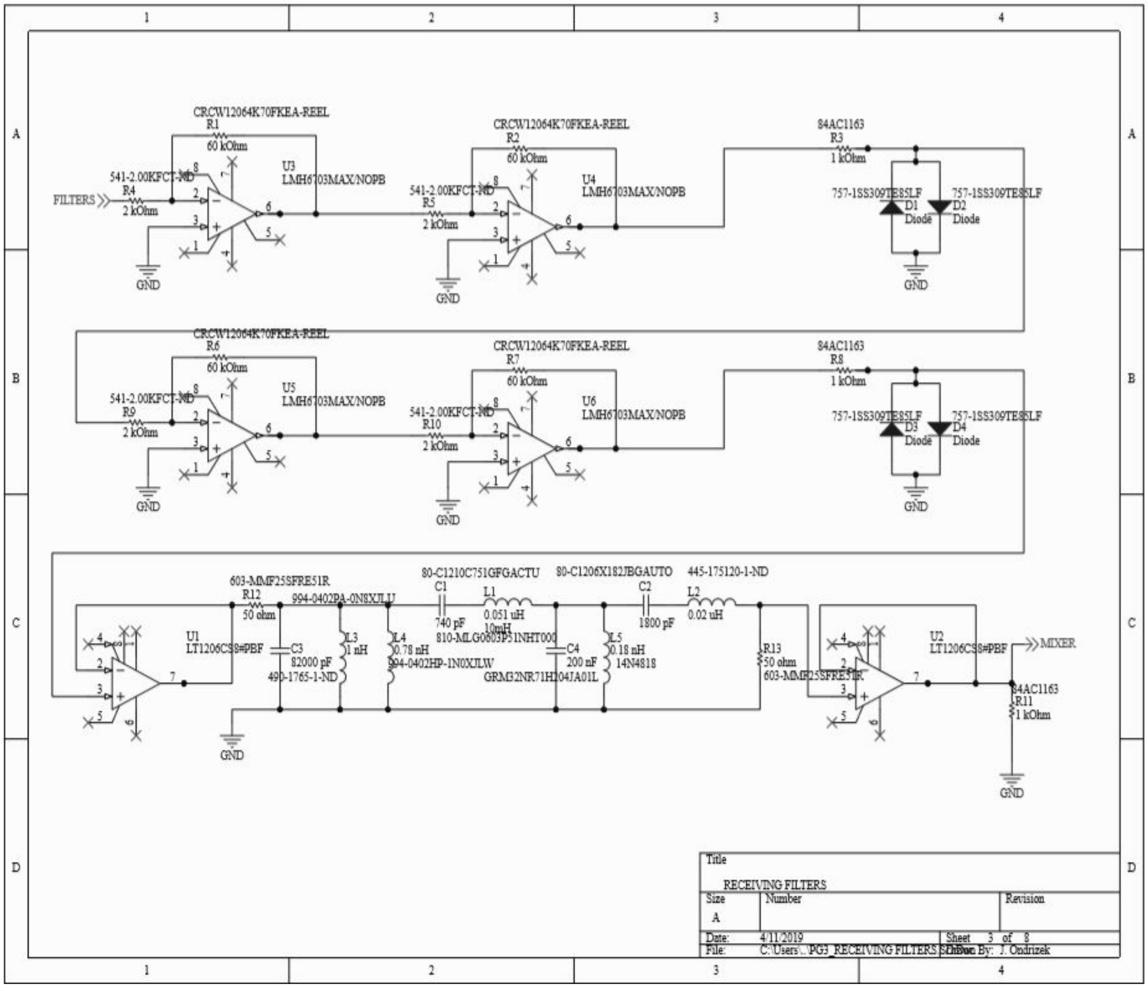


Figure 226: Signal Filtering and Amplification

After passing through the buffer, the signal travels through a second fourth order Butterworth bandpass to be filtered again. The signal passes through another buffer before the signal is sent to the frequency mixer. By repeatedly filtering and amplifying the signal, we can be reasonably sure that the signal will be sufficiently clean

At the frequency mixer stage (shown in Figure 27), the signal is sent to the LT5560 downconverting mixer (courtesy Analog Devices). Modifications to the test circuit have been made to function at 27 MHz. At this stage, the frequency is decreased. This stage is required to verify that the frequency lies within the desired range. This conversion must be performed before being passed to the ADC buffer stage for further digital signal processing.

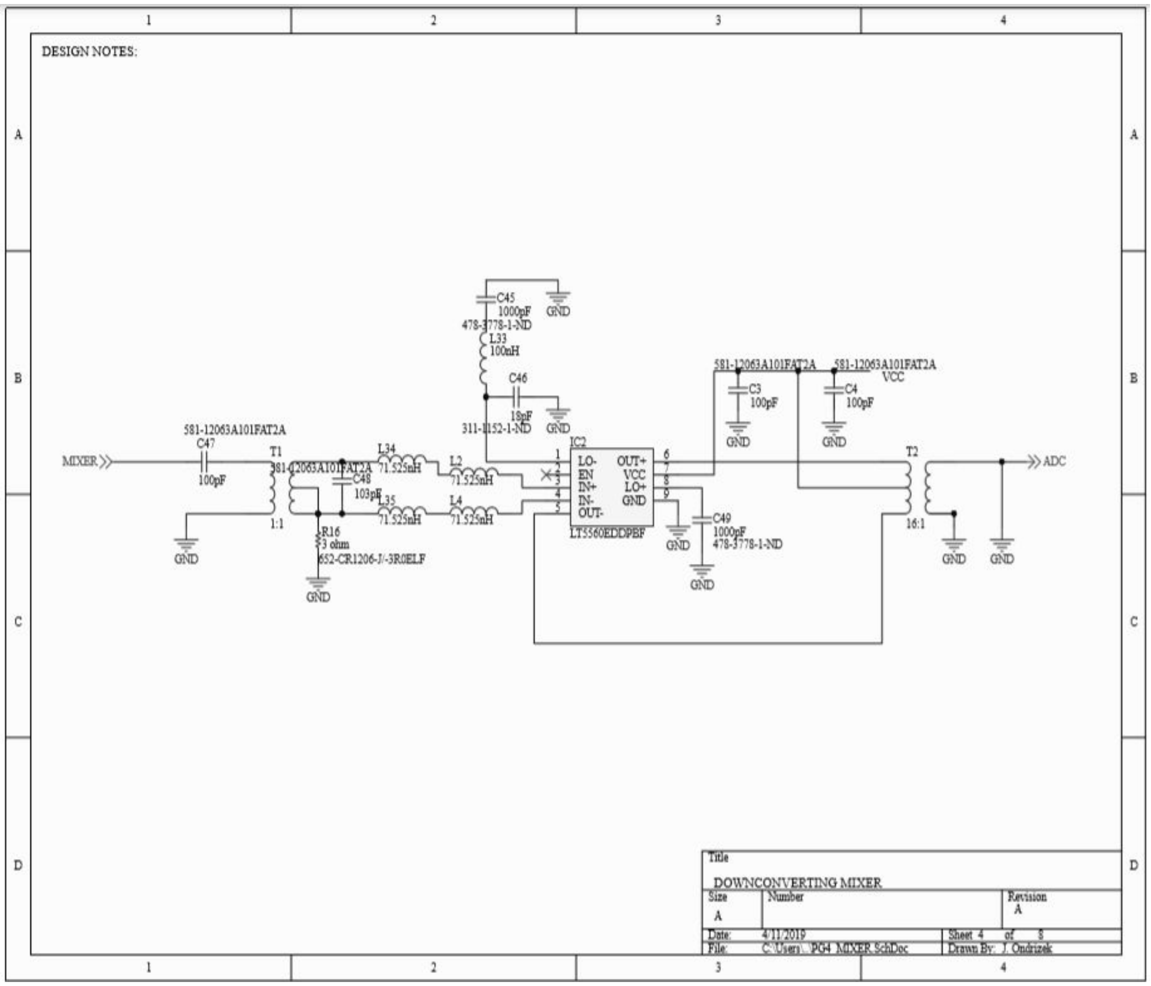


Figure 27: Downconverting Mixer (Courtesy Analog Devices)

In the ADC Buffer stage (shown in Figure 28), the signal is amplified once more by a wideband amplifier (part number LMH6703MAX/NOPB). This schematic is courtesy of Texas Instruments. The test circuit, which was optimized for a different frequency, has been modified for our purposes. This component differs from other amplifiers in that it requires certain nodes to be tied to a common ground point. Care has been taken to identify these nodes within the schematic, and they are denoted by *** next to the node identifier. Within the PCB design, care will also be taken to ensure that the nodes are tied together at the ground plane.

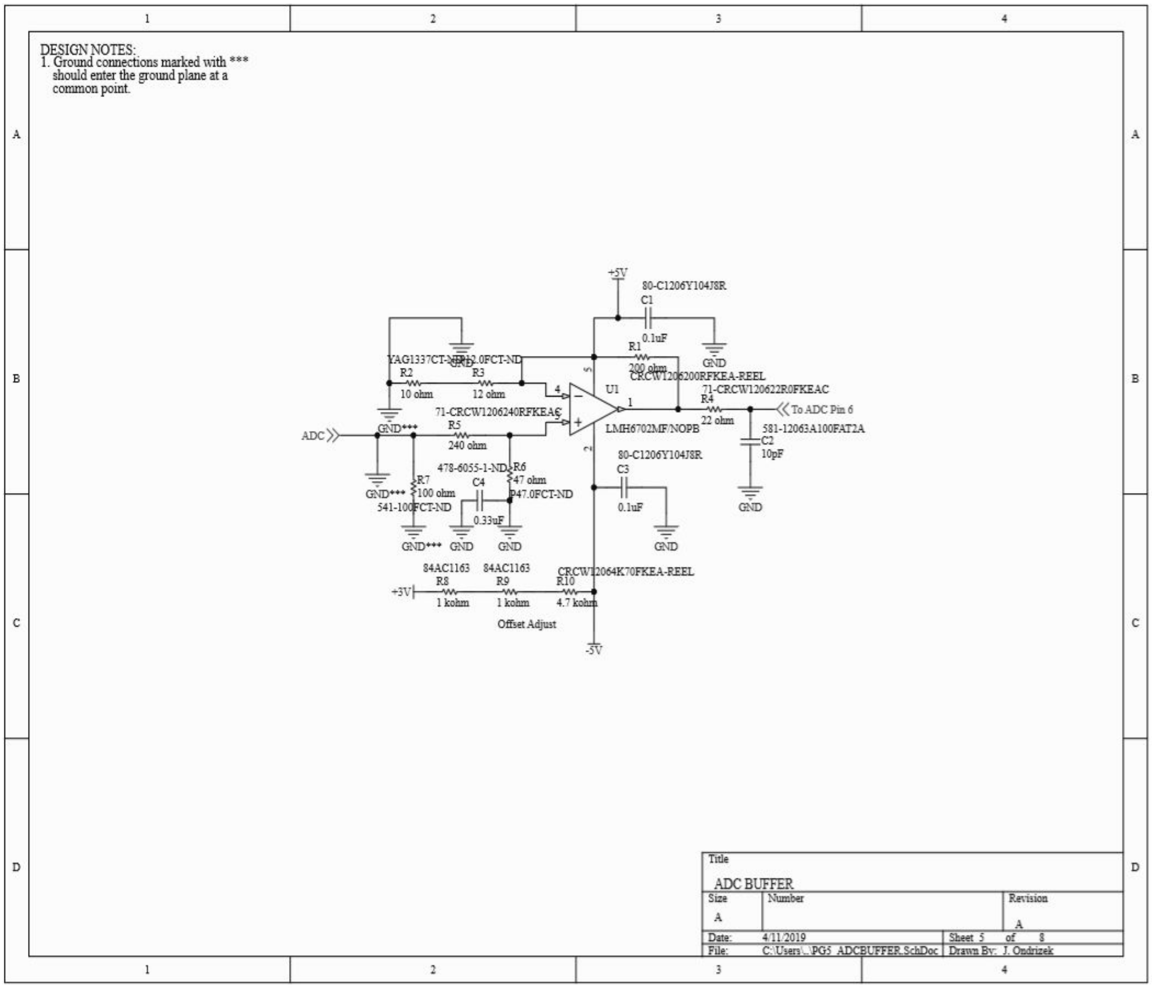


Figure 28: ADC Buffer (Courtesy Texas Instruments)

The schematic will also include layouts of the F228335 microcontroller system, power inputs, and the accessories for this device. The general schematic of the microcontroller system is shown in Figure 29. This schematic is courtesy of Texas Instruments. The purpose of this buffer is to have a low noise methodology to shift the DC bias of the signal that is being provided to the ADC.

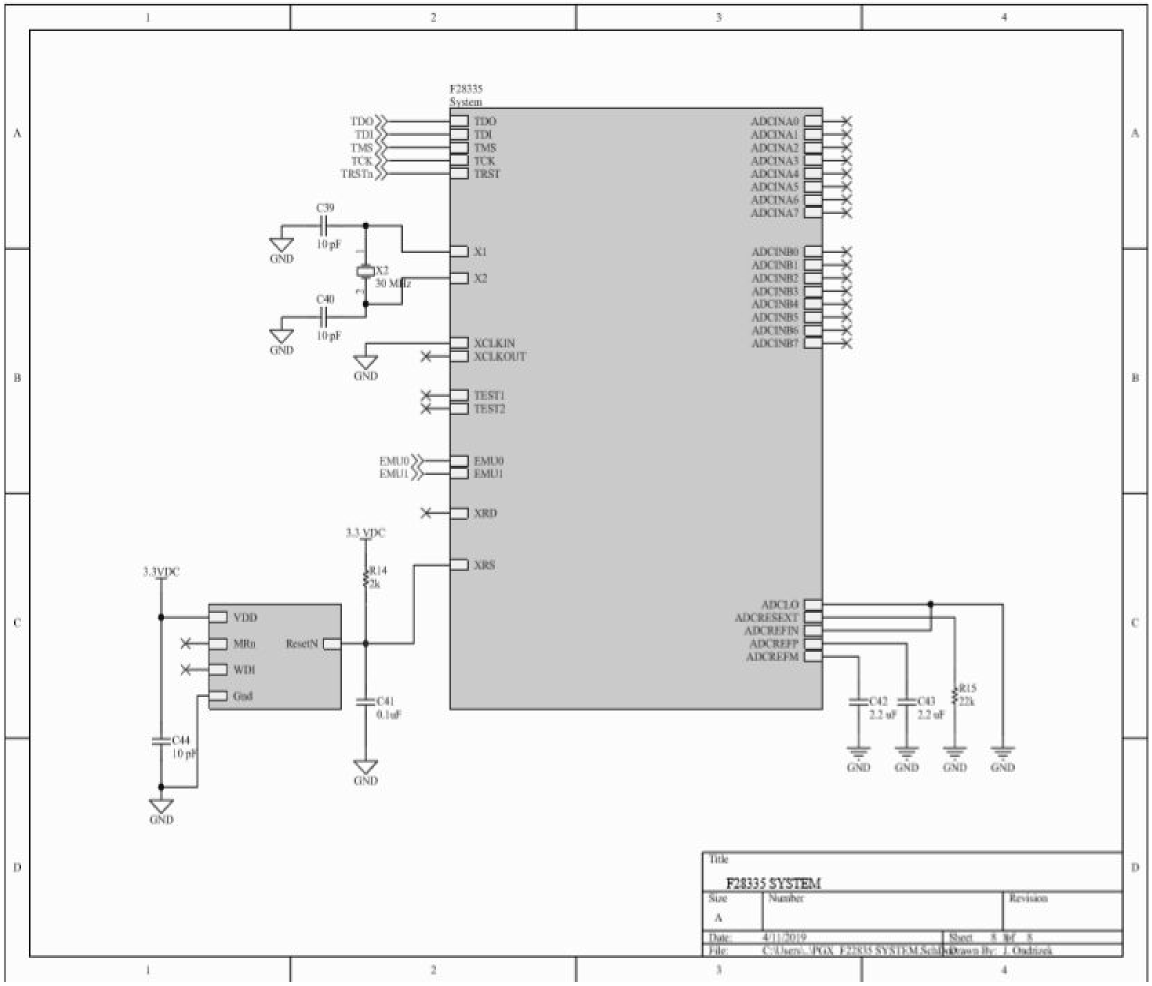


Figure 29: F28335 Microcontroller System (Courtesy Texas Instruments)

The power layout for the microcontroller is shown in Figure 30. This schematic identifies which ports will be used for digital input/output purposes, powering the device, and which pins will be grounded. This schematic is courtesy of Texas Instruments.

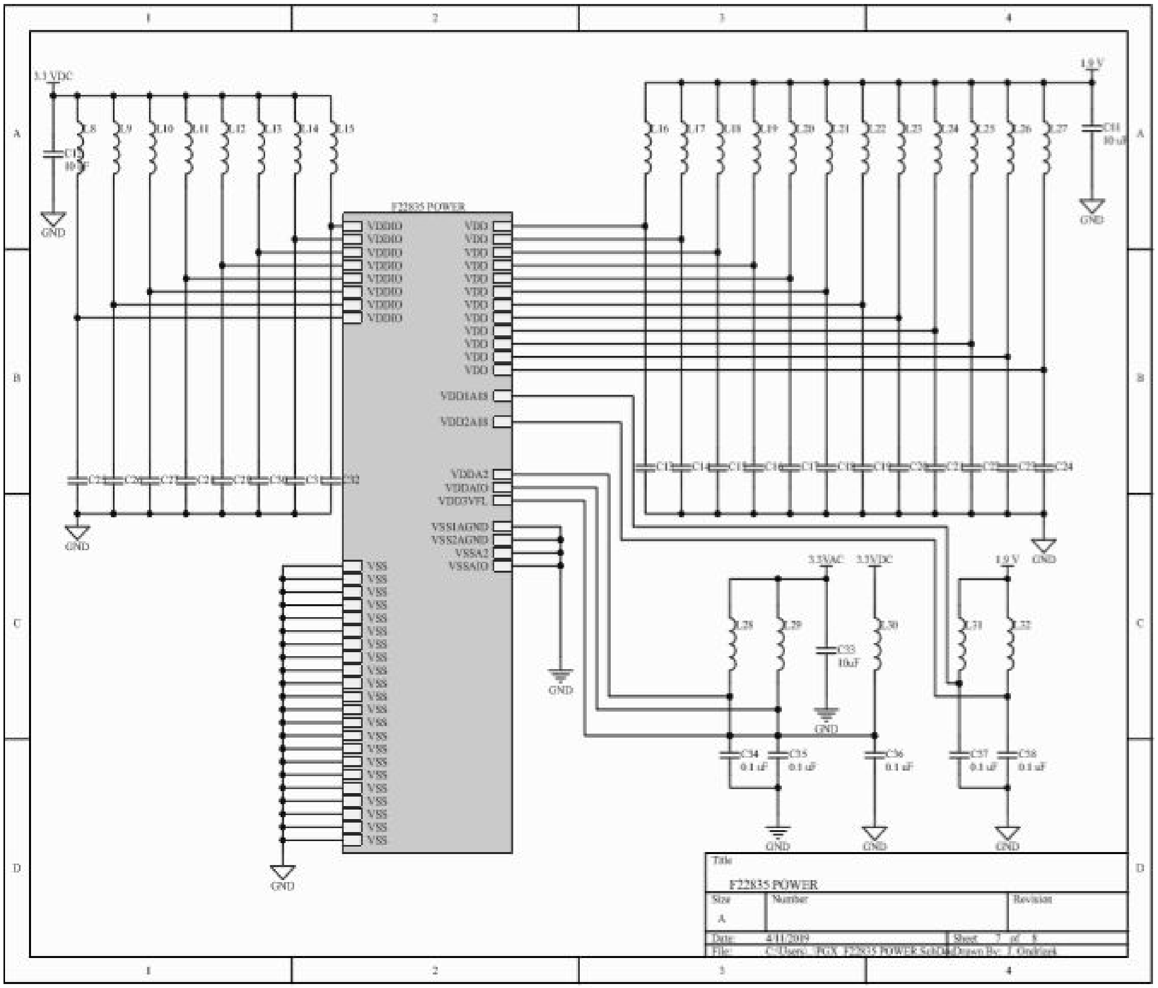


Figure 30: F28335 Power (Courtesy Texas Instruments)

5.3.2 Final Architecture Design and Related Diagrams

In the final 1 MHz design, the schematics were simplified to two Eagle schematic pages: one for transmission and one for reception. Each schematic was then used to generate the PCB design for two 2-layer PCB boards.

These transmitter and receiver schematics were then combined into a single schematic in order to generate the 4-layer PCB design.

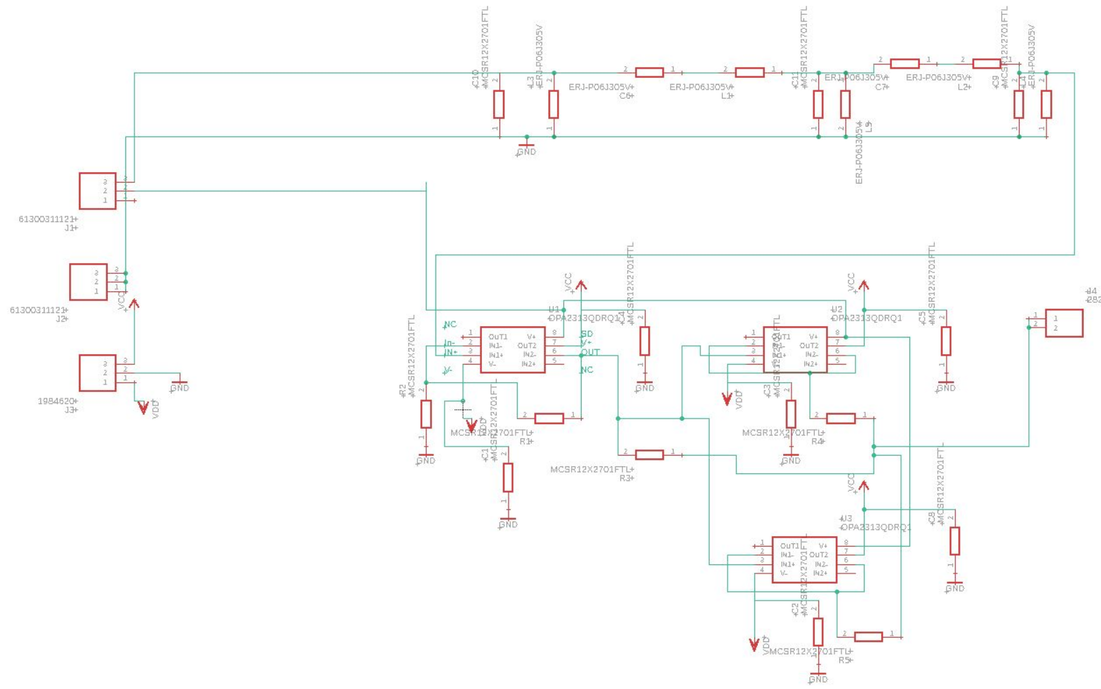


Figure 31: Eagle Schematic for the Transmitter PCB

The transmitter board consisted of a filter and a chain of operational amplifiers to clean the signal and increase the gain of the signal being transmitter. Female header pins were strategically placed along the board to ensure that it could interface directly with the F28335 experimenter kit and to allow for easy power and ground application.

The receiver schematic consisted of a variety of filters, buffers, amplifiers, and limiters to filter and shape the received signal to the desired form.

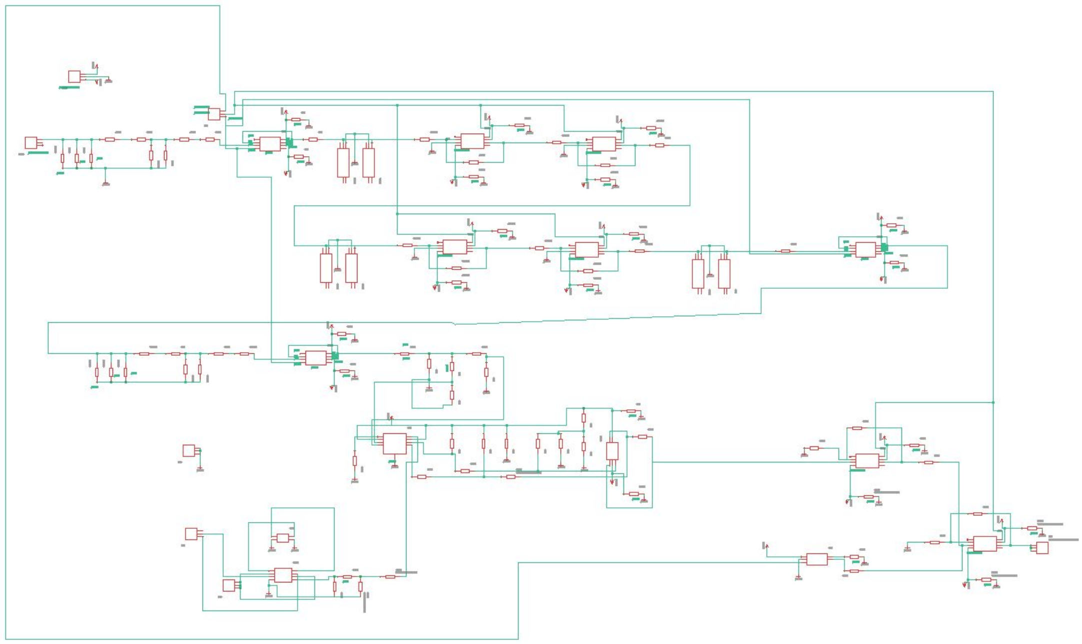


Figure 32: Eagle Schematic for the Receiver PCB

The combination of the receiver and transmitter schematics results in the schematic shown in Figure 35 below.

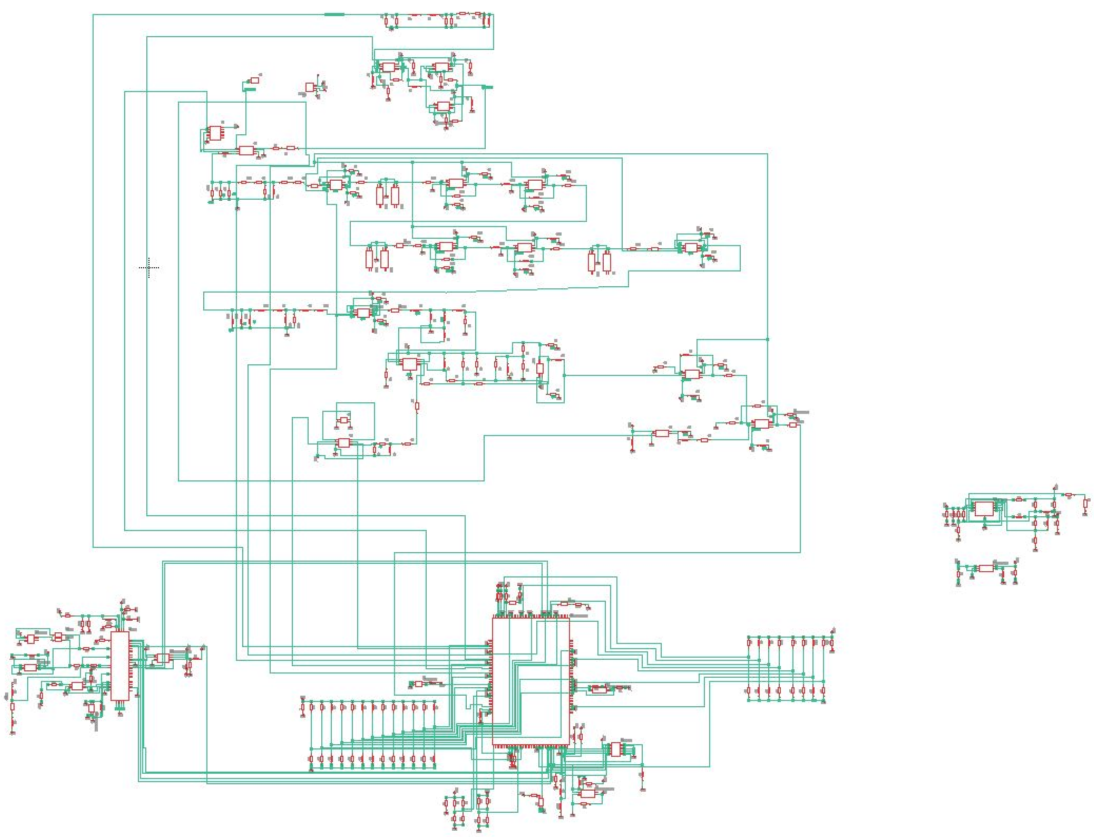


Figure 35: Eagle Schematic for the Four-Layer PCB

5.4 First Subsystem, Breadboard Test, and Schematics

The design of schematics purely in circuit software is insufficient because these simulations are not always accurate. To truly test the behavior of circuitry, the design must be built and prototyped on a breadboard with physical components. The sections below discuss the testing and validation procedures and results of the Butterworth filter and fast Fourier transform.

5.4.1 Filter Validation

The low-pass filter was prototyped in the senior design lab as shown in Figure 34. The low-pass filter was a fourth order Butterworth passive ladder filter that successfully converted a square wave to a sine wave. This filter will be employed directly before the signal enters the downconverter and is also connected to the RF switch. This filter design ensures that the signal is shifted properly, and the information is not lost by interference caused by the harmonics.

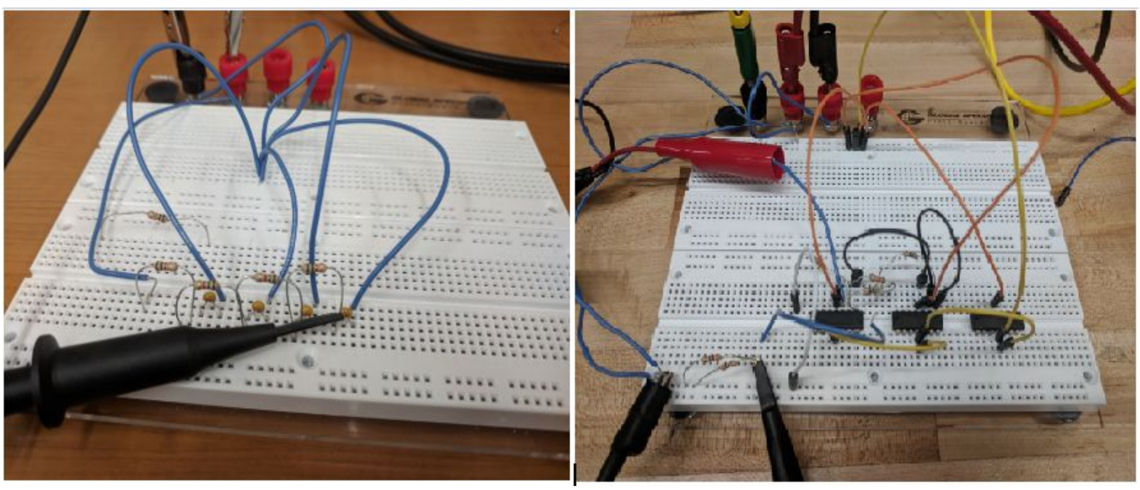


Figure 34 and Figure 35: The Prototyped Low-Pass Filter (shown on the left) and RF Amplifier for High Current Output Using Interconnected Operational Amplifiers

The filter comprised of only resistors and capacitors shown above (on the left) \ is not intended to be implemented in the circuit. The prototype was used only to determine that we could transform a sine wave into a square wave by removing the harmonics beyond the center frequency. The low-pass filter that will be used in the design will consist of resistors, inductors, and capacitors.

The consecutive operational amplifier design (shown in Figure 35 on the right) was also prototyped and tested in the senior design lab. The purpose of this test was to verify that the output current would linearly increase with the addition of multiple operational amplifiers. By using three TL084 operational amplifiers, we were able to supply 17.4 volts across a 50-ohm resistor. The transmitted power (1 Watt) required to drive the sensor was realized by this configuration. The resulting waveform, as seen on the digital oscilloscope, is shown in the screen capture shown in Figure 36.

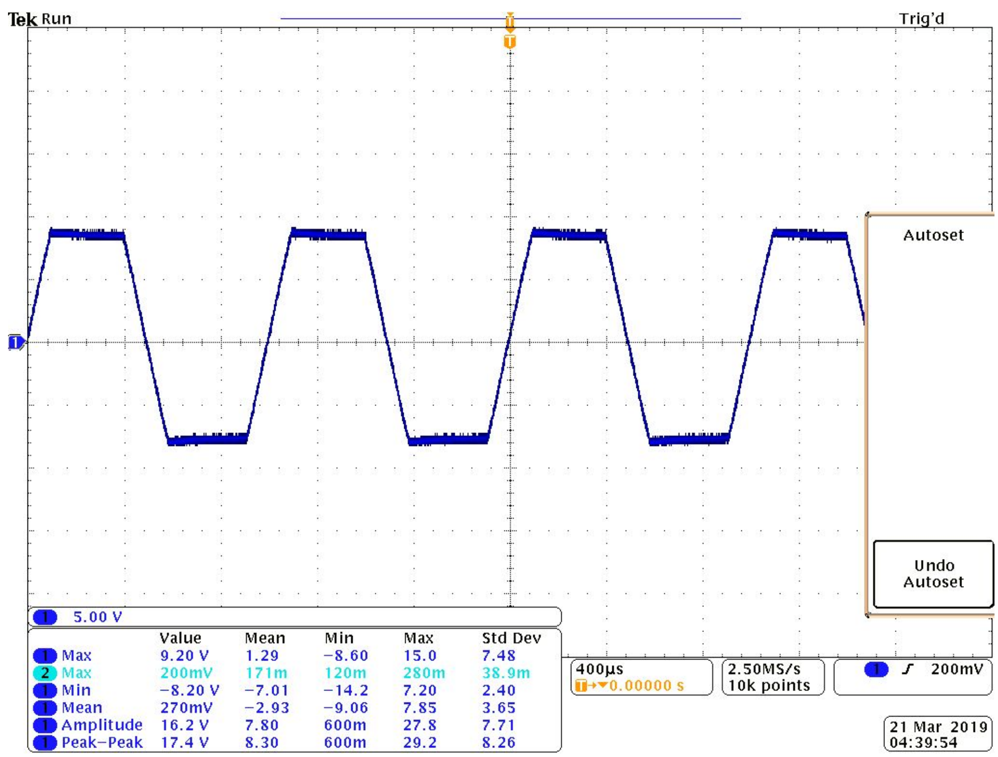


Figure 36: Operational Amplifiers Providing 17.4V Across 50 Ohm Resistor

This test demonstrated that the operational amplifiers could be combined in this configuration without distorting the signal and that the design could provide the current output we need for the project. This experiment proved that a multistage amplifier was feasible within our design.

The required transmitted power specification from the customer was to deliver 1 Watt of power from the transmitter to drive the MEMS sensor. However, after extensive searching through various parts suppliers, we were unable to find a power amplifier that could supply that much power at the given frequency while also satisfying the design specifications for the design. This meant that we had to come up with a way to transmit that much power without using a conventional power amplifier. We decided to follow another approach of using a specific configuration of operational amplifiers as opposed to using a single conventional power amplifier. The challenge of producing the required amount of transmitted power was overcome and the transmitted power required to drive the MEMS device was achieved. We were worried about potential signal distortion that might arise from using three operational amplifiers in this configuration. However, through simulation with Multism and testing in the senior design lab, as shown in the Figure 36 above, we were able to produce the required transmitted power with no signal distortion whatsoever.

5.4.2 Fast Fourier Transform Validation

Additional testing was done to prove the functionality of Fourier transforms. The diagram of Figure 37 showed a spike at a certain frequency, but the frequency did not match that which was input. The graph would shift when the frequency changed, but the accuracy proved insufficient for the project. The signal input was a 500 kHz sine wave. The sensitivity and resolution of the Fourier transform was incredibly low at the 500 kHz frequency. As such, it is not a viable option to be used in this design of this project as measurement accuracy, which is directly related to high resolution and sensitivity of the Fourier transform, is compromised.

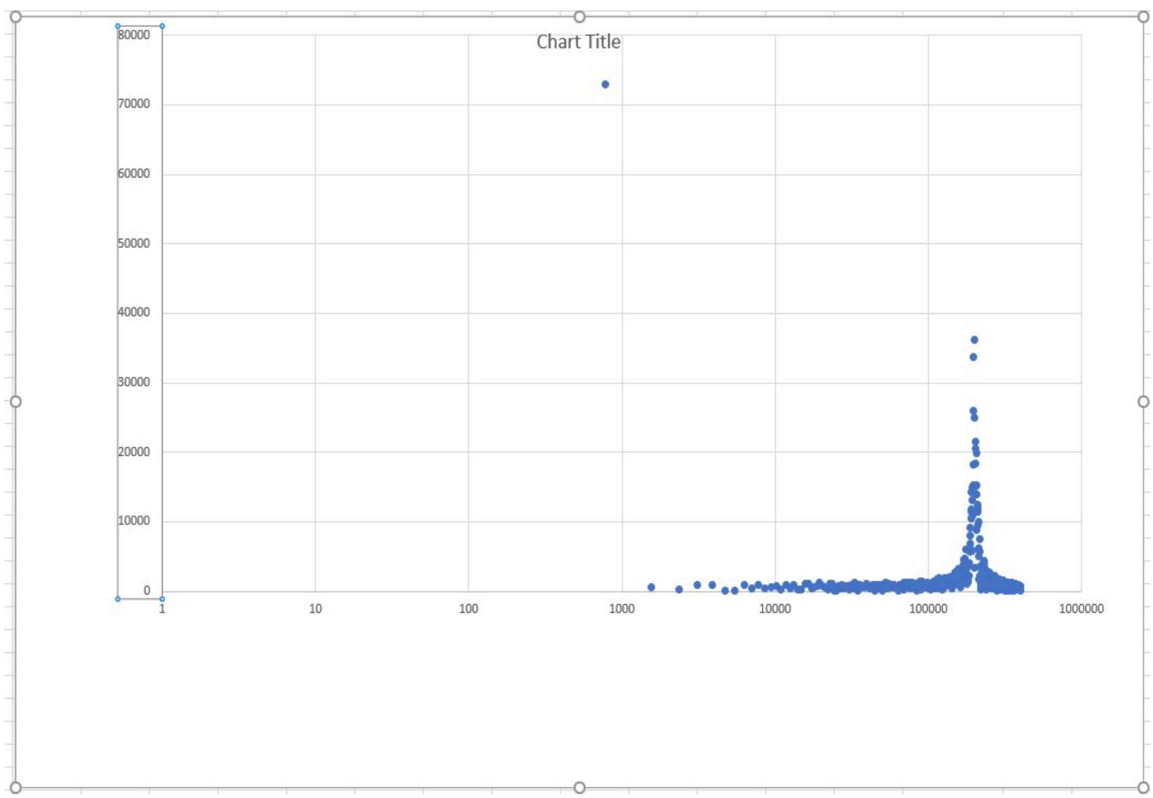


Figure 37: Prototyped Fast Fourier Transform Given a 500 kHz Sine Wave

It is further demonstrated that the Fourier transform was functional even though was not accurate enough, by the next graph shown below in Figure 38. This graph is the response of a square wave input. We see in the graph that there exists the characteristic exponential decay in the harmonics of the Fourier transform of the square wave. This graph was plotted within the Arduino IDE serial plotter and is representing a square wave at 75 Hz. The system proved to be more accurate at low frequencies but failed to perform at higher frequencies as previously above. Getting accurate Fourier transform data is crucial to the vibration profile analysis and it is therefore important to be able to provide accurate Fourier transform data with a high degree of precision and sensitivity. Due to the frequency limitation, the tested device could not be used to perform Fourier transform on the incoming sensor signal.

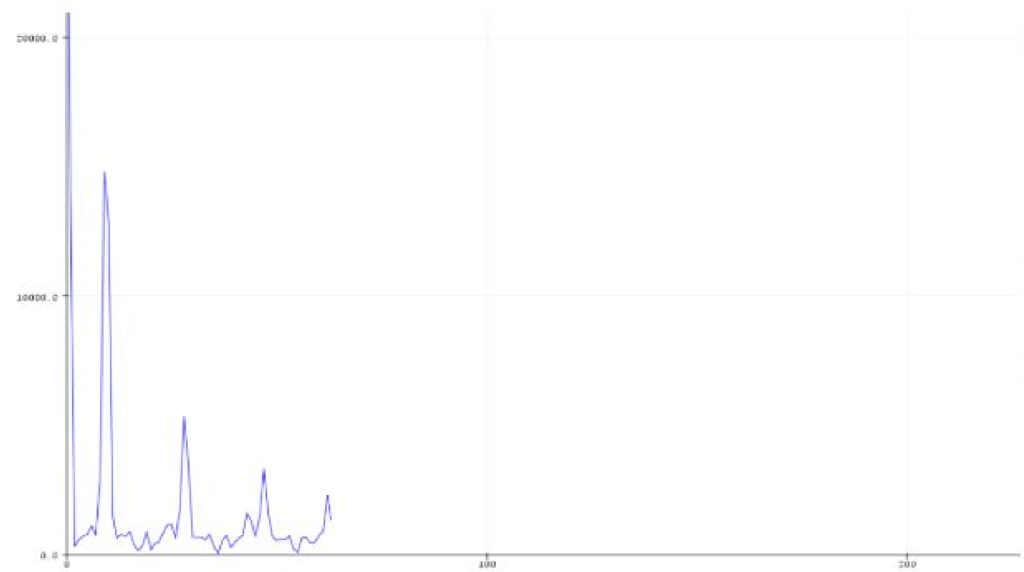


Figure 38: Prototyped Fast Fourier Transform Given a 75 Hz Square Wave

5.5 Parts Received

The above parts for the project have been received, as shown in Figure 39. The parts shown in the figure are as identified in Table 8.

Table 8: Parts Received

Identifier	Part
A	Amplifier
B	Oscillator
C	MCU
D	Oscillator
E	Oscillator
F	UART Interface
G	ADC Buffer
H	Voltage Regulator
I	Amplifier
J	Diode
K	Amplifier
L	RF Mixer
M	Power Operational Amplifier

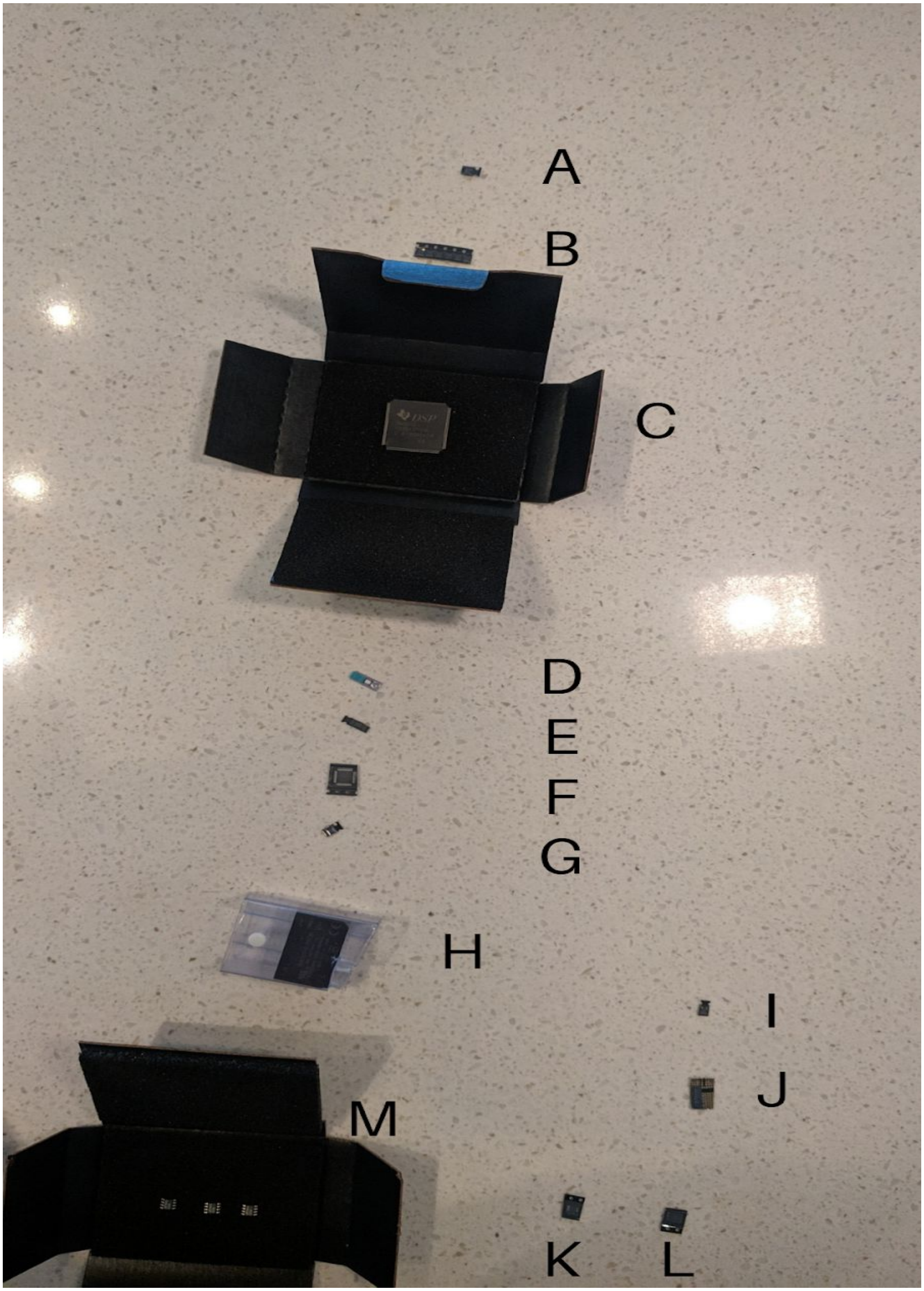


Figure 39: Received Parts

6.0 Project Prototype Construction and Coding

The prototyping phase begins once the schematic designs have been completed. During this phase, the printed circuit board is designed, ordered, and tested. It is important to consider the size of the components, and the capabilities and limitations of the design software and PCB vendor during this section of the design process. The sections below describe the process through which the parts, software's, and vendors were selected.

6.1 Parts Acquisition and BOM

There are a few main websites that were considered for parts acquisition: Newark, Texas Instruments, DigiKey, and Mouser. Newark was quickly rejected as a retailer because, although they are well known, they are a smaller online retailer and do not sell many of the components that are to be ordered. Texas Instruments was also considered as a supplier because many of the components used in the design are made by Texas Instruments. However, many of the parts are available from other suppliers like DigiKey and Mouser and purchasing directly from the manufacturer did not offer a significant amount of savings. To save on the cost of shipping and to avoid the hassle of ordering from multiple retailers, Texas Instruments will only be used if the components are not available anywhere else.

DigiKey and Mouser, which are two of the largest online retailers of electrical and electronic components, does offer many of the parts which are to be ordered. Both websites offer same day shipping for orders placed before a specified cutoff time. Additionally, both websites offer comparable parts pricing. Both Mouser and DigiKey also provide performance metrics, operating conditions, and other important general information about the devices being looked at which also helps to streamline the selection process as we can readily search for devices that fit our budget but also satisfy the required performance metrics. Because the sponsor is responsible for ordering the parts, we will suggest that they order from one of these two websites to avoid paying for shipping multiple times and to avoid shipments from multiple vendors. Moreover, purchasing all the parts of the device using both websites also helps to keep receipting and documentation more organized. For all the reasons, the decision was made to use both DigiKey and Mouser for all parts ordering except when it is not possible to do so.

The bill of materials (BOM) as supplied to our sponsor is shown below in Table 9 and Table 10. Table 9 identifies the most important components, such as the operational amplifiers, downconverter mixers, MCU, and power sources. The total cost of these major components is $230.71.

Table 9: Bill of Materials for Major Components

QUANTITY	DESCRIPTION	MANUFACTURER	PART NUMBER	PRICE (PER UNIT)
3	Operational Amplifier	Linear Technology	LT1206CS8#PBF	$9.74
10	Operational Amplifier	Texas Instruments	LMH6703MAX/NOPB	$3.78
6	Diode	Toshiba	1SS309(TE85L,F)	$0.48
1	Down Converter Mixer	Analog Devices	LT5560	$1.61
1	RF Switch	Analog Devices	HMC199AMS8 / 199AMS8E	$2.54
1	32-bit Delfino MCU	Texas Instruments	F28335	$25.00
1	USB to Serial UART	Future Technology Devices International	FT2232D	$6.99
1	D Flip-Flop	Texas Instruments	SN74LVC2G74QDCURQ1	$0.65
1	IC EEPROM	Microchip Technology	93LC46BT-I/OT	$0.21
1	Mix Frequency Oscillator	Microchip Technology	DSC1001CI2-026.8000T	$1.54
1	Transmit Frequency Oscillator	Epson	SG-210STF 27.1200ML3	$1.18
1	MCU	Texas Instruments	TMS320F28335PGFA	$22.75
1	JTAG Interface	Digilent	424-JTAG-HS2-H-S-C	$49.99
1	ADC Buffer	Texas Instruments	LMH6702MF/NOPB	$3.38
1	MCU Crystal Oscillator	Ecliptek	EC3645ETTS-30.000M TR	$1.22
1	Wall Wart Board Power Digital	RECOM Power	RAC05-12SK/480	$15.41
1	Wall Wart Board Power Analog	RECOM Power	RAC20-15DK	$11.32
1	On Board 3.3V Power Adapter	RECOM Power	RAC01-3.3SGB	$5.68
1	On Board 5V Power Adapter	RECOM Power	RAC15-05SK	$11.34

Table 10 summarizes the passive components which will be used in the design. Because the sponsor wishes to have an accurate quote for the total cost of the design and does not wish to utilize free elements in the design, the cost of these pieces must be included in the BOM. The total cost of the passive components is $45.68.

Table 10: Bill of Materials for Passive Components

QUANTITY	DESCRIPTION	MANUFACTURER	PART NUMBER	PRICE (PER UNIT)
6	2 kohm resistor	Vishay	CRCW12062K00FKEA	$0.10
6	50 ohm resistor	Yageo	MMF25SFRE51R	$0.24
1	470 ohm resistor	Vishay	CRCW060347R0FKEAHP	$0.17
2	27 ohm resistor	Bourns	CR1206-FX-27R0ELF	$0.10
8	1 kohm resistor	Vishay	CRCW12061K00FKEBC	$0.18
5	20 ohm resistor	Panasonic	ERJ-8ENF20R0V	$0.10
2	2.2kohm resistor	Panasonic	ERJ-8ENF2201V	$0.10
2	10kohm resistor	Vishay	CRCW120610K0FKEAC	$0.10
1	47kohm resistor	Vishay	CRCW120647K0FKEAC	$0.18
4	60 kohm resistor	KOA Speer	RN732BTTD6002B25	$0.80
1	1M ohm resistor	Yageo	RT1206DRD071ML	$0.33
1	3 ohm resistor	Bourns	CR1206-J/-3R0ELF	$0.10
1	10 ohm resistor	Yageo	RC1206FR-0710RP	$0.18
1	12 ohm resistor	Panasonic	ERJ-8ENF12R0V	$0.10
1	200 ohm resistor	Vishay	CRCW1206200RFKEAC	$0.10
1	22 ohm resistor	Vishay	CRCW120622R0FKEAC	$0.12
1	240 ohm resistor	Vishay	CRCW1206240RFKEAC	$0.18
1	100 ohm resistor	Vishay	CRCW1206100RFKEAC	$0.19
1	47 ohm resistor	Panasonic	ERJ-8ENF47R0V	$0.10
1	4.7k ohm resistor	Vishay	CRCW12064K70FKEAC	$0.19
12	100 nF / 0.1 uF	Kemet	80-C1206Y104J8R	$0.69
2	1 uF capacitor	AVX	12063C105JAT2A	$0.78
2	15.7 nF* capacitor	Murata Electronics	GRM3195C2A162JA01D	$0.45
2	820 pF capacitor	AVX	12103A821FAT2A	$0.72
2	7.4 pF capacitor	Kemet	C1206C829J5GACTU	$0.47
2	1800 pF capacitor	Yageo	CC1206JRNPO9BN180	$0.29
2	200 nF capacitor	AVX	12061C202JAT2A	$0.33
3	100 pF capacitor	AVX	12063A101FAT2A	$0.67
2	1000 pF capacitor	AVX	12061A102FAT2A	$0.70
1	10 pF capacitor	AVX	12063A100FAT2A	$0.67
1	0.33 uF capacitor	AVX	12065C334JAT2A	$0.54
1	102 pF capacitor	AVX	08051AVEDFAT2A	$0.67
1	18 pF capacitor	Vishay	VJ1206A180JXBAC	$0.34
2	0.43 nH inductor	LQP02TQ0N4B02D	Mutura Electronics	$0.21
2	0.18 nH inductor	MHQ0402PSA0N2BT000	TDK	$0.10
2	0.051 uH inductor	0805HQ-51NXGLC	Coilcraft	$1.26
1	22 uH inductor	AISC-0805F-220G-T	Abracon	$0.36
4	12 nH inductor	1206CS-120XGLB	Coilcraft	$1.06
2	1 nH inductor	L-14C1N0SV4T	Johanson Technology	$0.10
2	0.78 nH inductor	0402PA-0N8XJLU	Coilcraft	$1.43
2	0.02 uH inductor	0805AS-R20G-01	Fastron	$0.25
4	72 nH inductor	744917172	Wurth Electronics	$0.72
1	100 nH inductor	AISC-1210-R10J-T	Abracon	$0.32
1	LFSPXO025820Bulk	6 MHZ Oscillator	IQD	$1.47

6.2 PCB Vendor and Assembly

The sections below compare the various software's and companies that were considered in the PCB design process. The design software was chosen based on cost, ease of use, and additional features. The vendor which was used to fabricate the final PCB design was chosen based on cost, location, turnaround time, and reputation.

6.2.1 PCB Design Software

Once the schematic design is finalized, the design of the printed board may begin. A printed circuit board is a device which provides an interface for integrated circuits to be placed and provides the pads and lines which create the electrical pathway between various components. PCBs are typically made of a FR-4 substrate, a copper conductive layer, and a solder mask which insulated the copper layer. Because printed circuit boards can interface with numerous integrated circuits, silkscreen printing is typically done at the end of the fabrication process to label various components or provide an outline of where components will be soldered. If the PCB has multiple layers, the complexity of the device increases. Pathways between each of the layers are created by drilling vias, or holes in the board which allow electrical signals to travel between layers.

Because the design of the PCB is so complex, it requires powerful modeling software. Most PCB software allow for 3D modeling to show the height, width, and depth of the components and traces. Schematics which include the sizing information of the components may be imported to speed up the design process.

A couple of PCB software's were considered for design: Eagle, OrCAD PCB Designer, and Altium Designer. Eagle, which is the software suggested typically suggested to senior design students, is available to University of Central Florida students for free. Like most PCB software's, Eagle includes parts libraries and allows users to customize the operation of the application by creating design blocks. Additionally, users can create design rules that will make the design process easier. The software separates the design into schematic and board designs. Since Eagle includes the capability to design both, it will be easy to integrate the schematic into a prototype PCB board. Another advantage of using Eagle for prototyping is its prevalence among engineers. It is a well-known design platform so there are variety of resources available to assist new users. The biggest disadvantage of this program, which prompted the search for other software's, is the ease of use. The schematic software is not very intuitive as it requires users to place the exact parts that will be used into the design. Although this is not a problem for the larger components, this is problematic due to the number of resistors, capacitors, and inductors that will be used in the design. Another disadvantage of Eagle is that it is typically used to prototype hobby designs rather than for professional-level design.

OrCAD PCB Designer is another professional-level PCB software that was considered. Since two of the members of the group have previous work experience with OrCAD programs, this would have been the ideal solution. However, PCB Designer is not available for free to UCF students and is expensive for a full version of the software. A trial version (OrCAD PCB Designer Lite) is available for free and does not have a time limitation like most trial versions of software. Instead, the trial version is limited by the size of the design and will support a set number of pins and connections. It is possible that our design will fall below this threshold, but we do not wish to risk the chance of reaching the limit halfway through the design.

The PCB design software that will be used for this project is the student version of Altium Designer. This version of Altium Designer is available as a yearly license that is offered a discounted rate. This design environment was ultimately chosen due to four key factors:

1. Price - The student version of Altium is available for $99.
2. Ease of use - Altium supports schematic and PCB designs as well as simulation capabilities within the same software. This will minimize the amount of design transfer that occurs between design programs and the individuals responsible.
3. A large component library - A large component library ensures that all simulations and designs include the correct parts information. Additionally, the use of the built-in library will make the PCB design process easier by providing the footprint of the components.
4. Real-time bill of material (BOM) management - Rather than spending unnecessary time creating and updating a parts list, Altium Design can track component changes as they occur. The information provided by ActiveBOM includes supplier information, availability, and component prices from various supplies.

The table shown summarizes the key factors that led to the selection of Altium Designer:

Table 11: Comparison of PCB Software

Software	Cost	Advantages	Disadvantages
Eagle	FREE	● Free	● Prototyping software; not professional grade ● Not intuitive
OrCAD PCB Designer (Lite)	FREE	● Previous experience ● Free	● Limited number of pins
Altium Designer	$99	● Professional grade software	● Not intuitive

		• Many useful tools	

Although Altium Designer was selected for the design, the group had to resort to EAGLE Premium to redesign the software when it was discovered that there is a bug within Altium Designer 18 and 19 that prevents the NC drill file from being generated.

6.2.2 PCB Vendor

A few vendors were considered for the fabrication of the printed circuit board. The sponsor requires a 4-layer PCB board, so the PCB vendor must be capable of fabricating devices with multiple layers. One vendor considered, which was recommended by classmates in Senior Design II, is PCBWay. Although this vendor is in China, the company offers 24-hour turnaround time and free international shipping. However, to ensure that the project progresses at a reasonable pace, we will place priority on cost and production and shipping times and will prefer companies located within the United States.

Two other vendors, Express PCB and Precision Technologies have also been considered but will likely not be chosen as the vendor. Although both companies have fast production times, Express PCB requires customers to design and order the PCB in their software. This would require additional design time since the PCB for this project will be designed in Altium Designer. Precision Technologies is targeted for customers who need assistance in designing the PCB and customers who are purchasing numerous boards.

Table 12: Summary of PCB Vendors and Considerations

Company	**Location**	**Production Time**	**Cost of Production and Shipping**
PCBWay	China	5 days	$111
Advanced Circuits	United States	5 days	$80
ExpressPCB	United States	Typically, 1-day lead time	Unknown - price quotes only available in their ExpressPCB software
Precision Technologies	United States	Offer same day production	$400

PCBWay was the selected vendor. Three separate orders, one for the transmitter daughterboard, one for the receiver daughter board, and one for the four-layer board, were placed.

6.2.3 PCB Component Selection

Two primary mounting methods are available for components: through-hole mounting and surface mounting. Through-hole mounting requires the PCB to have holes drilled through the surface. The metal leads of the through-hole component can connect to layers of the PCB beneath the surface. This allows for a better connection and the device can withstand more environmental stresses. However, through-hole components take up more space than surface mounted components. Surface mounting requires the component to be soldered to the surface of the PCB. Since this method does not require holes to be drilled into the PCB, it decreases the fabrication cost. The cost of through-hole and surface mounted components are comparable, so the cost is not a deciding factor for our project.

The components chosen for the PCB will primarily be surface mounted (SMD) parts. When choosing components for the design, the rated value of operation is the primary consideration. After selecting the rated value for the passive components, the size of the component is considered. Components which are too small will be incredibly difficult to solder to the board. Conversely, components which are too large will take up more space on the PCB and will cause the PCB to appear bulky. The components used have been selected to fall within the 1206 to 1500 imperial size range.

Resistors have been chosen to have a tolerance of 5% or less to ensure that the rated value is as close as possible to the desired value. The two main types of SMD resistors are thin-film resistors and thick-film resistors. The main difference between these two resistor types is the method of fabrication; thin-film resistors are produced through sputtering techniques while thick-film resistors are produced through screen and stencil printing. Thin-film resistors typically cost significantly more when compared to thick-film, so thin-film resistors are typically reserved for high-frequency microwave applications or applications where high-precision is of the utmost importance. Since thick-film resistors are capable of handling frequencies in the megahertz range and are generally less expensive, they will be our resistor of choice.

Inductors have been selected so that their self-resonant frequency is approximately 10 times greater than the frequency of operation. By ensuring the self-resonant frequency is significantly higher than the frequency of operation, it prevents the inductor from acting as an open and impeding the signal from passing through. In most cases, the self-resonant frequency of the chosen inductors is significantly higher than then required 270 MHz range. However, it was often difficult or impossible to find inductors with the exact rated inductance value that was required. The parts chosen were often a few values off from the desired value.

6.2.4 PCB Design Considerations

The PCB design process can be made simpler by researching and considering the design process prior to beginning the design process. The follow sections discuss some of the tutorials and important information which is relevant to design of the four-layer PCB used in our design.

6.2.4.1. Inductance and Capacitance of Copper Traces

Most materials, especially metals, have inherent resistance, conductive, and inductive properties. Even if these effects are small, it is important consider them in some cases. The resistive effects of the copper traces can be neglected because the PCB likely will not support more than a few mA of current and will be very mall. However, because our design includes small capacitor and inductor values, it is possible for the intrinsic inductance and capacitance of the copper traces to exceed the ratings of the components of the design. Therefore, it may be possible to design the length of the copper traces to meet our required inductance and capacitance values. If it is possible to design the PCB traces to intrinsically have the desired values, it would reduce the number of parts to be purchased and soldered and thereby help decrease the cost of the design.

To design for the capacitance and inductance values of our design, the length, width, height, and thickness of the copper trace needs to be considered. The inductance value of a length of copper wire can be approximated by $L(nH) = 2ln(5.98h/0.8w + t)$ and the capacitance can be approximated by $C(pF) = [0.264(r + 1.41) / ln(5.98h/0.8w + t)]$ [44]. Additional considerations include the characteristic impedance, which describes the capacitive and inductive behavior of the transmission line as the voltage and current waves propagate along the length, and the dielectric of the PCB material [43]. The dielectric of the PCB material is easier to account for, as most PCBs are made of FR-4 which has a typical permeability of 4.5.

Although the inductive and capacitive effects of the copper traces may prove to be beneficial to our design in some cases, is could also introduce stray capacitance and inductance. To minimize these effects, the length, width, height, and thickness of the copper trace will be kept to a minimum when possible.

6.2.4.2 Inductance and Capacitance of Vias

Just as copper traces can introduce capacitance and inductance effects, vias can introduce similar effects [44]. Vias typically introduce capacitance and inductance at high frequencies (on the order of hundreds of MHz) or if energy is passing through the via. Because our sponsor requires the use of a 4-layer PCB, the device will contain numerous vias, so it is necessary to take these effects into consideration. Although our design does not utilize very high frequencies, it is possible that the 27 MHz may introduce some undesired effects.

The inductance of the vias can be approximated by $L(nH) = (h/5)[1 + ln(4h/d)]$ and the capacitance of the vias can be approximated by $C(pF) = (0.0555rhd1) / (d2 - d1)$ where *h* is the height of the via, *d* is the diameter of the hole, d_1 is the diameter of the top layer of the trace, and d_2 is the diameter of the trace of the bottom layer [44].

6.2.4.3 High Frequency Input and Output Current Path

Because high frequency signals will be routed through the PCB, it is necessary to consider the effects of frequency on current paths. In high frequency applications, signals will not follow the path of least resistance - rather they will follow the path of least impedance [44]. In most cases, the path of least impedance will occur just under the trace path.

To improve the quality of the signal and to provide the best current path, the trace length should be kept to a minimum and minimize the number of loops between the signal source and destination. Ideally, the distance between the source of the signal and the destination will be kept to a minimum.

6.2.4.4 Suggested PCB Layout

The PCB design of this device is required to have four layers to allow for a more organized and intuitive layout and improved functionality. To keep the design organized, the PCB is expected to be arranged with the following layers: component layer, signal layer, power layer, and ground layer.

1. The component layer will form the top layer of the PCB. Here, the various components will be mounted to the device. Components have been chosen to be surface mounted rather than through hole components to simplify the design.
2. The second layer of the device will be the signal ground plane.
3. The power plane will form the third layer of the PCB. Here, voltage will be applied and will connect to the various layers of PCB through the strategic placement of vias.
4. Finally, the bottom layer will be a ground plane. Components which need to be grounded will be connected to this plane through the strategic placement of vias. Additionally, this layer will serve as the return path for current passing through the various components.

6.3 PCB Design

Altium Designer will be used throughout the PCB design process because this software includes a feature to convert schematic designs to an elementary PCB design. However, not all the components used in the schematic designs have predesigned footprints that are immediately available for use. Some elements of the design will need to be designed as 2D and 3D models and added to a PCB library before the rest of the design may proceed.

The major components, which will be placed on the top layer of the PCB, are shown as 2D and 3D models in the images below. Due to the vast number of resistors, inductors, and capacitors that will implemented in the design, these elements have been eliminated from the images.

The PCB layout, shown in the Figure 40 below, was autogenerated by Eagle. Autoroute was used for this PCB because it had a small number of components and because the computer could optimize the number of trances and the trace width of the two-layer board fairly easily.

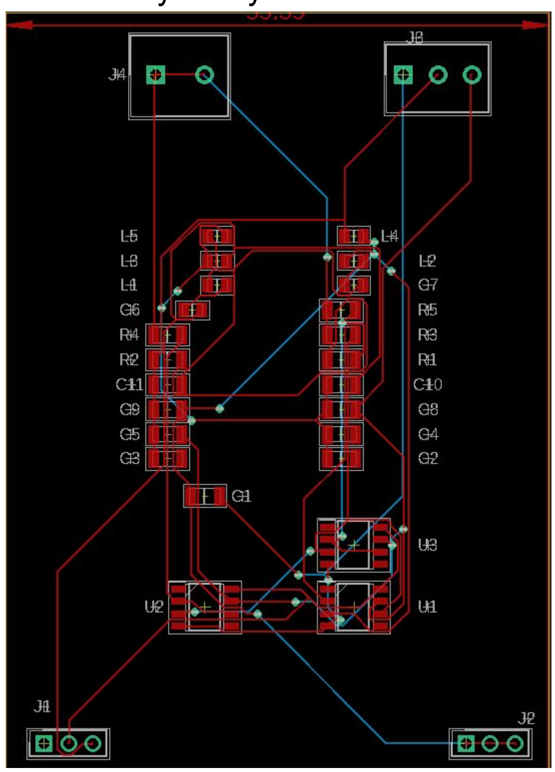


Figure 40: Eagle PCB Layout for the Transmitter PCB

The schematic for the receiver was used to generate the layout of the PCB. Because this device had more frequency dependent components that were more susceptible to noise, the board was arranged with more care. The received signal is intercepted at the bottom right header pin and wraps along the path until it reaches the left side of the board. Care was taken to ensure that the output of one component lead to the input of the next component and that dependent components were not placed too far from one another.

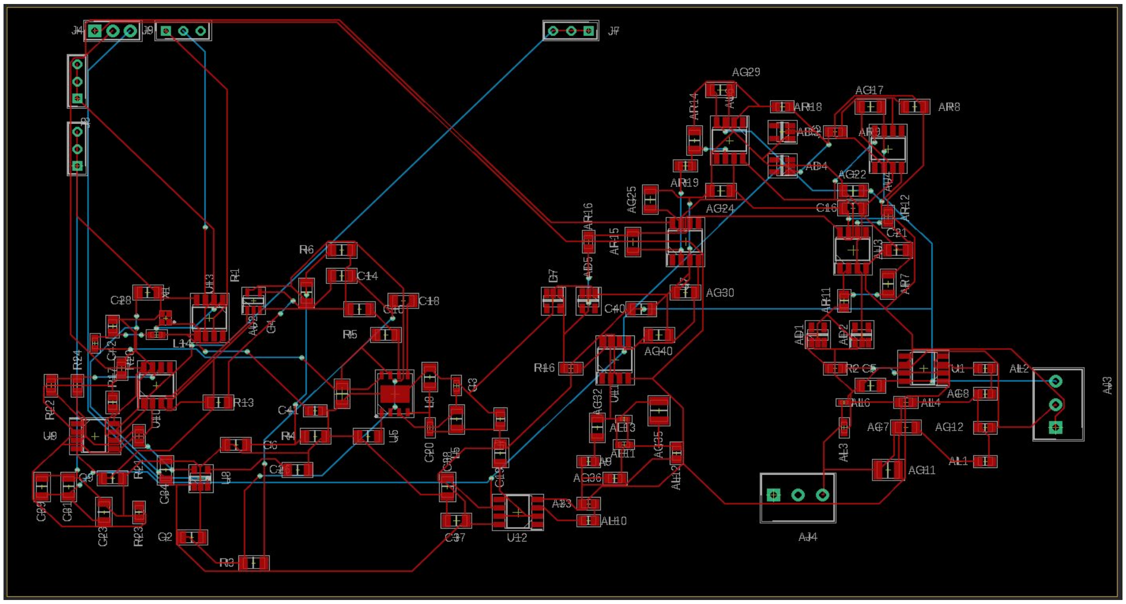


Figure 41: Eagle PCB Layout for the Receiver PCB

Because there are so many components, a four-layer board is the best design approach to the PCB. The PCB was designed to consist of a top layer for component mounting, a power plane, a ground plane, and a signal layer on the bottom layer. The completed four-layer PCB design is shown in Figure 36.

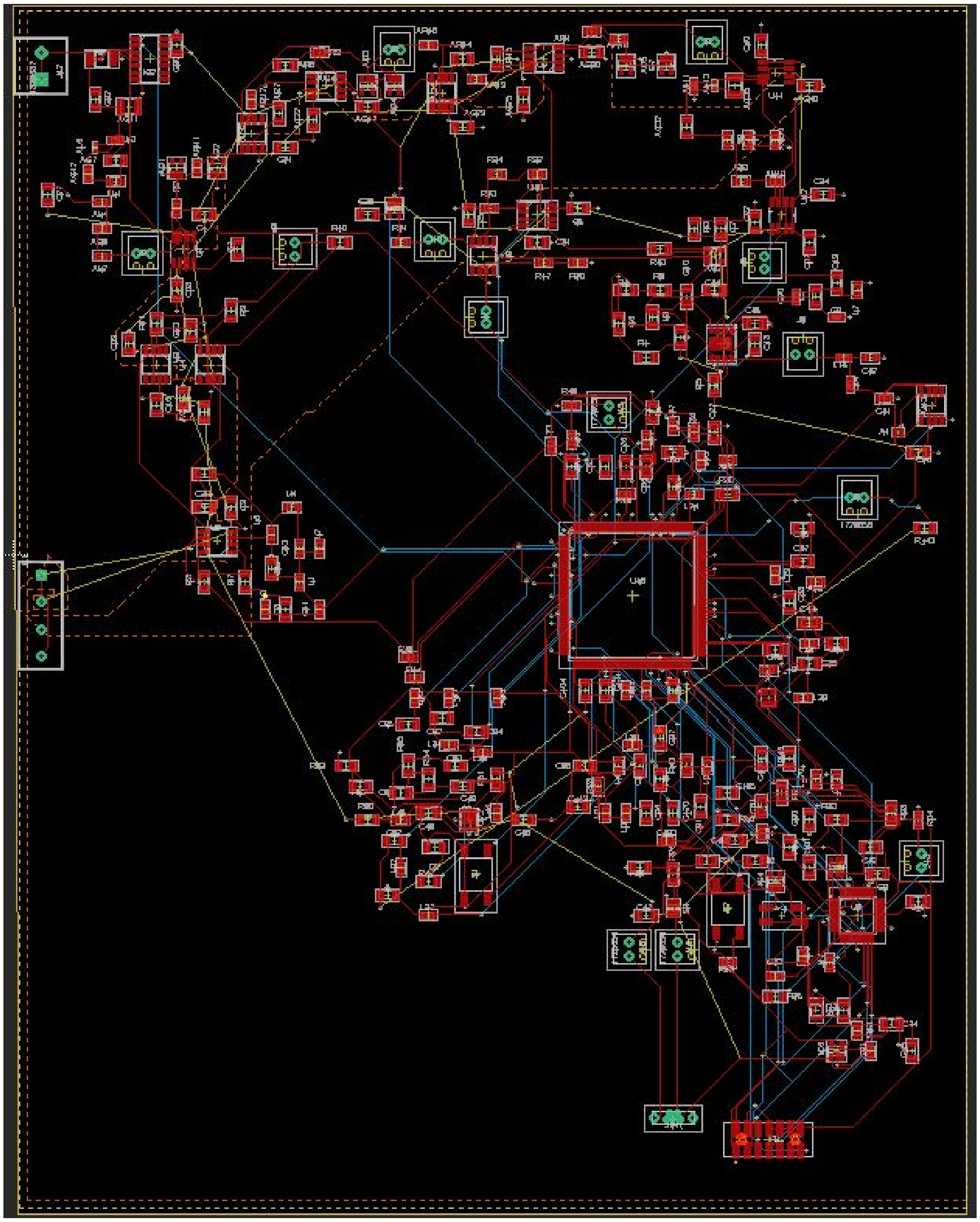


Figure 42: Eagle Board Layout for the Four-Layer PCB

6.4 Software Overview

The software will have several main functions. In this section the software routines will be explained and detailed.

The first and main function that the software will fulfill is the actual Fourier transform calculation. When the data is received through the ADC, the software will process that data and be able to display shifts in frequency of the received signal from the MEMS sensor. This will be accomplished using the floating-point Fourier transform library for C2000Ware (the Texas Instruments interface that will allow us to use Code Composer to program the DSP). C2000Ware is discussed in further detail in section 7.5.

The next major function that the software will have to perform is the RF switch modulation. This will consist of a timed output of logic levels to switch the positions between transmit and receive.

The DSP will also need to use the information obtained from the Fourier transform data to modulate a voltage-controlled oscillator which will transmit back the same frequency as the one received. This is important for efficiency. Since the resonant frequency of the device changes with vibrations, it is important to match our excitation signal to the resonant frequency. The code for this will run a calculation from the voltage-controlled oscillators data sheet to determine what the voltage required for that frequency is then it will output that voltage level. This will be useful to the customer during the prototyping stage because if their initial design is outside the desired frequency band they will still be able to run the product.

Lastly, the device will manage the logic levels of miscellaneous components on the board. This will be achieved by programming the software to output a voltage level. This programming function can be selectively turned off for debugging purposes.

The software used to control the microprocessor will follow the general flow chart below in Figure 43.

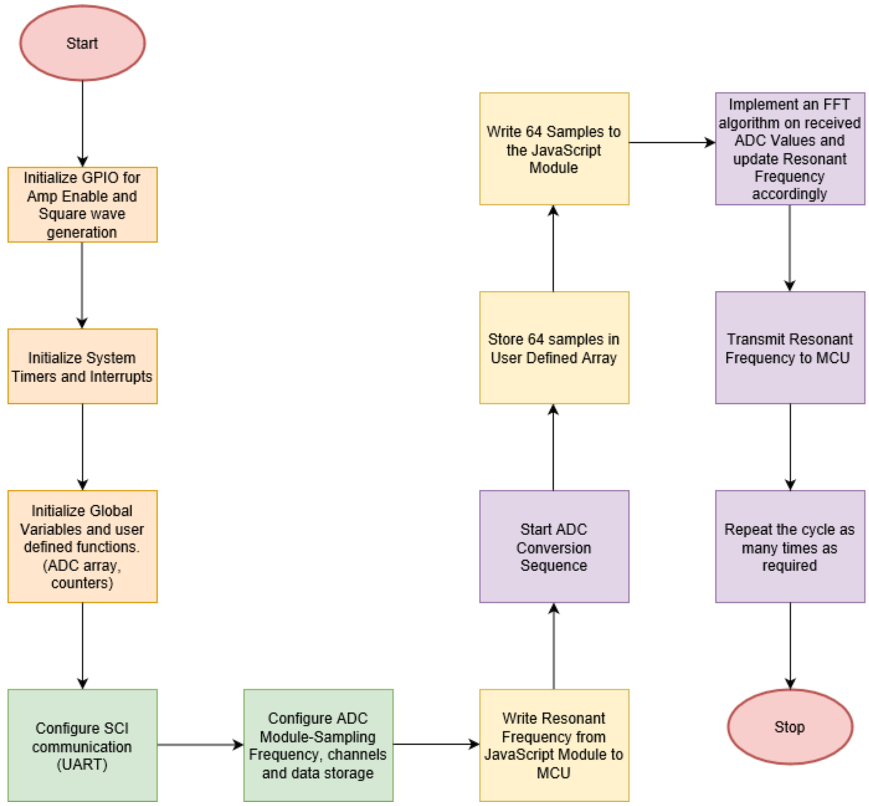


Figure 43: Reception and Processing Flow Chart

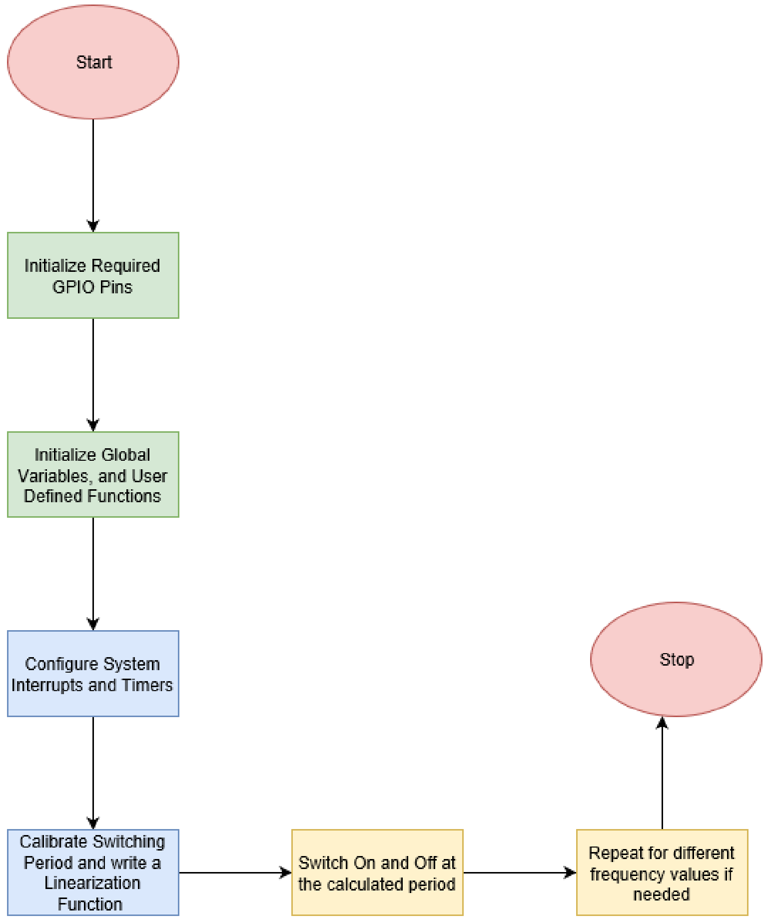


Figure 43: Transmission Software Flowchart

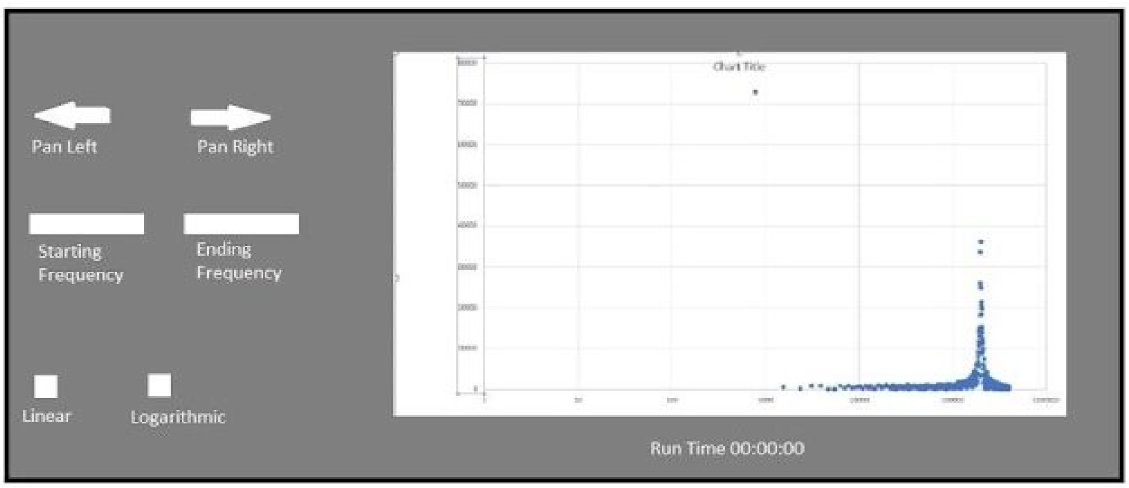
The idea of the flowchart is to give a generalized overview of the functionality and logic that our microprocessing unit will follow in the product implementation. As can be observed from the flowchart below, the DSP is the control center of the device. All other peripherals, including the RF switch, voltage-controlled oscillators, and ADCs, are controlled are by the DSP. The RF switch, which determines if the antenna is in transmitting or receiving mode, the voltage-controlled oscillators which need to be controlled via a feedback mechanism, the ADCs required to convert the received sensor signal into a digital signal that can be digitally processed by the DSP. All these steps stated in the preceding statements must be scheduled and timed accurately by the DSP else the signal received will be corrupted thus compromising the measurement results. As such, it is important to ensure that all the timers and interrupts are configured correctly. This means that the clocks provided in the DSP architecture needs to be properly configured, calculated and initialized. Proper planning and adequate research have been undertaken to ensure that all these guideline are properly adhered to. The importance of the DSP in the design of this project cannot be overstated as it is such an integral part of the design.

6.4.1 Software Graphical User Interface Overview and Layout.

The Graphical User Interface (GUI) will be built with the primary function to display the fast Fourier transform to the user. The GUI design will include the following features:

- Display Screen: This will be the interface which displays the graphed function
- Pan Left/Right: This feature will allow the user to scroll along the graphed function as needed
- Zoom: This function will allow the user to zoom in or out of the graphed function
- Frequency Range: This function allows the user to quickly identify the starting and ending frequency of the graphed function
- Linear or Logarithmic Toggle: This function will allow the user to select between linear or logarithmic scale.
- Run time: This feature will keep a running clock of how long the system behavior has been recorded.

Figure 44. Software GUI Example



It is important that the product is both functional as well as aesthetically pleasing. This is important to our customer in the case that the product is marketed, the aesthetics of the GUI can be a large sale factor influencing the performance of our product on a market. The aesthetics will be adjusted throughout the development process of the design and inspiration will be taken from other tools that are currently on the market.

7.0 Project Prototype Operation and Testing Plan

The purpose of the following paragraphs is to provide users with an instruction manual for the operation of the transceiver device. All instructions related to the operation of the device should be followed to guarantee the safety of the operators and the functionality of the device. General information related to the functions of the device and the expected test environment is also provided. If the exact equipment described is not available, equivalent test equipment is also acceptable. Finally, test procedures related to hardware and software testing are established. The test procedures may be performed in the sequence in which they are presented or performed individually, depending on the requirements of the test. If the device does not perform as expected, the most common failures and their suggested solutions are described.

7.1 Safety Precautions

To ensure the safety of personnel and the device, the following safety precautions are to be followed by anyone handling the device:

1. Visually inspect the device prior to applying power to ensure that there are no exposed wires or loose electrical connections.
2. Verify that the device is properly grounded.
3. Verify that power has been removed, power supplies have been turned off, and that the device does not contain any stored electricity prior to performing maintenance to the device.
4. Keep the device away from food and liquids to prevent damage to the device.
5. If components are being installed, store them in anti-static containers until they are required.
6. When the device is not being tested or used, keep it in a container to protect it from accidental damage.

7.2 General Information

The transceiver device, coupled with the MEMS sensor, is a powerful diagnostic tool. The system provides capabilities such as:

1. Signal reception and transmission
2. Signal filtering and processing
3. Fast Fourier transforms
4. Transfer of data from transceiver to PC via serial USB
5. Display of a graphed function

7.3 Using the Transceiver Device

This section of the report will detail the Engineering Operating Instructions for the use of the device. This will include all steps from set up, use and disconnect and power down.

Prior to use of the device, electrostatic discharge (ESD) precautions shall be taken. If ESD equipment, such as ESD shoes, wrist straps, gloves, or mats are readily available, they should be utilized.

The first step is to connect the antenna to the main board system. This antenna will be directional, and it is important that it is focused on the sensor. This antenna must also be within 1 meter of the device. It is also important that the sensor be obstructed by metal to prevent the metal from blocking the RF energy and communications between the device and our transmitter.

Now that the device is properly positioned, the device must undergo a visual inspection. This is to ensure that if there any damaged connector pins or debris on the board that it is removed and or fix before power is applied.

Next the board is plugged into the 11V and 5V power supplies. The board is then connected over micro USB to the accompanying computer for operation. Once these steps have been completed the board is then powered on for operation. At this point the computer is also turned on if it is not already. A program will next be launched on the computer.

From the computer program, an input will be taken from the user that begins the transmission from the device as well as begins to plot the output response. From the user interface, the Fourier transform can be viewed and display of the Fourier transform may be altered. The types of alterations are to be limited to changing the bounds of the display as well as selecting linear and logarithmic views of the graph.

When the user is ready to end the measurement, the application on the computer is closed out and the USB device is ejected from the computer. The device is then powered off and all connections unplugged and removed from the board.

The antenna may now be disconnected from the device and stored away. The PCB may now be disconnected from its power sources and also stored away. It is important that when the board is packed away that there are no sharp or metal objects near the device that could damage or short the PCB.

7.4 Hardware Test Environment

The equipment used throughout the testing phase will consist of the units identified:

1) Agilent E3630 A or equivalent
2) Tektronix DMM4050 or equivalent
3) Tektronix MSO4034B or equivalent
4) Rohde and Schwarz FSUP or equivalent

The functionalities and tolerances of this test equipment, which is readily available in the senior design lab, is discussed in detail in the following sections.

7.4.1 Power Supply

The Agilent E3630A is a multiple-output DC power supply. It features three output channels - Output 1 can support up to 6 VDC and 2.5 A, Output 2 can support up to +20 VDC and 0.5 A, and Output 3 can support 0 to -20 VDC and up to 0.5 A. The output values can be changed individually or output 2 and 3 can auto-track one another so that they are adjusted simultaneously.

The power supply is sufficiently accurate for our applications. The line regulation, or the ability of the power supply to maintain a constant output voltage given variances in the input voltage, is given as 0.01% + 2 mV. Similarly, the load regulation, or the ability of the power supply to maintain a constant output voltage despite variances in the load, is also listed as 0.01% + 2 mV. The ripple noise, or noise due to converting an AC source to a DC voltage, is given as less than 350 μV (for RMS voltages) and less than 1.5 mV (for peak-to-peak voltages). The resolution of the meter is accurate within 10 mV and 10 mA of the actual value. Finally, the power supply has a low normal (differential) mode noise specification of less than 0.35 mV to minimize the amount of noise introduced across power supply lines.

7.4.2 Digital Multimeter

The Tektronix DMM4050 is a power digital multimeter which features 6 ½ digit resolution and boasts a multitude of functions:

- Voltage measurements
- Current measurements
- Resistance measurements
- Capacitance measurements
- Temperature measurements
- Diode testing
- Continuity testing
- Frequency measurements
- Period measurements
- 2- and 4-wire measurements

This multimeter has a basic VDC accuracy of up to 0.0024% (guaranteed for up to one year) and boasts a resolution of up to 100 nV for voltage measurements, 100 pA for current measurements, and 10 μΩ for resistance measurements. Since the accuracy of the instrument can vary because of time and the range of the input being measured, the datasheet for this device provides users with tables to calculate the most correct accuracy.

7.4.3 Oscilloscope

Tektronix MSO4034B is a digital oscilloscope which features 4 analog channels and a bandwidth of 350 MHz. This oscilloscope allows users to customize the measurements that are displayed on the screen and how waveforms are shown on the screen. It also allows for up to four waveforms to be compared simultaneously. A USB 2.0 port on the front panel also allows measurements to be captured and retained for future use.
The specifications of this model of oscilloscope are listed below:

- Maximum input voltage: ± 42 Vpeak
- Rise time: 1 ns
- Sample rate: 2.5 GS/s
- Record length: 20 M
- Waveform capture rate: 340,000 waveforms/second

7.4.4 Spectrum Analyzer

The Rohde & Schwarz FSUP is a digital signal source analyzer and spectrum analyzer. Though it has a smaller bandwidth than other models in the FSUP family, it can analyze signals between 2 Hz and 8 GHz, so the range is wide enough for our purposes. To preserve the signals being analyzed, it has a low-noise DC output for the supply and tuning voltages. Additionally, the internal oscillator has a nearly negligible phase noise. For input frequencies on the scale of 1 GHz, it has a -143 dBc at a 10 kHz frequency offset and a -172 dBc at a 10 MHz frequency offset.

Another important feature of this analyzer is the ease of use. Although the device features a preset button, it also has a wide variety of settings for the user to customize to their specific need. Buttons along the edge of the display screen allow the user to adjust the information that is display and zoom in or out of the graph as needed. The front panel also features two USB ports so that the data can be externally saved.

7.5 Prototype Testing Plan

Product validation is the process of verifying that the final product meets the requirement specifications of the customer. The validation process ensures that designers are building the correct product. Testing plans provide a step-by-step process for verifying and tracing each of the main requirements.

Two testing plans are described within this section: a hardware testing plan and software testing plan. The hardware testing plans verifies that the product is built and connected correctly by measuring physical components. The software testing plan is used to validate the logic and memory components.

7.5.1 Hardware Specific Testing

The hardware testing will consist of various procedures to verify functionality of certain project deliverables. The hardware test procedures will be performed prior to software testing and will be used to ensure that the final design operates as expected.

7.5.1.1 Visual Inspection

The device must pass a basic visual inspection before continuing with hardware testing. The unit should be inspected for the following:

1) Improperly grounded or connected power supplies,
2) Loose or damaged wires
3) Visible damage to components (cracks, ruptures, warping, discoloration, etc.)
4) Missing components

Testing may proceed at the engineer's discretion.

7.5.1.2 Resistance Checks

Prior to applying power to the device for the first time, resistance verifications must be performed and completed successfully. Each individual resistor used in the design will be measured and its value recorded. The resistance value measured shall be within ±10% of the nominal value. If the measured resistance does not lie within ± 10% of the expected value, the resistance checks shall continue until all resistors have been measured. If any resistor values fail to meet the expected value, the resistance check is considered a failure and hardware testing may not proceed until the failure has been corrected. If the resistance check is a success, hardware testing may proceed. After the device has successfully passed resistance testing, it will not be required to undergo resistance testing again unless resistors have been replaced or major rework has been done.

7.5.1.3 Voltage Checks

When applying power to the device, the voltage values will be measured and recorded with the multimeter or oscilloscope. The device shall be powered using the input voltages specified in Table 13. Power shall not be applied to the device until all voltage sources have been appropriately grounded or connected to prevent the risk of electrocution.

Table 13: Expected Voltage Values

Signal Name	Nominal Voltage	Tolerance
P3.3_DC	+3.3 VDC	2.97 < VDC < 3.63
P3.3_AC	+3.3 VAC	2.97 < VAC < 3.63
P5_DC	+5 VDC	4.5 < VDC < 5.5
N5_DC	-5 VDC	-5.5 < VDC < -4.5
P5_USB	+5 V-USB	4.5 < VDC < 5.5
P11_DC	+11 VDC	9.9 < VDC <12.1

The voltages measured shall be within ± 10% of the expected voltage value. If the measured voltage does not lie within this range, the hardware test is to be terminated and will not proceed until the correct voltage is achieved. After successful application of power, hardware testing may proceed.

7.5.1.4 Current Checks

With all power applied to the device, measure and record the current at each voltage source with the multimeter or oscilloscope. Verify that the current measurements fall within the limits specified in Table 14.

Table 14: Expected Current Values

Signal Name	Nominal Current	Tolerance
P3.3_DC	3.3 mA	2.97 < mA <3.63
P3.3_AC	3.3 mA	2.97 < mA <3.63
P5_DC	5 mA	4.5 < mA < 5.5
N5_DC	5 mA	4.5 < mA < 5.5
P11_DC	0.011 A	9.9 < mA <12.1

If the measures currents do not lie within this range, the hardware test is to be terminated and will not proceed until the correct current is achieved. If the measured currents fall within the specified range, hardware testing may proceed.

7.5.1.5 Power Consumption

According to the customer's specifications, the entire device shall consume less than 10 W while it is fully operational. To verify the power used voltage and current measurements will be taken at each input using the digital multimeter or oscilloscope. The power absorbed at each input shall be calculated using P = VI. The power absorbed by each input shall be summed to obtain the total power consumption. The expected power consumption of each input is specified in Table 9.

Table 15: Expected Power

Signal Name	Nominal Voltage	Nominal Current	Nominal Power
P3.3_DC	+3.3 VDC	3.3 mA	10.89 mW
P3.3_AC	+3.3 VAC	3.3 mA	10.89 mW
P5_DC	+5 VDC	5 mA	25 mW
N5_DC	-5 VDC	5 mA	25 mW
P11_DC	+11 VDC	11 mA	121 mW

If the calculated power is greater than 10 W, the hardware test is to be terminated and not proceed until the issue has been resolved. If the power consumption is less than 10 W, the hardware testing may proceed.

7.5.1.6 Transmission Range - System Level Check A

According to the customer's specifications, the transceiver shall have a transmission range of approximately 1 meter. To verify the transceiver can transmit at this distance, the transmitter and receiver are manually placed at varying distances. The transmitter and receiver should be placed with an initial distance of 1 meter and tested. If the transmission fails at this distance, the distance between the transmitter and receiver shall be gradually decreased by 0.25 meter each time the transmission fails. If the transmission continues to fail, the hardware test is to be terminated and will not continue until the issue has been resolved.

The transmission range will be verified through a standalone commercially available antenna interface. The antenna will be used in conjunction with a spectrum analyzer to determine the signal strength over the given distance.

7.5.1.7 RF Frequency Track Test - System Level Check B

The system's ability to maintain frequency emitted by an RF source will be verified by a sensor simulator. The function of the sensor simulator is to mimic our client's device to verify that we can meet the customer's needs. The simulator will consist of a SN54S124 voltage-controlled oscillator, potentiometer-based voltage divider circuit, operational amplifier, commercially available 27 MHz antenna, and 27MHz cut-off low-pass filter. The simulator will be constructed in the manner shown in Figure 27.

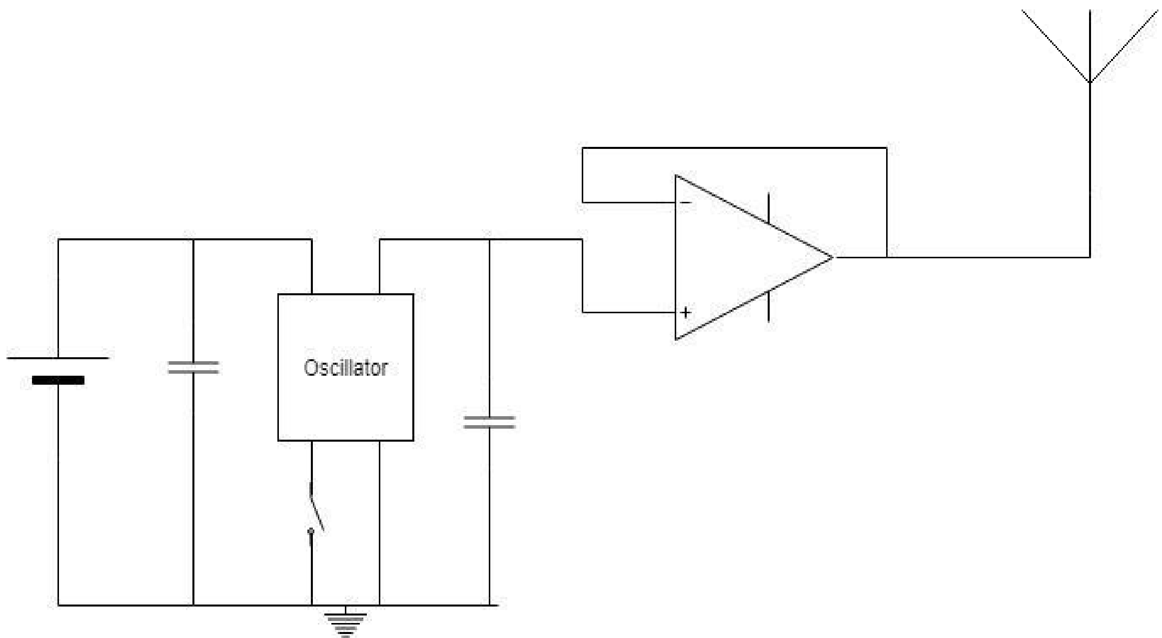


Figure 45: Oscillator Sensor Simulator

The purpose of the figure above is to demonstrate the general architecture of the sensor simulator that may be used for testing purposes. The simulator consists of an oscillator, buffer, and an antenna for transmission.

The simulator shown in the image above is not a deliverable to the customer. This design is only used to verify our main systems functionality before customer buy off.

7.5.2 Software Test Environment

To support the software and drivers used, the computer used for testing must meet the following system requirements:

- Have a minimum of 2GB of free memory
- Have a minimum of 900MB of free disk space
- Have a 1.0 GHz x86 compatible processor
    - Windows OS must be Windows 7 (SP1 or later), Windows 8.x, or Windows 10
    - Mac OS must be the most current version

The software's and drivers used are listed below:

- ControlSUITE v3.4.9
- C2000Ware v1.00.06.00
- Code Composer Studio v8
- Future Technology Devices Virtual COM Port (VCP) v2.12.28

7.5.2.1 C2000Ware

C2000Ware is a free development software for the C2000 microcontroller family produced by Texas Instruments. Because it supports Delfino devices, this software will be used to control the F28335 microcontroller in our design. This software features software and design documentation that can be used to set up projects, so it is suggested as a starting point for programming. The program libraries and device-specific examples provide additional support to new users. Additionally, this software provides a graphical user interface (GUI) that eases the programming process.

7.5.2.2 ControlSuite

ControlSUITE is another free development software for the C2000 microcontroller family produced by Texas Instruments. It is a collection of device-specific drivers, tools, documentation, and other software resources that will be useful in programming the F28335 microcontroller. Like C2000Ware, it features example projects, device-specific documentation, a graphical user interface (GUI), and libraries. This software package is suggested for all stages of development and evaluation.

7.5.2.3 Code Composer Studio

Code Composer Studio is an integrated development environment (IDE) for microcontrollers produced by Texas Instruments. This software is primarily a platform used to develop and debug embedded applications, so it features tools such as a code optimizer, and tracing and profiling tools. Code Composer Studio interfaces with the ControlSUITE and C2000Ware development software's so software development can occur across multiple platforms.

7.5.2.4 Virtual COM Port (VCP)

Virtual COM port (VCP) is a free device driver provided by Future Technology Devices International Limited. This software was created to support the FT2232D Dual USB to Serial UART/FIFO integrated circuit. The use of this driver is desirable because it eliminates the need to develop our own USB driver.

7.6 Software Specific Testing

After the hardware has been successfully tested, software testing may begin. These tests will be used to verify that the device can communicate as expected and respond to inputs within a reasonable time. Additionally, software testing will ensure that information can be stored for future processing.

7.6.1 JTAG Testing

At least one of the components within the design will have JTAG capabilities. This test method will ensure that the small devices on the PCB (that are too difficult to test via external probing) are tested and verified. Since JTAG can test more than a simple external probe, JTAG testing will be used to test and verify each component of the PCB if possible to verify that the JTAG is functional, a test script will be uploaded to the microprocessor that blinks an onboard LED. The demonstration of the LED blinking verifies that communication through the JTAG device was established.

7.6.2 GUI Testing

The functionality of the GUI shall be tested by allowing the system to run while a signal is being transmitted to the PC via USB. The GUI shall be tested in the following order:

(1) Verify a waveform is graphed on the display screen.
(2) Use the “zoom” feature to focus on the graphed function.
(3) Use the “pan” feature to scroll along the length of the function.
(4) Verify the frequency range is accurately reported.
(5) Use the zoon feature to return to the original function view.
(6) Toggle between the linear and logarithmic view and repeat steps 1 -5.
(7) Verify that the run time has updated and reports an accurate time.

7.7 Troubleshooting Tips

If problems are encountered during the operation of the transceiver, the following table may present a solution to the issue. If the issue is not identified in the table below or continues to occur after attempting the presented solutions, further analysis must be performed.

Table 16: Troubleshooting Tips

Problem Description	Solution
The device will not turn on	● Verify that the device is connected to power ● Inspect the device for loose wires or connections ● Verify that connector pins are not damaged. ● Verify that there are no short connections between any two or more points on the PCB ● Verify that no components are abnormally much hotter than normal. This may indicate component failure.
The device will not connect	● Verify that device is on ● USB is properly connected ● Verify that driver is recognized and functioning properly ● Verify that proper USB cable is used and that it is meant for data transfer as well as just power.
The only shows noise on the Fourier transform analysis	● Verify that the antenna is connected properly ● Verify that the sensor is within functional distance ● Verify that sensor is working properly ● Verify that there are no obstructions between the sensor and the antenna ● Verify that there are no very large sources of electrical noise immediately adjacent to the device ● Verify that all tunable components are tuned properly and that the lock tight was not damaged.

8.0 Administrative Content

The most successful projects are projects which have been well-planned and managed. The following sections summarize the managerial aspects of this project through the entire product lifecycle and the cost of designing, testing, and implementing the product. The project milestones section fulfills the product planning function by dividing the tasks of the project into smaller ones that are easier to achieve. These tasks are then organized by due dates and staffed by a single team member or the team. Duties which have been assigned primarily to a single individual were assigned based on his or her strength and larger tasks have been assigned the group.

The financial considerations section summarizes the expected cost of the main components, software licenses required for prototyping, and costs associated with the class. This section also discusses some of the cost-saving methods that have been considered by our team and sponsor. The cost breakdown of the project summarizes all costs and identifies the party responsible for the expenses.

8.1 Project Milestones

The major project milestones have been identified and divided into two tables - Table 17 summarizes the important tasks to be completed for Senior Design I and Table 18 lists the expected tasks for Senior Design II. Each table lists the individual responsible for the task, the expected start and end date, and the most current status of the task. Most of the tasks assigned to Senior Design II have undetermined start and end dates, but these will be identified and updated as the semester progresses and when the syllabus for the second semester of senior design becomes available.

All the research, parts selection, design, and project reports have been completed within the first semester of senior design. Tasks have been completed in a timely manner except for the PCB design. This is due to delays caused by parts being unavailable in Altium Designer and causing additional design work. We anticipated some research and design work would also continue during the second semester; but we attempted to keep this to a minimum. As previously discussed, all major components have been ordered and received.

Table 17: Project Milestones for Senior Design I

SENIOR DESIGN I	Tasked to:	Projected Start Date:	Projected End Date:	Status:
Project Assignments	Group 9	1/7/2019	1/12/2019	Completed
Final document	Group 9	4/12/2019	4/22/2019	Completed
Design Efforts				
Low-pass filter design	Primary: Justin	1/14/2019	4/1/2019	Completed
Amplifier Designs	Primary: Justin	1/14/2019	4/1/2019	Completed
Downconverter mixer	Primary: Jessica	1/14/2019	4/1/2019	Completed
ADC buffer	Primary: Tolu	1/14/2019	4/1/2019	Completed
Transmitting and mixing frequency	Primary: Jessica	1/14/2019	4/1/2019	Completed
Antenna and RF Switch	Primary: Tolu	1/14/2019	4/1/2019	Completed
MCU	Primary: Tolu Secondary: Justin	1/14/2019	4/1/2019	Completed
Schematics	Primary: Jessica	2/1/2019	4/12/2019	Completed
PCB Design	Primary: Jessica	2/1/2019	4/12/2019	Completed
Order and Test Parts	Group 9	4/12	5/5/18	Completed

During the second semester of senior design, all the building, testing, and redesigning was performed.

Table 18: Project Milestones for Senior Design II

SENIOR DESIGN II	Tasked to:	Start Date:	End Date:	Status:
Build Prototype	Group 9	5/6/2019	6/6/2019	Completed
Testing and Redesign	Group 9	5/6/19	6/6/2019	Completed
Finalize Prototype	Group 9	6/6/2019	7/5	Completed
Peer Presentation	Group 9	6/7	6/7	Completed
Final Report	Group 9	7/26	8/3	Completed
Final Presentation	Group 9	7/26	7/26	Completed

8.2 Budget and Financial Considerations

The parts listed in Table 9 and Table 10 gave a basic idea of the components that were initially required for this project. This bill of materials includes the cost of basic components such as resistors, inductors, capacitors because this these are being purchased by the sponsor. Electrical wire and the cost of duplicate parts in the case something breaks were excluded from these considerations. Some of the most important components of this design were the frequency dependent parts. The mixers, downconverting mixer, antenna, and transceiver were all carefully chosen so that they supported the required frequency bands and filtering out undesired frequencies. Because some components did not function as expected, this increased the cost of materials.

The total price was only a rough estimate, as it is likely that parts will need to be replaced and the design will change as the semester progresses. The parts required for the design will be purchased by the sponsor. The sponsor has requested that we minimize the cost of the components as much as possible while keeping quality, power, and footprint considerations in mind. Although the cost of the project could be decreased by requesting sample parts from suppliers, the sponsor has requested that we avoid doing this to provide them with a more accurate production cost for future device reproduction. Sample parts will be requested in addition to the parts ordered so that we have a minimum of three backup components in case a piece of the design needs to be replaced.

An additional cost consideration is the software required to prototype the PCB. Ultimately, Altium Designer was chosen. The student trial version is available for $99, and this cost will be absorbed by the students. However, due to software bugs within Altium Designer, a license for EAGLE Premium had to be purchased (due to the size of the four-layer board). This unexpected cost caused us to go significantly over budget in this area.

The total cost of the project is estimated below in Table 19. The estimated cost is compared to the actual cost of the project as calculated at the end of the semester. Most costs associated with the project (including the cost of parts and the PCBs) will be assumed by the sponsor, while some costs (including the cost of software and printing of the final document) will be assumed by one student or split evenly between. The total cost which the sponsor is responsible for is $736.39, which falls below the $1,500 project cost.

Table 19: Cost Breakdown of the Project

Category	**Estimated Cost**	**Actual Cost**	**Variance**
Total Parts	$736.39	$558.37	-24.17%
PCB Software	$99	$164	+65.65%
PCB (5 boards)	$400	$509	+27.25%
Total Project Cost	$1,315.39	$1,231.37	-6.38%

9.0 Conclusion

This project throughout the design posed several large design challenges that we had to overcome. Issues such as higher frequency effects on passive components as well as limitations of RF amplifiers (such as gain bandwidth constraints for amplifying) have been carefully researched and designed around. Another main difficulty faced were limitations in the component selection. The 27 MHz frequency of operation is below the RF range that components and filters are typically designed for, but above the operation range that individual components can operate in. The frequency constraints imposed by components lead to extra design work that typically would not be necessary had the frequency been shifted either higher or lower range.

To overcome these design challenges, we had to design unique architecture to be able to meet contrary requirements such as needing to provide both high frequency and high power. Designs such as master-slave operational amplifiers had to be implemented to meet the requirement. Finally, design specifications had to be changed to operate at 1 MHz rather than 27 MHz.

The project has been challenging, but its impact will be broad and worth the difficulty. Currently wind turbines contribute to over 8% of the total energy generated in the United states [25]. Each wind turbine alone can cost as much as 4 million dollars. On average, most commercial wind turbines fail at least once per year. This failure rate dramatically drives up the cost of electricity and makes wind as a renewable energy source much less desirable. Our project will give the industry the information it needs to know when a wind turbine will fail before it does. Furthermore, maintenance prior to failure will lower cost of repair. By predicting failures before they happen, repairs can be performed before damage is done to other components of the turbine. This will allow for more timely repairs, less downtime per wind turbine, and eventually improved cost efficiency.

Wind power is projected to grow rapidly in the United States as well as the rest of the world. Currently, it is estimated that the amount of power generated by wind in the United States alone will continuously increase by 8-11GW/year before 2050 [24]. This rapid growth will bring a growing demand for failure prediction methods and noninvasive methods of testing overall system health.

In summary, our project could make a large and tangible impact on the United States as well as the rest of the world. Renewable energy is a growing market and trend and reducing the cost of the total energy production will help to fuel that market and make a positive impact on the world.

Appendix A: Copyright Requests

RE: Copyright Permission

Bassuk, Larry <l-bassuk@ti.com>
Mon 4/15/2019 12:23 PM
To: Jessica Ondrizek <jondrizek@Knights.ucf.edu>

Dear Jessica Ondrizek,

Thank you for your interest in Texas Instruments. We grant the permission you request in your email below.

On each copy, please provide the following credit:

Courtesy Texas Instruments
Regards,

Larry Bassuk
Senior Patent Counsel &
Copyright Counsel
Texas Instruments Incorporated
214-479-1152

From: Jessica Ondrizek [mailto:jondrizek@knights.ucf.edu]
Sent: Thursday, April 11, 2019 9:15 AM
To: copyrightcounsel@list.ti.com - Copyright and trademark web requests (May contain non-TIers)
Subject: [Requests & questions from ti.com] [EXTERNAL] Copyright Permission

Good morning,

I am requesting the copyright permission for the following:

Company/organization name: University of Central Florida Senior Design Group 9
Requesting to copy: schematic of Docking-Stn USB-EMU [R3] from ControlSuite
Number of copies to be made: 1
Intended use of the information: Use in a schematic document for our senior design project

Sincerely,
Jessica Ondrizek

Figure 46: Copyright Permission Request for Docking-Stn USB-EMU [R3] (FT2232D Schematic)

RE: Copyright Permission

Bassuk, Larry <l-bassuk@ti.com>
Mon 4/15/2019 12:23 PM
To: Jessica Ondrizek <jondrizek@Knights.ucf.edu>

Dear Jessica Ondrizek,

Thank you for your interest in Texas Instruments. We grant the permission you request in your email below.

On each copy, please provide the following credit:

Courtesy Texas Instruments
Regards,

Larry Bassuk
Senior Patent Counsel &
Copyright Counsel
Texas Instruments Incorporated
214-479-1152

From: Jessica Ondrizek [mailto:jondrizek@knights.ucf.edu]
Sent: Thursday, April 11, 2019 9:16 AM
To: copyrightcounsel@list.ti.com - Copyright and trademark web requests (May contain non-TIers)
Subject: [Requests & questions from ti.com] [EXTERNAL] Copyright Permission

Good morning,

I am requesting the copyright permission for the following:

Company/organization name: University of Central Florida Senior Design Group 9
Requesting to copy: schematic of LMH6702MF/NOPB
Number of copies to be made: 1
Intended use of the information: Use in a schematic document for our senior design project

Sincerely,
Jessica Ondrizek

Figure 47: Copyright Permission Request for LMH6702MF/NOPB

RE: [Requests & questions from ti.com] [EXTERNAL] Copyright Permission

Bassuk, Larry <l-bassuk@ti.com>
Mon 4/15/2019 12:23 PM
To: Jessica Ondrizek <jondrizek@Knights.ucf.edu>

Dear Jessica Ondrizek,

Thank you for your interest in Texas Instruments. We grant the permission you request in your email below.

On each copy, please provide the following credit:

Courtesy Texas Instruments
Regards,

Larry Bassuk
Senior Patent Counsel &
Copyright Counsel
Texas Instruments Incorporated
214-479-1152

From: Jessica Ondrizek [mailto:jondrizek@knights.ucf.edu]
Sent: Thursday, April 11, 2019 8:50 AM
To: copyrightcounsel@list.ti.com - Copyright and trademark web requests (May contain non-TIers)
Subject: [Requests & questions from ti.com] [EXTERNAL] Copyright Permission

Good morning,

I am requesting the copyright permission for the following:

Company/organization name: University of Central Florida Senior Design Group 9
Requesting to copy: schematic of TMS320F28335
Number of copies to be made: 1
Intended use of the information: Use in a schematic document for our senior design project

Sincerely,
Jessica Ondrizek

Figure 48: Copyright Permission Request for TMS320F28335

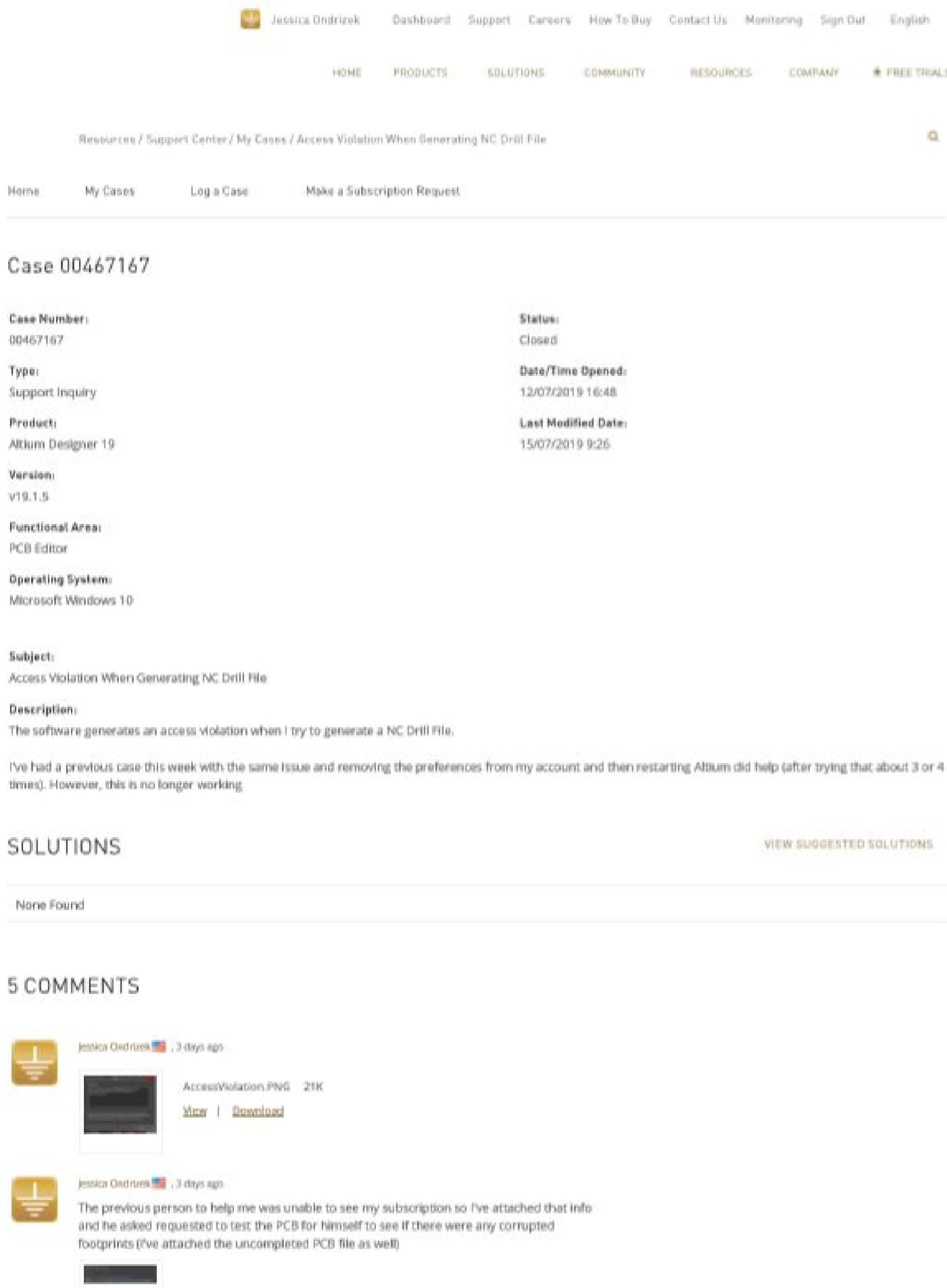
Jessica Ondrizek
Sat 4/20/2019 1:45 PM
cic.americas@analog.com

Good afternoon, I am requesting the copyright permission for the following:

Company/Organization name: University of Central Florida Senior Design Group 9
Requesting to Copy: Schematic of LT5560
Number of Copies to be Made: 1
Intended Use of Information: Use in a schematic document for our senior design project

Sincerely,
Jessica Ondrizek

Figure 49: Copyright Permission Request for LT5560



Jessica Ondrizek | Dashboard | Support | Careers | How To Buy | Contact Us | Monitoring | Sign Out | English

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Resources / Support Center / My Cases / Access Violation When Generating NC Drill File

Home | My Cases | Log a Case | Make a Subscription Request

Case 00467167

Case Number:
00467167

Status:
Closed

Type:
Support Inquiry

Date/Time Opened:
12/07/2019 16:48

Product:
Altium Designer 19

Last Modified Date:
15/07/2019 9:26

Version:
v19.1.5

Functional Area:
PCB Editor

Operating System:
Microsoft Windows 10

Subject:
Access Violation When Generating NC Drill File

Description:
The software generates an access violation when I try to generate a NC Drill File.

I've had a previous case this week with the same issue and removing the preferences from my account and then restarting Altium did help (after trying that about 3 or 4 times). However, this is no longer working

SOLUTIONS

VIEW SUGGESTED SOLUTIONS

None Found

5 COMMENTS

Jessica Ondrizek , 3 days ago

AccessViolation.PNG 21K
View | Download

Jessica Ondrizek , 3 days ago

The previous person to help me was unable to see my subscription so I've attached that info and he asked requested to test the PCB for himself to see if there were any corrupted footprints (I've attached the uncompleted PCB file as well)

Figure 50: Altium Designer Access Violation Resolution (1)

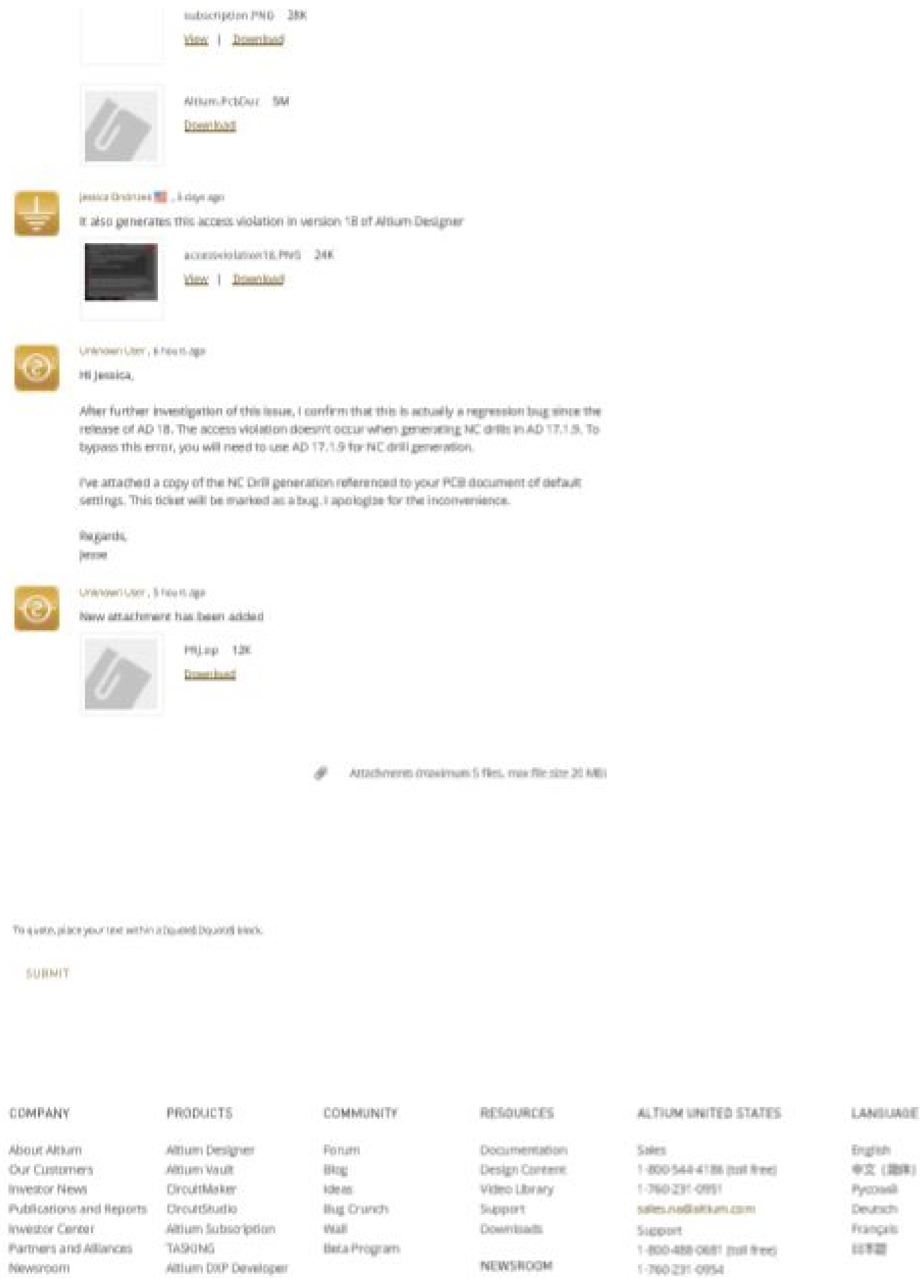

Figure 51: Altium Designer Access Violation Resolution (2)

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Appendix C: Acronyms

AC	Alternating Current
ADC	Analog-to-Digital Converter
ANSI	American National Standards Association
ARM	Advanced RISC Machine
BOM	Bill of Materials
BR	Basic Restrictions
CPU	Central Processing Unit
DC	Direct Current
DSC	Digital Signal Controller
DSP	Digital Signal Processor
EMF	Electromagnetic Field
ESD	Electrostatic Discharge
FCC	Federal Communications Commission
FIFO	First In/First Out
FTDI	Future Technologies Devices International
GPIO	General Purpose Input/Output
GUI	Graphical User Interface
IEEE	Institute of Electrical and Electronics Engineer
IF	Intermediate Frequency
IO	Input/Output
IP3	Third Order Intercept Point
ISM	Industrial, Scientific, and Medical
I2C	Inter-Integrated Circuit
JTAG	Joint Test Action Group
LED	Light Emitting Diode
LO	Local Oscillator
MCU	Microcontroller Unit
MEMS	Microelectromechanical Systems
MPE	Maximum Permissible Exposure

NCRP	National Council on Radiation Protection and Measurements
PC	Personal Computer
PCB	Printed Circuit Board
PdM	Predictive Maintenance
PWM	Pulse Width Modulator
RAM	Random Access Memory
RF	Radio Frequency
RFID	Radio-Frequency Identification
RoHS	Restriction of Hazardous Substances
SAR	Specific Absorption Rate
SMD	Surface Mounted Device
SOP	Sum of Products
SPI	Serial Peripheral Interface
UART	Universal Asynchronous Receiver-Transmitter
UCF	University of Central Florida
USB	Universal Serial Bus
VAC	Voltage (Alternating Current)
VCP	Virtual COM Port
VDC	Voltage (Direct Current)