MegaHurtz:
Phone-to-Car FM Transmitter

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Capstone Design ECE 4440 / ECE 4991

Kaelyn Carroll || Mike Traynor

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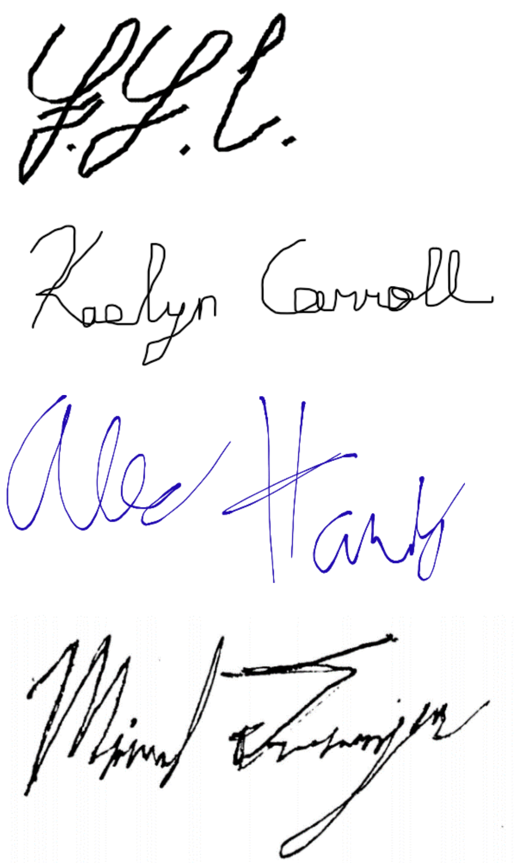
Signatures



Statement of work:

Kaelyn was the primary programmer for the project. Her first task was to write the programming libraries used for Inter-Integrated Circuit (I2C) communication. This was accomplished using a bit-banging technique. A software implementation of I2C was used because it was recommended for the chip that was selected, rather than a hardware implementation. Next, she used the I2C code to get the chip to power up as well as to figure out which commands to send to the chip to get it to transmit, along with Alec. After the chip was successfully transmitting, she wrote the code to convert the transmission frequency from kHz to MHz to send to be displayed on the LED display, as well make sure it only displayed odd frequencies that could be tuned to with a car radio. Finally, she programmed the button to power on the chip and start scanning on the first chip and used an interrupt to start rescanning any time the button was pressed after the initial press.

Alec was the primary circuit designer for the project. He was responsible for designing several iterations of the PCB, which included selecting components, creating footprints when needed, and laying out/running traces for the PCB. This mainly consisted of the spy-bi-wire implementation for programming the MSP430; the I2C, power, audio, and transmission lines that feed to/from the Si4713 chip; and the push-button and LED hex display connections (the display was designed to be off the board). He then soldered what components he could on each board, with the exception of the Si4713, which had a very small 3 square mm QFN package which required the assistance of WWW Electronics. He also assisted Kaelyn in determining what commands should be sent in what order and what we should set certain internal properties of the chip. Alec additionally set up the testing environment using and Adalm-Pluto SDR and the SDRSharp program.

Finbar was responsible for the engineering and integration of the chassis and external circuitry. He machined the aluminum container, which was selected for the purposes of aesthetics and heat dissipation, and designed the physical interface between the board and peripheral hardware. He mounted the power, RF, and audio sockets to the chassis, and soldered connections to the board, which were tested for functionality. The chassis was designed to allow the board to be easily removed and mounted, e.g. a non-permanent interface for optimal testing. Additionally, he was responsible for the design of the antenna. He initially experimented with fabricating a monopole rubber-duck antenna but settled for a manufactured one instead. He assisted Alec with the RF testing and measurements and final integration of the board with the external hardware, including push button and LED display.

Michael was the primary power circuit designer and was responsible for determining the power source and keeping track of all the materials used for the overall circuit design. Throughout the entire course of the capstone design, Michael made sure that all the necessary components for the power circuit, communication between the microcontroller and SI4713 chip, LED display, tactile switches, and FM transmission were in steady supply and readily available for soldering and testing. He also assisted Alec with the initial PCB design for power lines between the power source and the necessary subcomponents that needed a voltage supply of either 3.3V or 5V for necessary function. Michael also was responsible with selecting the proper LED display and tactile switch components that were compatible with the MSP430 via I2C communication. He also made a couple of trips to WWW Electronics to get components professionally soldered for the power circuit. Lastly, throughout the course of the technical project, he had to make several modifications to the power circuit to avoid overcurrent, switching of voltage regulators, issues with soldering, and reductions in footprint.

Table of Contents

Contents

Table of Figures

Abstract

MegaHurtz designed and built a device that can connect a handheld phone to any vehicle's car stereo and play back audio that is chosen by the user on their smartphone. This process was achieved through the development of a software-defined radio containing a barrel connector that is able to connect to an automobile's power outlet, which will in turn, power the SDR. Within the software-defined radio, there will be an FM transmitter and receiver, microcontroller, reset button, LED display and antenna. When all of the sub circuits and systems are integrated together, the SDR will receive the audio that is played on the phone, find the lowest power empty frequency modulation (FM) band on the car stereo, and transmit the audio signal. There are several different parts to this project that are related to current and emerging technologies such as wireless radio communications, digital signal processing, and embedded computing systems. To search for the open FM band, a chip would have to be programmed to perform this function and this is related to embedded system technology. The SI4713 chip is used and it involves both signal processing and radio communication since it includes the FM transmitter and receiver, which will it turn transmit the signal from the phone to the car radio.

Background

The older and more recent car models generally do not contain auxiliary jacks to connect a user's handheld device to the vehicle to play back music, audio books, podcasts and more. Many of the newer car models solve this issue by using Bluetooth, however, older car models do not have this capability and there can still be complication that arise with this technology. Bluetooth can be hacked into, it has connectivity issues, and can make handheld devices prone to viruses. Distracted driving is another issue that has grown in intensity and has created the need for technologies that can help reduce cell phone usage. The cell phone can be considered to be a cognitive distraction and can result in shorter following distances, inability to stay in the correct lane, longer reaction times, and road traffic crash injuries. Overall, phones have caused "drivers to take their eyes off the road, their hands off of the steering wheel, and their minds off the road and the surrounding situation" [3]. This has motivated our capstone team to develop a technology that allows drivers to operate a device with minimal distraction and can reduce the risk of safety concerns.

Software-defined radios also have a large number of applications including, but not limited to, its use for military defense, telecommunications, manufacturing plants, GPS and signal tracking, and public safety [4]. Over the past few decades, SDR technology has been progressing at a much faster rate and the applications of this technology have become endless. These devices have replaced the traditional, bulky radio that the United States Military had to use with something much more compact that can be used over a much larger range of frequencies for data and voice communication over two channels [5]. There is also research being done to use this technology as a real-time software defined radio GP receiver for indoor and vehicular navigation in areas where there may be signal blockage [6]. The automotive industry has been picking up on the benefits of this device as well.

In the past few years, the automotive manufacturers have been recognizing the usefulness of software defined radios and have been implementing this modern radio receiver technology due to its low cost and performance. The SDR is believed to be the best approach to supporting the simultaneous reception of a large number of broadcast channels, and to complying with the upcoming digital standards within the United States, Europe, India and China [7]. Automobile companies have been replacing the traditional car radios in some of the newer models with this technology. To accomplish this, engineering companies such as NXP semiconductors have used state-of-the-art embedded digital-signal-processing cores to the present set of radio standards used in automotive applications to support AM/FM reception along with existing scenarios of seven different digital radio standards [8].

On another note, a research project similar to our approach was worked on by undergraduate students who graduated from University of Virginia back in 2017. They had designed a simple device for automobile applications that used signal power processing to scan for an unused FM frequency, and then begin a broadcast on that frequency. They used the cigarette lighter within an automobile as their source of power and had difficulty keeping the audio uninterrupted due to power level on the current channel constantly surpassing the noise threshold that was set [9]. They also encountered issues with debugging code, but successfully made a functioning device.

Based on our research, the automobile industry has primarily been focusing on developing software defined radios that only contains a receiver, is powered by the vehicle, and has been integrated into the vehicle’s framework. A previous capstone team also built a device similar to the approach that we had in mind. This project focuses on designing and building a device that is completely portable and solely relies on power that will be coming from the automobile. It will also contain both a transmitter and receiver that will reduce noise as much as possible so it stays in working frequencies for extended periods of time, which will allow audio that is played on a user’s phone to be broadcasted through the car’s stereo wirelessly for an extended period of time. One other factor that differentiates this project from past work and research is that although testing will be done with a car radio, the device would be able to properly function with other radio technologies that operate on the FM band.

This project would incorporate several different aspects of our previous course work: embedded system design, digital signal processing, radio communications and RF circuit design. There will be heavy reliance on our experience with software tools such as Multisim, Ultiboard, Code Composer Studio and Microwave Office when designing the power regulators, amplifiers, and data communication between the microcontroller and chip within this project as well. Adalm-Pluto SDR and the SDRSharp program will also be used to test frequency detection and audio playback. Several of the group members have experience with signal processing, power systems and hardware design. One of the group members is extremely proficient with embedded C and will be able to work with the I2C interface. Through our previous coursework and experience, successful completion of the project should be achieved.

Constraints

Manufacturability

Device will be on a PCB, which includes upon it an RF chip, various support circuitry, and an MSP chip. This PCB will be printed at Advanced Circuits. The display and pushbutton will be wire connected to the board in order to be easily fitted into the final casing. The casing will be 3D printed with appropriate openings for USB, 9mm audio, and the display and pushbutton. The layout will be constrained to two layers. The QFN package of Si4713 chip required the help of professionals at WWW electronics. If the device were to be full scale manufactured, we would most likely employ stenciling and machine soldering.

Parts Availability

All parts are available from reputable online retailers such as Mouser and DigiKey. No major constraints are foreseen in sourcing components.

Economic and Cost Constraints

All parts are quite inexpensive, and cost is not foreseen as a major concern. The board will only be two layers which will save on manufacturing costs. Mass production of a final product would be significantly less expensive per unit due to bulk discounting.

External Standards

Wireless transmission in the United States is regulated by the FCC. We are compliant with Title 47 Section 15.239 subsection b, concerning home-made devices operated without license, reproduced below. [10] 250uV/m corresponds to approximately -50dBm for a low gain antenna.

> (b) The field strength of any emissions within the permitted 200 kHz band shall not exceed 250 microvolts/meter at 3 meters. The emission limit in this paragraph is based on measurement instrumentation employing an average detector.

The Si4713 as well as the hex LED display use I2C protocol to communicate on a common bus. [11] The IPC-2221 standards for PCB part and trace spacing, annular ring size, soldermasking, etc were adhered to by the design rules used in Ultiboard and by Advanced Circuits, as verified through the FreeDFM program. [12] The pre-emphasis setting on the chip was set to the US standard, a 75 microseconds time constant. [13] Viable channels were also constrained to channel spacing specified by FFC section 73.201, which is essentially “odd” channels (88.1, 88.3, etc.) [14]

Tools Employed

The main programming for the microcontroller was completed using embedded C in Code Composer Studio. An Arduino environment was also set up for testing the transmission of the SI4713 chip and figuring out what commands were necessary to get it to transmit, since there was already a code library in Arduino available for transmitting with the SI4713 chip. Additionally, Adalm-Pluto SDR and the SDRSharp program were used to tune to different FM bands to see if our transmitter was successfully playing our music on the indicated FM band. The board itself was designed using Multisim and Ultiboard. The majority of the components were soldered by our team using equipment in the National Instrument (NI) Lab, except the SI4713 chip was soldered by 3W. The board was tested using a VirtualBench, digital multi-meters, function generators, oscilloscopes and power supplies provided in the NI Lab. A mill and drill press were used to machine the chassis. This was supplemented with files and metal saws.

Most of this software and equipment was familiar to the team as they were used in previous coursework. Prior use of Code Composer Studio made debugging a little easier, although it took a while to figure out how to check if I2C was actually working or not. This ended up being done by checking the bit changes in every relevant register during each stage of I2C, this allowed for a deep learning experience with software-implemented I2C. Although no one had worked with Adalm-Pluto SDR before, it was fairly intuitive and didn't take long to have up and running.

Ethical, Social, and Economic Concerns

Environmental Impact and Sustainability

Low to none. The only real concern environmentally would be whether silicon and other resources used in electronics manufacturing are mined in sustainable and low impact ways, although this is outside our control and little to no information is available on the supply chain of the individual components we will be using.

Health and Safety

All power levels used in the device's operation are too low to be harmful to human health. This includes both direct contact with live electrical components and the transmission power of the signal.

Ethical Issues

The first ethical issue of consideration is the unsecured nature of the transmission, which allows anyone with an FM receiver to pick it up. The very low transmission range (<10m) means that the risk of unwanted interception is low, especially in a moving car, for which it is designed. Moreover, this device is only programmed to transmit at "open" frequencies, meaning the likelihood of passing by another car listening to that open frequency is already negligible.

The second issue of concern is deliberate close-range interference. Should someone choose to reprogram the device to transmit at a specified frequency, it could theoretically be used to interfere with a real (licensed) FM transmission, although this does not have much nefarious potential because the frequency range of the chip, 88-108MHz, is primarily used for entertainment or news (non-essential) content. In cases where the Emergency Alert System is activated, multiple FM channels will have the same warning message, so the person being interfered with could simply change the channel, which they are likely to do anyway because of the large distortion caused by the interference.

Intellectual Property Issues

Our device uses existing technology that would likely be subject to patent enforcement. While there doesn't seem to be any devices with the exact same design and functionality on the market, there are several patents with similar and identical claims to the solution created by our device. Below we have highlighted three similar patent claims. Our first example of this is US Patent No. 7,801,497 which discloses a device described as

> A radio modulator and method with a radio band scan function. The apparatus consists of a frequency selectable RF signal transmitter… the controller couples the transmitter to the antenna, tunes the RF signal to the present transmit frequency, and displays the present transmit frequency on the display. [17]

This patent makes 17 claims and each of these claims either definitely cover our device or could potentially cover our device. Another example is US Patent No. 8,364, with the major claim being

> An audio broadcasting system, comprising: a vehicle stereo device with a FM receiver; an audio player including: a storage unit for storing a plurality of audio files; and a processing unit for generating a channel frequency converting signal corresponding to a FM channel frequency of the FM receiver of the vehicle stereo device; and an adaptor coupling to the audio player and comprising: a controller unit for receiving the audio files and the channel frequency converting signal from the audio player, so as to generate a particular FM signal based on the audio files and the channel frequency converting signal; and a ***FM transmitter*** for wirelessly transmitting the particular FM signal to the FM receiver of the vehicle stereo device wirelessly for broadcasting. [16]

This Patent makes 11 claims all which cover our device. Finally, US Patent No 8,909,147 claims a method of selecting

> … at least one unoccupied media broadcast frequency; determining to automatically select a one of said unoccupied media broadcast frequencies; and determining to media broadcast the media data, via the second communication interface, using the automatically selected frequency.
> [15]

This final patent makes 26 claims, most of which don't apply to our device since it focuses on a Bluetooth connection and we didn't have that. However, claims 8 and 18 could possibly cover our device since it incorporates the use of an FM transmitter to transmit audio in a car. Also, the general method of choosing an unoccupied media broadcast frequency would most likely overlap with our device.

Detailed Technical Description of Project

General Description

The device will be powered from the standard automobile power supply, rated at 12V. This power will be fed into a power regulator, which will maintain the proper 5 voltage supply and currents for the LED display. Another power regulator will bring the 5V supply down to 3.3V to power the rest of the subcomponent

The primary component of the device is the SI4713 chip. This chip will process the mixing, digital-signal-processing, and transmission of FM signals. The chip will be controlled by the MSP430 chip, which will communicate via the I2C interface and will be coded in embedded C. The transmission and receiver hardware of the device will consist of the antenna. The antenna will be a simple dipole antenna, arranged in a vertical fashion.

Upon startup, the MSP430 chip will command the SI chip to sweep through the FM band and relay the power frequency spectrum. The chip will perform an algorithm to determine an empty frequency at which to transmit. The MSP will then display this frequency on the LCD screen of the device. Once a frequency is set, the device will receive analog audio from a 9mm audio jack. This audio signal will be routed to the SI4712's analog-to-digital receiver. The SI chip will digitally mix the signal and frequency modulate the proper output frequency. The chip will then output the signal, where it will be amplified, and transmitted.

The device will also feature a which will allow the user to reset the device and rescan for an empty band. The overall concept diagram is shown in Figure 1.

To develop this project, we intend to use CAD tools, such as Multisim and Ultiboard, to design the circuit components and PCBs. Microwave Office may also be useful to test the transmitter and receiver hardware. Code Composer Studio will be used to code the MSP, and Inventor may be used to design a 3D printed case. Metal machining for the antenna may be useful, as well as RF spectrum equipment to test the transmitter and supporting circuits.

The most anticipated problem will be finding times to meet, as we all have very busy schedules. Proper communication will be critical to ensure that we can develop the project independently of each other, and use time efficiently when we can meet.

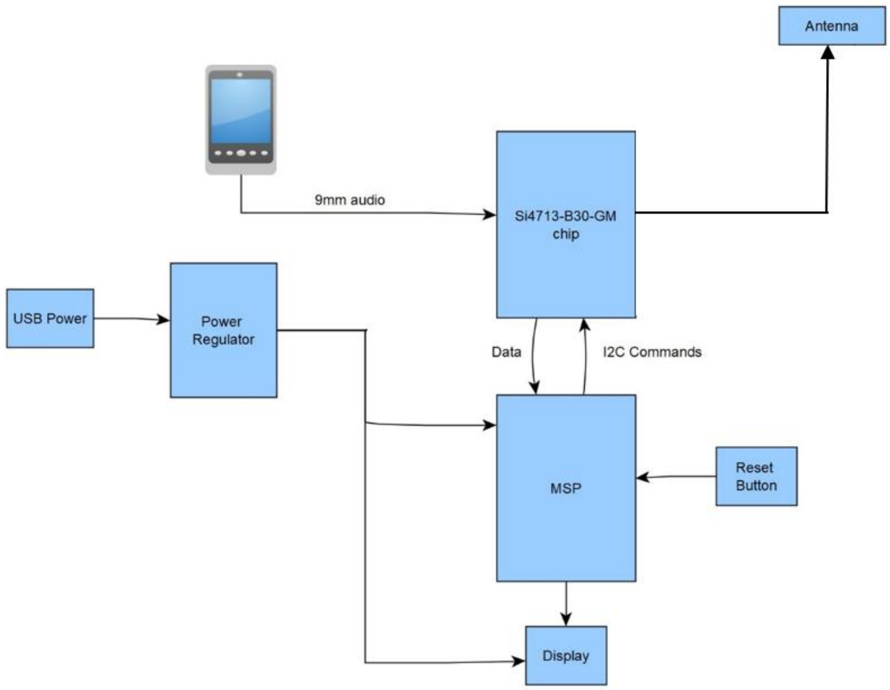


Figure 1: Concept Diagram

Power Circuit

The design and development of the power circuit was primarily produced using Texas Instrument's WEBENH Power Designer tool. Initially, there was difficulty in determining the power source that would be used to power the short-range FM transmitter. Before determining the power source that would be utilized, a power tree was built to consider which subcomponents within the device would need power and what voltages were needed to power each subcomponent. According to the datasheets for components including the MSP430, SI4713 chip, tactile switch, and LED display, voltages of 5V and 3.3V needed to be used. The figure with all of the components that needed power is shown below.

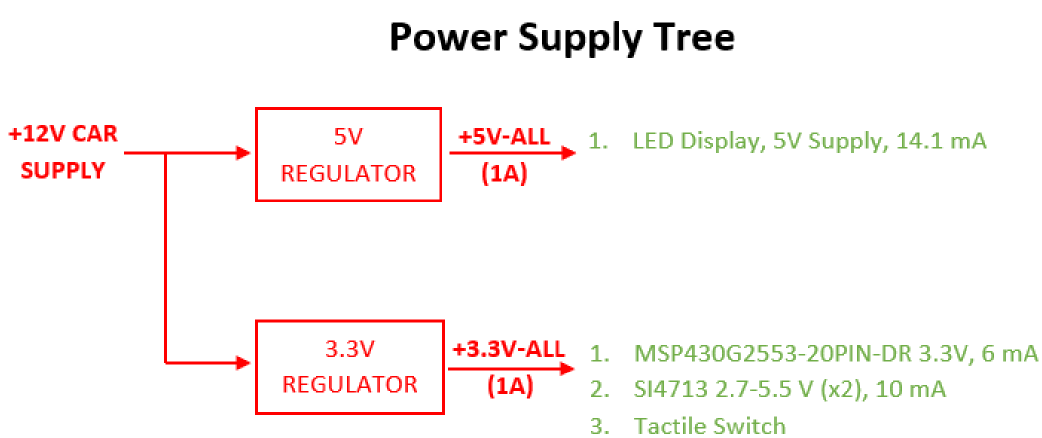


Figure 2: Power Supply Tree

After determining the voltages needed for each of the components, several different options for the power source were considered. Options included using USB power from our smartphone using a bidirectional cable, rechargeable lithium ion batteries to make our device portable, and the car cigarette lighter outlet that is available in all car models. It was concluded that the automobile outlet was our most reliable option since it had a stable, long-lasting power supply of 12 volts with a load dependent current that ranged from 1 ampere to 10 amperes. The ripple voltage, which varied from 9 volts to 15 volts also had to be taken into consideration. To connect the automobile to the device, a stable 12V DC/DC power supply adapter cable was used and it connected to a 2.1x5.5mm barrel connector which is shown on the left in the figure below. When the power circuit was developed, two voltage regulators were integrated into the circuit to step down the 12V voltage supply down to 5 volts, and step down the 5 volts output from the first regulator down to 3.3V. Both of the regulators also employed internal current limiters that provided overcurrent protection and thermal shutdown compensation. A zener diode was also incorporated into the circuit to provide unidirectional current. Figure 3 displays the final Multisim design for the power circuit used to power the device.

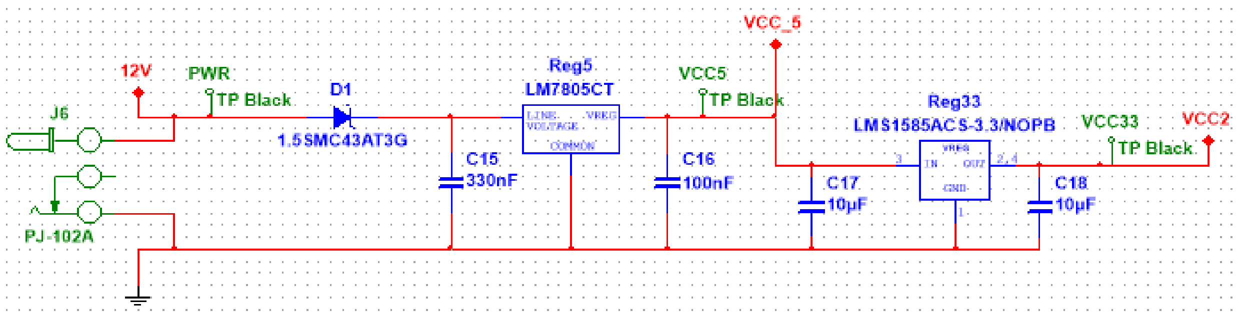


Figure 3: Power Circuit and Barrel Connector

Microcontroller & Chip

The MSP430G225 microcontroller was selected as all team members has used it in previous courses and were already familiar with the documentation. This also allowed the team to use some code libraries written in those previous classes. Our initial I2C pin mapping, as well as the spy-bi-wire layout is shown in Figure 4 below.

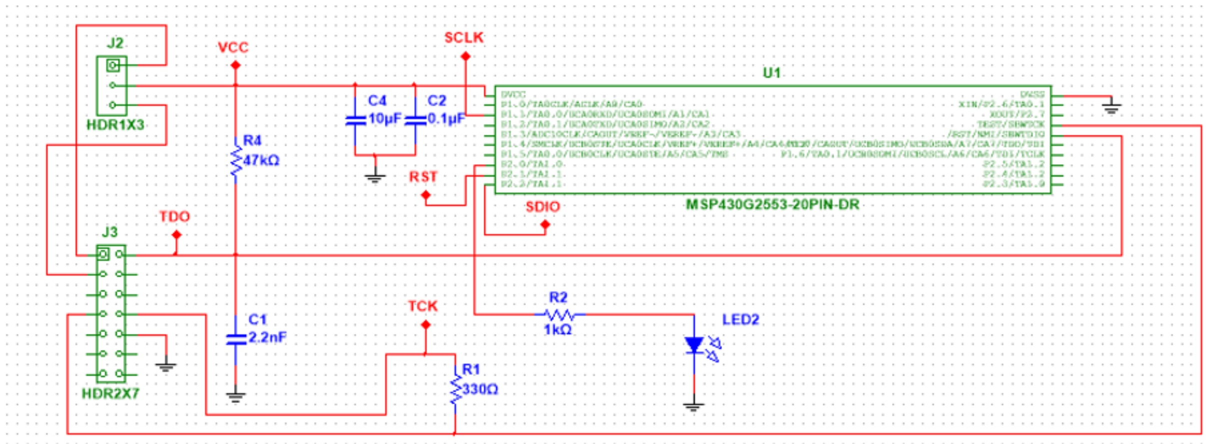


Figure 4: MSP430 with Spy-Bi-Wire Layout

The Si4713 chip was selected as it had everything we needed for transmission and already had a list of commands that could be sent with I2C to customize the transmission. Our initial test circuit is shown below in Figure 5.

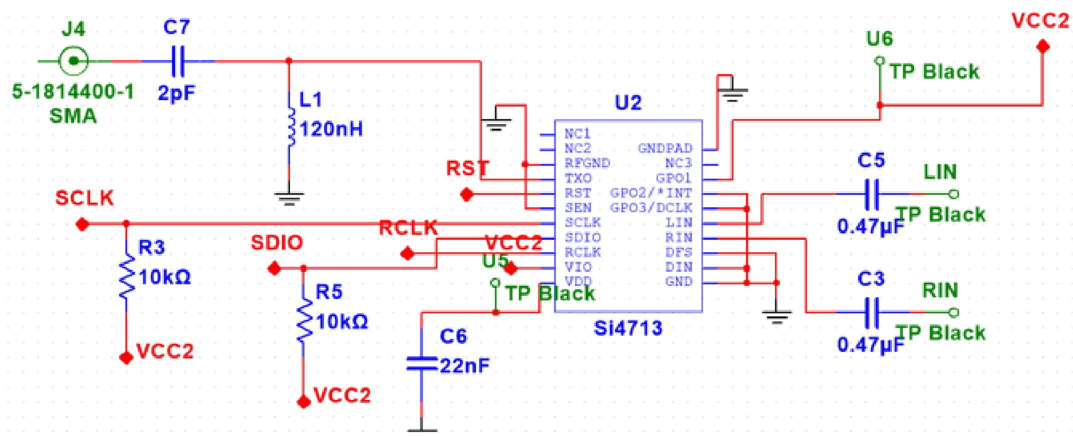


Figure 5: Si4713 test circuit

Crystal

In the final design we utilized the ABS25 32.768kHz crystal as a reference source for the Si4713 which, through an automatic frequency control servo loop is used in the final mixing stage upconverting from the intermediate frequency (IF) to RF. In accordance with the design guidelines document, the crystal was loaded with 20pF on either side, which generates resonance at the desired frequency. One side of the crystal was connected to the RFCLK port, and the other to the GPO3/DCLK, which was unused since we were only dealing with analog input signals

In the initial design we used a fully packaged reference source, which has just a single ended output to connect to the RCLK port, which should hypothetically be an acceptable option.

However, we were unable to get a transmission from this board, although it was inconclusive if this was simply a poor connection to the TXO (FM output) trace, or an issue with the reference signal, since there was no way to manually verify connection with the chip due to all the pads being underneath. In later iterations the pads were extended outwards both to make soldering easier and to help verify connectivity.

Antenna

The function of the antenna is to sufficiently transmit RF power at an FM operating frequency. Originally, an antenna was to be designed, but prototypes were too flimsy. A simple rubber-duck antenna was chosen to allow operation at the FM band, but minimize physical space. The coil of the antenna presents an inductance and lengthens the effective wavelength of the device. The chosen antenna was a multiband handheld radio replacement with a BNC mount. This antenna had effective gain at the FM band and was therefore sufficient for the project.

Tactile Switch

The function of the tactile switch is once pressed the first time, it signals for the chip to turn on and start the code for transmission. Any time the button is pressed after the initial press, the signals the device to stop transmitting, rescan for an open channel, and then resume transmitting on the selected channel. This was done by setting up an interrupt on the pushbutton.

LED Display

This display was chosen because it seemed to be extremely simple and had a lot of documentation explaining how to set it up. It also was designed for easy connection with I2C protocol. The display component was manufactured by Sparkfun and can be shown in Figure 6 below. The LED was set up to display the word ‘SCAN’ while the transmitter was scanning for an open band, then once a band was selected it displayed the FM band that our transmitter selected.

Figure 6: I2C lines for LED Display

Board Layouts

The first board design, shown in Figure 7 and 8, was intended to verify Spi-Bi-Wire functionality with the MSP430, as we had previously been unfamiliar with interfacing with an MSP that wasn’t on a launchpad. This was done with large through-hole components for simplicity on this iteration. On the right half of the board, a test circuit for the Si4713 was attempted. The pads for the chip are only the size that they are on the package itself which led to difficulty soldering and may have contributed to the inability to transmit. A ground via was created in the center of the footprint, which had the thermal pad, in order to create an easy centralized ground location. The design documents suggested multiple small vias here, but these would have been smaller than could be manufactured by Advanced Circuits. Note that some traces are narrow near the pads of the chip, but widen out farther away. This was done with the intention to improve stability of the connections, and although this practice was continued in later designs, it may not have been necessary in hindsight because the power levels were so low.

The second iteration, shown in Figure 9, was designed to incorporate parallel amplification stages: a LNA on a receiving pathway, and a power amplifier on the transmission pathway, which would have been toggleable by an RF logic controlled switch. The footprints and bias-T components for the amplifiers were created, but ultimately this board never made any progress, due to issues with the power supplies, some small layout problems, and mostly the fact that at this time we had still not demonstrated any transmission with the first board so it seemed futile to attempt to deal with this one. Ultimately the plans for amplification stages were scrapped completely due to time constraints.

The next board was designed to work with a breakout board for the Si4713 designed by Adafruit (See Figure 10 and 11). At this point in development we had acquired one in order to make more headway with the coding. The board would simply slide into a socket with appropriate power, ground, and data connections. This board used mostly surface mount components in order to reduce footprint. The barrel connector for power, in the top left, called for thin rectangular holes, which could not be manufactured. Instead, holes with a diameter equal to the diagonal length of the rectangular holes was used. This board worked perfectly the first time.

In parallel with this, a final board iteration was designed to have all the parts on the PCB, this time using the wider footprint, and a crystal instead of packaged oscillator. This board, the one finally used in the end product, is shown in Figure 12. The ground plane of this section was connected by narrow bridges in order to minimize noise from other parts of the circuit, especially the MSP. Since return currents will always follow the lowest impedance return path on a ground plane, the digital and RF ground currents should have minimal to no interference like this. As in previous iterations, wide traces are used until close to the board, where they narrow in. Again, in hindsight the very low power levels on these lines may have meant this practice was unnecessary. C6 and C11 are bypass capacitors to keep power levels stable. The crystal traces were routed to avoid capacitive coupling with the data lines. The test point near the shunt matching inductor was intended for use with a wire antenna, but ultimately we used the SMA connector to connect to the rubber duck antenna in the final design. This board had a width of 4.7 inches in order to slide into the slot in the case.

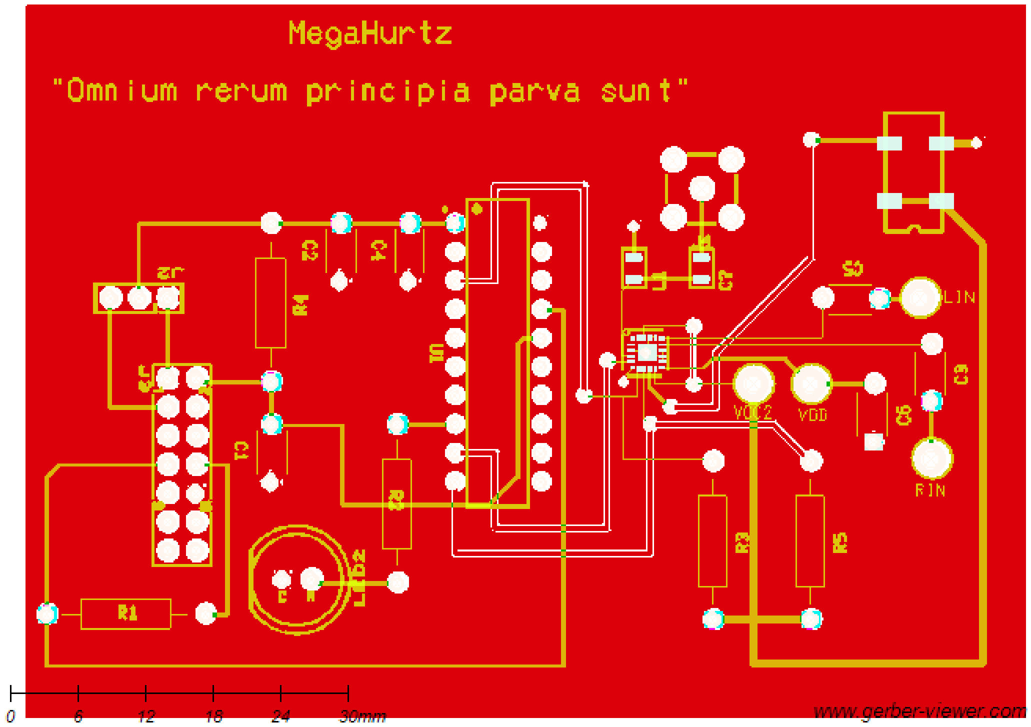


Figure 7: First Layout

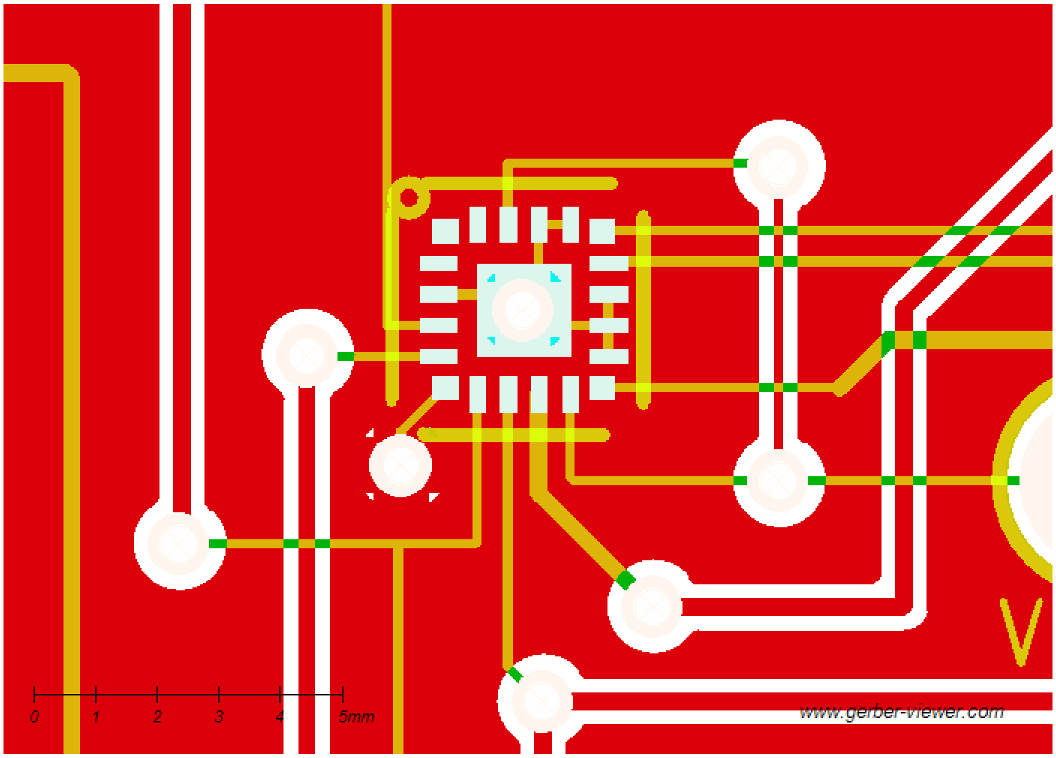


Figure 8: Closeup of Chip Connections

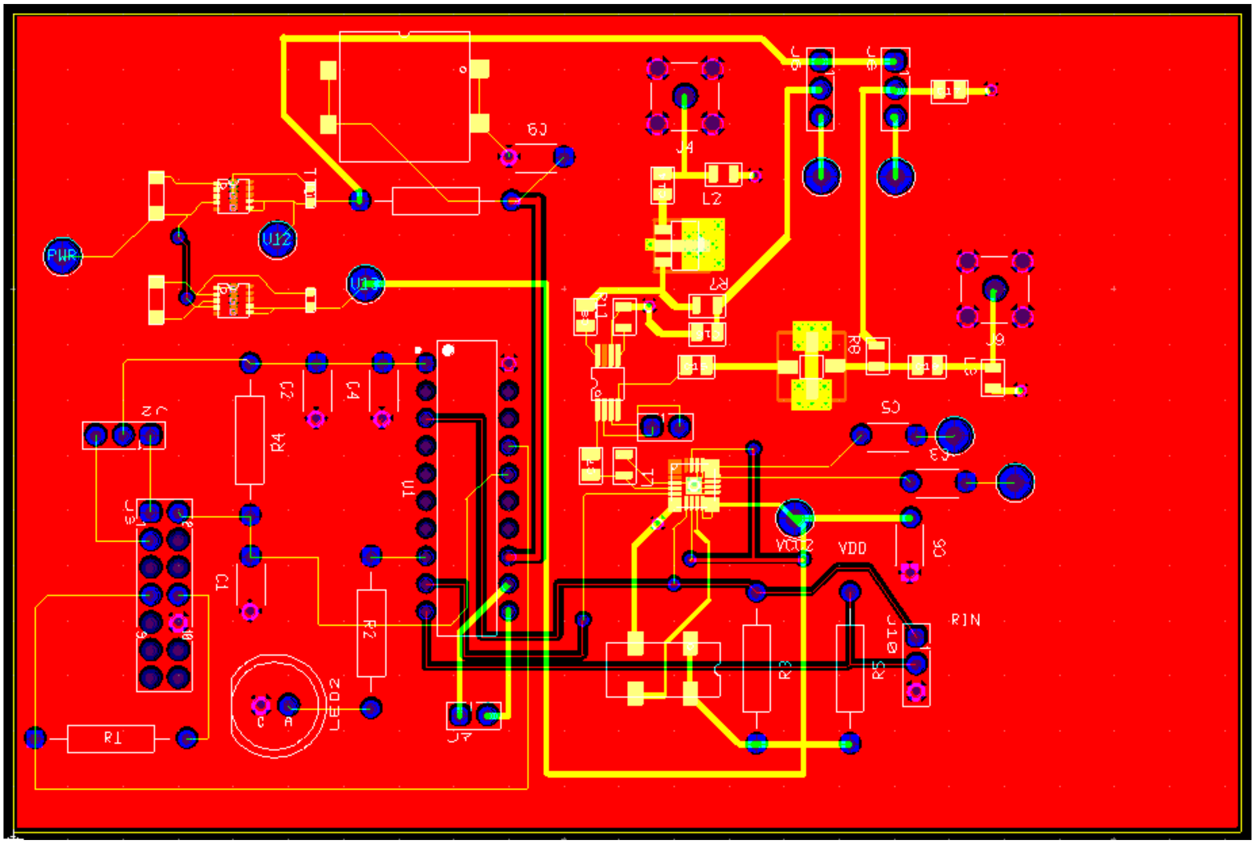


Figure 9: Layout Iteration 2

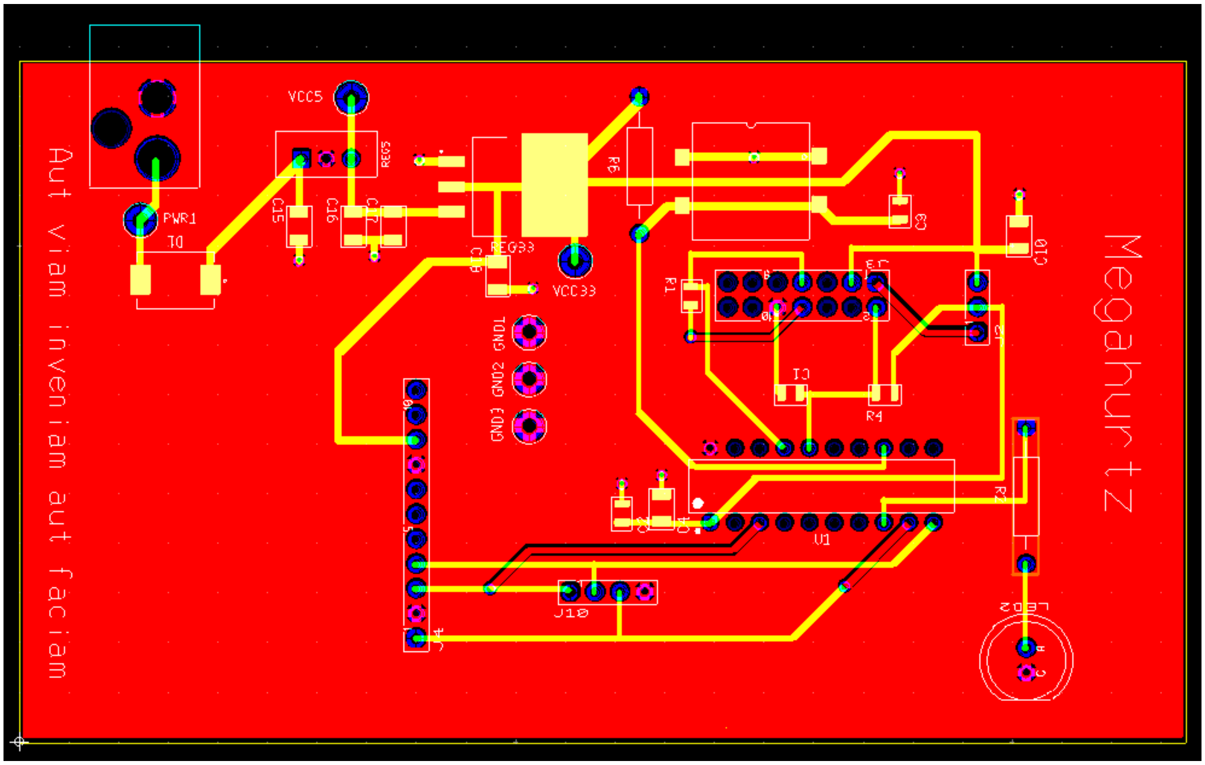


Figure 10: Board for Adafruit Breakout Board

Figure 11: Adafruit Breakout Board for Si4713

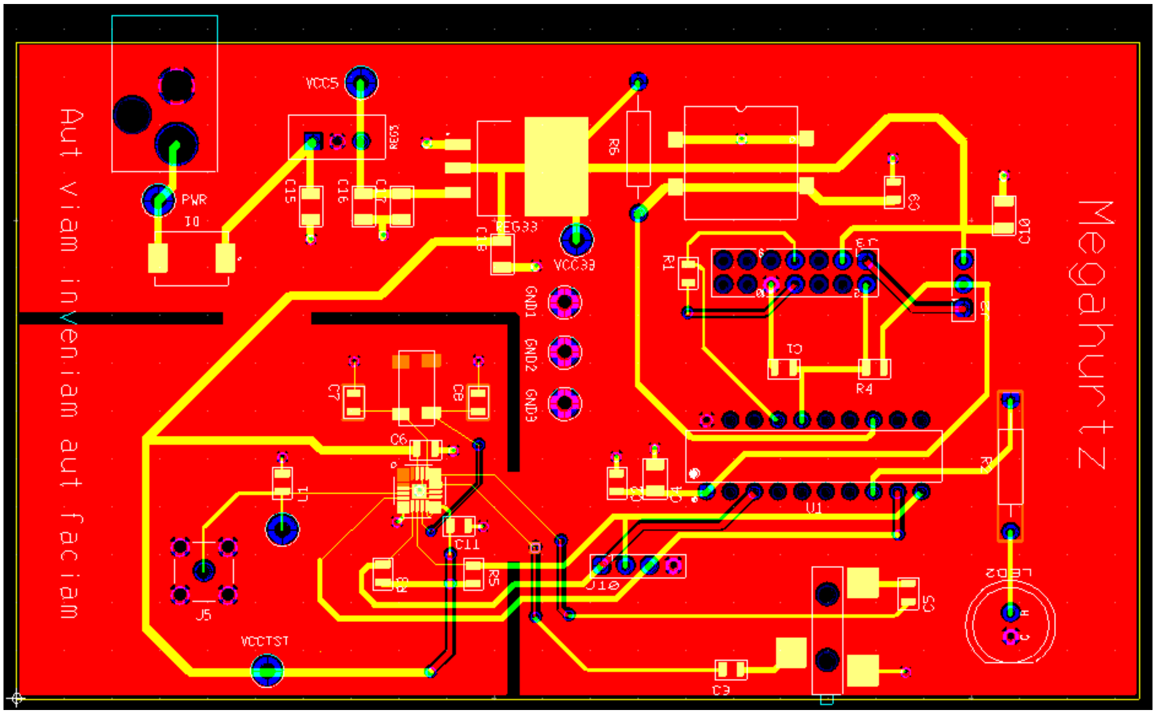


Figure 12: Final Board Design

Project Time Line

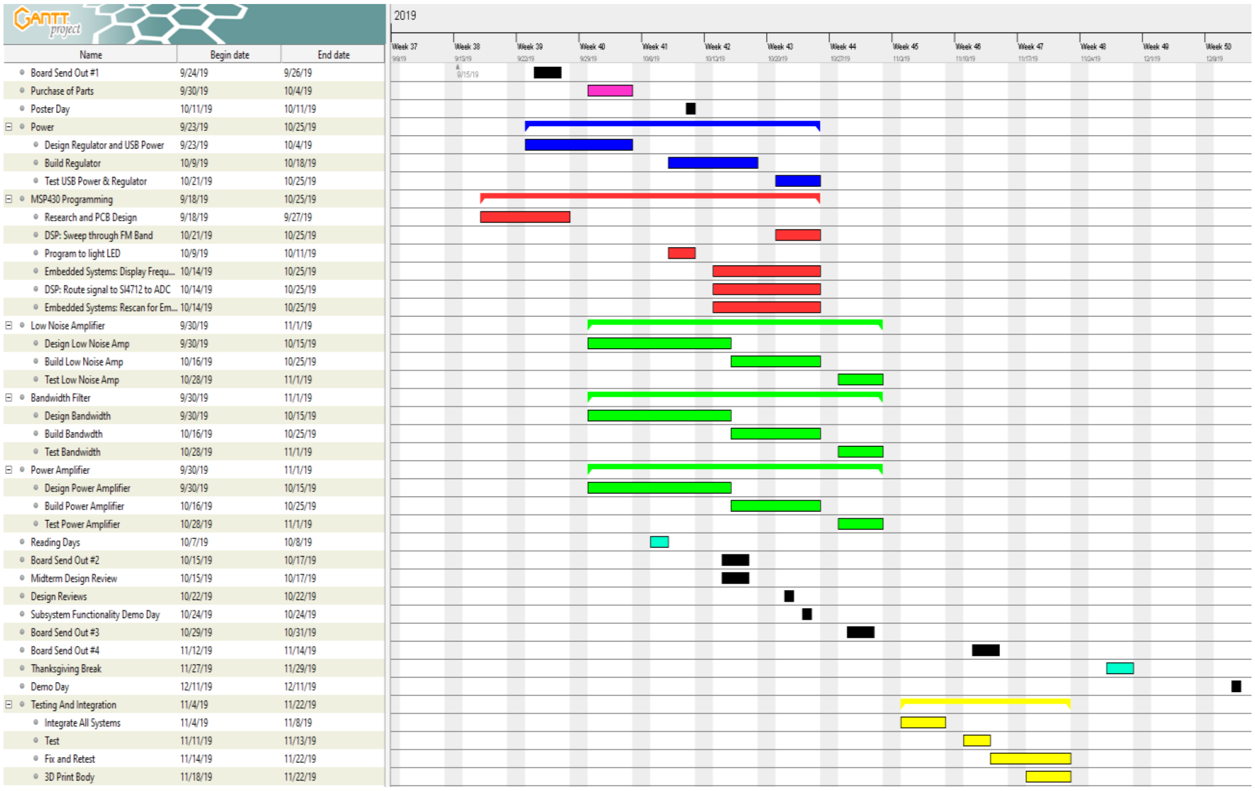


Figure 13: Initial Project Timeline

The above Gantt Chart (Figure 13) was our initial projection of what we expected to complete throughout the semester when we submitted our proposal back in late September. The timeline shows MegaHurtz's planned project schedule, which includes the largest components of our project, as well as deadlines and upcoming holidays. The four major parts of this project originally included developing a source of power and a regulator, designing and building the three major electrical systems that will be found on the main PCB, computer programming, and then integrating all of the systems and testing it. Some of these tasks could be done in parallel, such as developing the low noise amplifier, power amplifier, and bandwidth filter since they all assist with the functioning between the antenna, and the transmission and receiver hardware. However, the amplifiers and filters were removed from the timeline as shown in Figure 14 below.

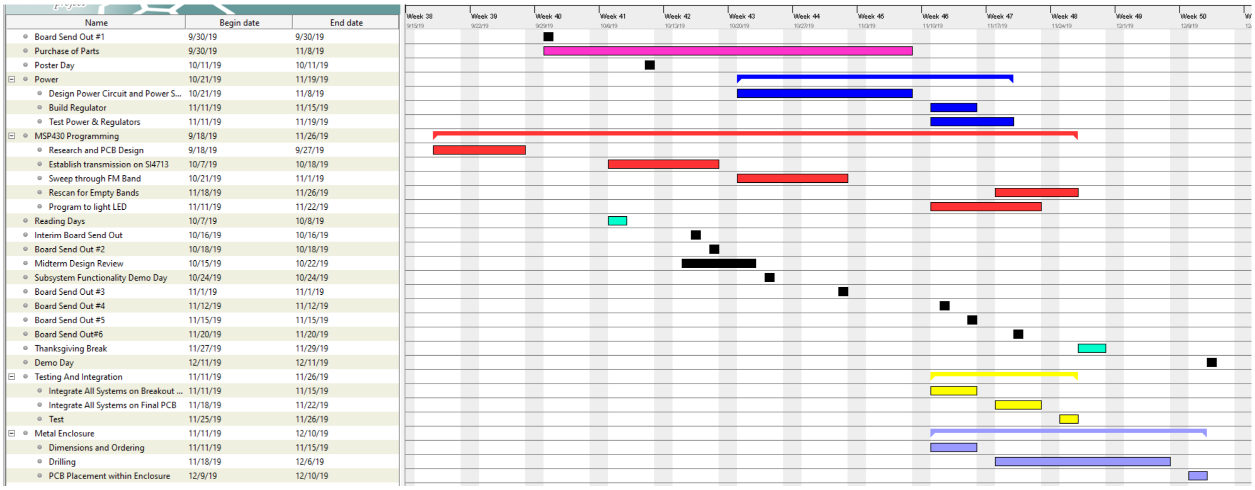


Figure 14: Final Project Timeline

When these two charts are compared to one another, it can be seen that the entire green section, which consists of the power and low noise amplifiers, as well as the bandwidth narrowing filter, was eliminated. We realized that the components were not necessary for the overall function of the device because with proper implementation of the embedded code and the other subcomponents that were in use, audio signals were already amplified and noise was reduced. Another difference between the two timelines was that establishing complete communication between the microcontroller and SI4713 to perform all our intended functions was extended to span over the majority of the semester. This was due to issues with designing our PCB layouts. Our initial layout only allowed us to verify that audio transmission was occurring and that there was communication between the chip and microcontroller. It did not allow us to implement functions for rescanning for open frequency bands and displaying them on the LED display since these parts were not readily available to us yet and they were not on the PCB. We also encountered issues with our second PCB design and this prevented us from making further progression in communication between the chip and microcontroller.

Also, design of the power circuit was pushed back by approximately two weeks because before the circuit design could be pursued, it had to be verified that we had all the necessary parts that were compatible with the I2C interface. Since the power circuit design was pushed back and I2C implementation was extended, testing and integration of all the subcomponents was pushed back as well. This, however, did not pose to be an issue because we initially expected to complete our technical project a couple of weeks before the final demonstration day. We were able to submit out two final PCB designs before the final board send out. After Thanksgiving break, all the components were soldered by hand and testing was done to confirm that the device was functioning as it should. The last difference between our proposed timeline and official timeline was the design of the enclosure that the PCB would be placed into. Originally, we had planned to model and 3D print an enclosure for the device. However, we revised this plan and ordered a metal enclosure that could be drilled and altered by hand.

Kaelyn took the primary role of implementing the algorithms and I2C interface necessary to determine the empty frequencies at which audio should be transmitted. She will also be implementing the code that is needed to show the empty frequency that was found on the LED display, as well as resetting and rescanning empty FM bands whenever it is required to be done.

Since Alec has experience with wireless communications and RF circuit design, he took the primary role of designing, building and testing the PCB layouts and establishing the hardware communication between the chip, microcontroller and crystal oscillator. He determined all of the necessary components to develop these systems in order to make them compatible with the SI4713 chip, and allow audio signals to be transmitted to the antenna. Finar, who has also has experience in RF circuit design, took a secondary role in this portion of the project. He was responsible for making sure that the audio signals can be relayed to the antenna without any noise interruption.

Michael took the primary role of designing the entirety of the power circuit due to his experience with power systems. He was tasked with developing a power regulator that will correctly maintain the necessary voltage and currents needed for all of the subsystems found in this device. Michael was also responsible for determining if the selected power source will have sufficient power to allow the entire system to function after integration. He was able to determine that car power would pose to be most reliable and stepped down the 12V supply down to 5V and 3.3V.

Finbar assumed the primary role in designing the metal enclosure that the final PCB would be encased in. Using the machine shop, he was able to drill and carve out portions of the metal enclosure so that the barrel connector, auxiliary input for the handheld device, LED display and antenna could be mounted. He was also able to securely place the PCB within the enclosure that would allow minimal movement and disruption.

Test Plan

The test plan for the final board followed three distinct stages: testing the board components and connections, testing the embedded MSP code, and testing the functionality and interface with the chassis. Testing the board components followed basic verification and troubleshooting techniques learned in basic circuit curriculum. The power system was verified to work by checking the output voltages from the regulators and ensuring stability. The soldered connections between different components were tested with an ohmmeter and minor corrections were fixed by resoldering.

With board configured correctly, the MSP chip functionality could be verified. The embedded MSP code was continuously tested during development, as software often is, and corrections were made during the coding process. However, to specifically test the MSP with the board, an LED circuit was added to the PCB and code was written to flash the LED. This confirmed that the code was being correctly written to the chip, and the chip was interfaced to the board.

With the code and hardware properly integrated, the final functionality could be tested. This was initially done by supplying simulated car power and receiving the transmission on a software defined radio. Then, the board was brought to a vehicle, where it was plugged into the car power. After verifying that the device was properly receiving power, an audio signal was supplied and the transmitting capabilities of the device was tested with the car radio.

Final Results

The final results were very successful. The device successfully identifying the band with the lowest power level, and show that center frequency it on the LCD display. Only odd frequencies (88.1, 88.3, etc) were scanned to be aligned with the standard 200kHz channel spacing used in the FM band, and thus able to be tuned in on by car radios. Pushbutton functionality successfully interrupted behavior and rescanned for an open band. Although we had initially intended to use USB power, we ultimately changed to using a generic 12V barrel connector to allow connection to either a car cigarette lighter port or a 12V wall adapter. See the video included in the submission for a demonstration of operation.

The screenshots below are taken about 1 meter away from the transmitter, which is the approximate operating distance for intended use. Figure 15 shows an unmodulated carrier, and Figure 16 shows the spectrum with a signal (a song playing). We deliberately interfered with the signal to verify that the scan will change frequencies, and it did consistently. That interference is generated by the Adafruit breakout board. Notice that is significantly stronger than our version at a similar distance, even though they are both using the same amount of power. This is possibly due to a number of factors, including the penalty of using an antenna that is not the resonant wavelength (rubber duck antenna), as well as the possibility of internal losses, since the distance from the chip to the antenna is significantly quite long on our board; and internal coaxial cable was needed to connect the board to the antenna mounted on the chassis. The overall routing on the breakout board was also significantly more optimized in general. Regardless, the signal to noise ratio achieved is more than enough to be able to be demodulated. Finally, the device was tested in a moving car and worked perfectly. The final product with the metal enclosure, as well as its internal components is shown in figure 18.

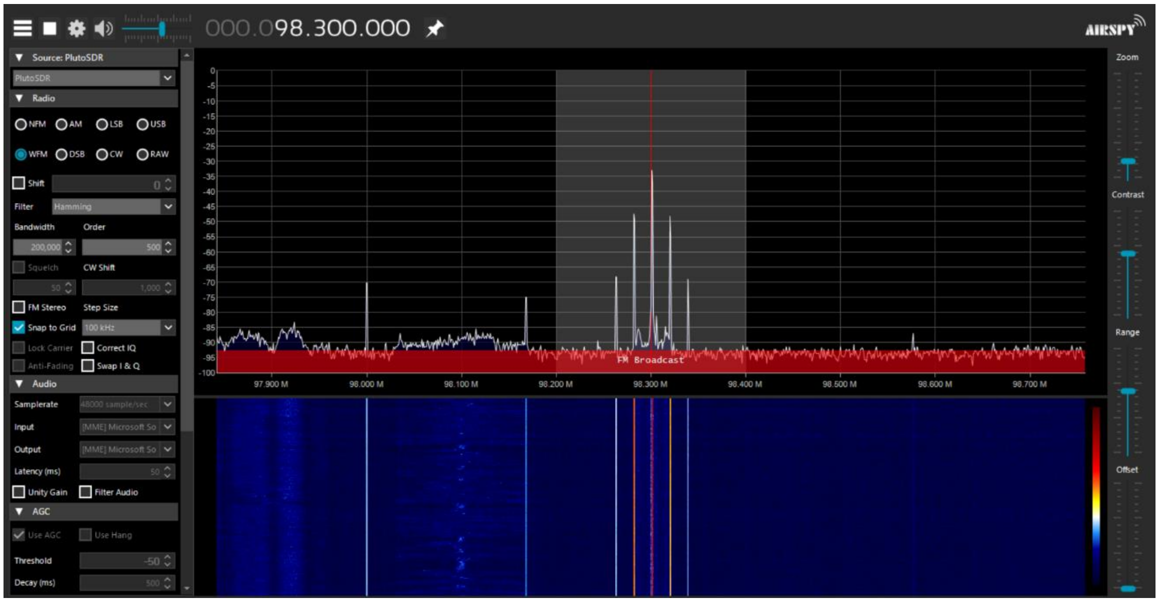


Figure 15: Transmission with No Signal

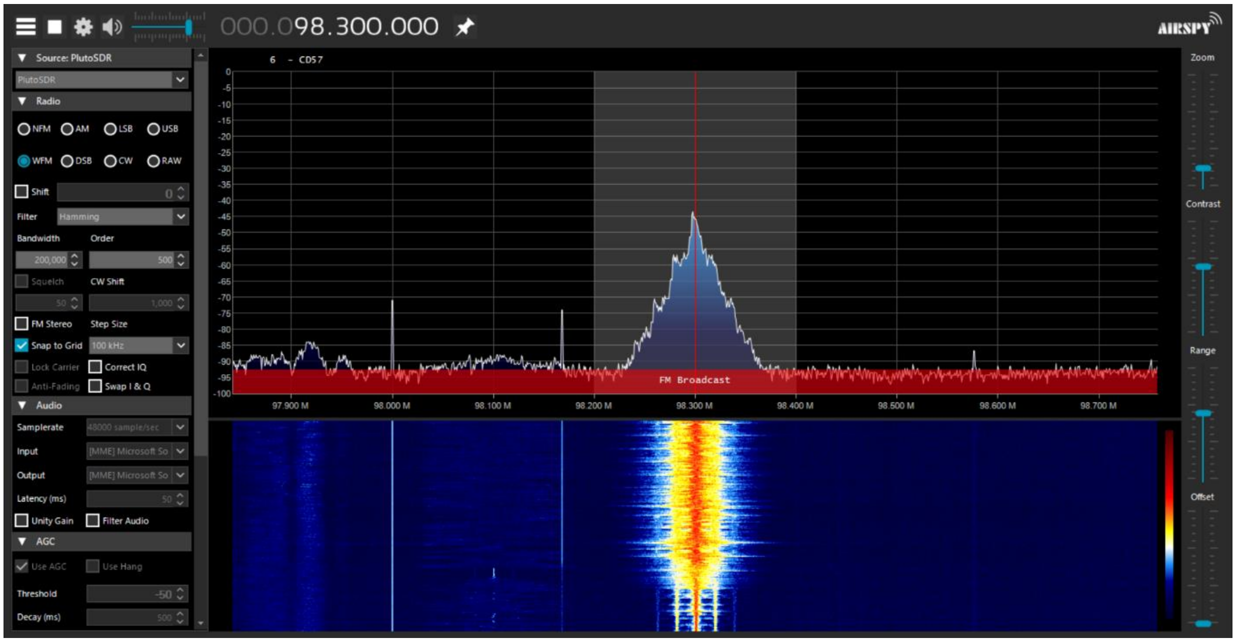


Figure 16: Signal Transmission

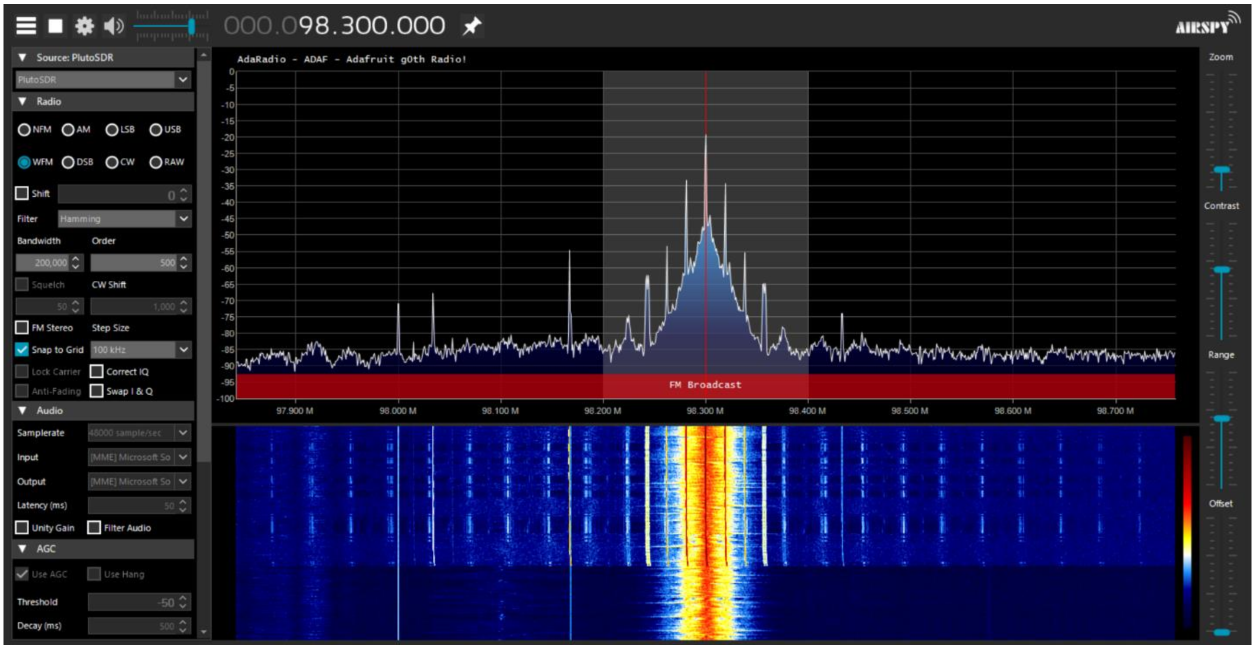


Figure 17: Deliberate Interference

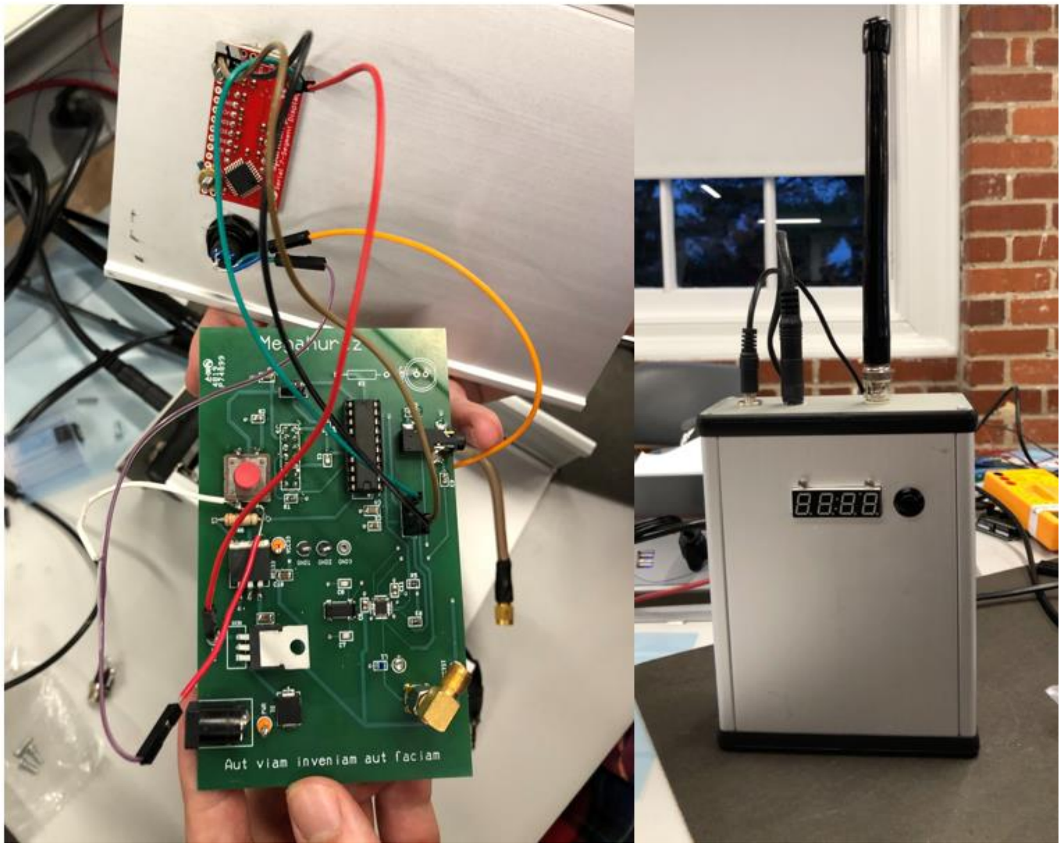


Figure 18: Metal Enclosure and Internal Components

Costs

After the completion of the design and assembly of the short-range FM Transmitter, detailed calculations of the total cost to make the device was compiled. Using the bill of materials documents that were submitted throughout the semester for each part order, the total cost invested in designing our product was able to be calculated. According to our documents, we had submitted five orders out of the seven total orders that Professor Harry Powell made available to us. A summary of the approximate cost for each order, along with the total cost with orders compiled together is shown in figure 19 below.

COST OF ALL ORDERS	
Part Order #	**Cost**
First	$ 19.68
Second	$ 63.66
Third	$ 19.94
Fourth	$ 60.61
Seventh	$ 91.94
TOTAL	$ 255.83

Figure 19: Total Cost Invested in Research and Design for Product

As it can be seen in the figure above, approximately **$255.83** was invested in designing and producing our product. This involves ordering parts so that all of our PCB designs could properly be soldered and tested. After the completion of each testing period, we were able to conclude which parts were deemed necessary for our final product, and which ones could be eliminated since they were not necessary for the overall function of our device. A more detailed calculation of each part order is included in Appendix A (Figure A-1), which is located at the end of this report. It contains the number of parts that were ordered for each order send out, along with the estimated quantities for each part and their unit costs.

Once we completed the production of our final device, which was used for out final demonstration, a more accurate calculation of the cost of the product could be conducted. Using excel, the parts that were integrated into our final product, along with the quantities for product and their unit costs were added together. It was concluded that the production cost for a single unit of the short-range FM transmitter was calculated to be about **$85.81**. A detailed calculation of this result is also included in Appendix A (Figure A-2). This overall cost does not include the estimated totals for PCB production, as well as soldering by hand. Finally, the total cost to produce 10,000 units of the short-range FM transmitter was estimated. Using Digikey, the total cost for each part estimated in mass quantities was estimated and was summed together to find the total cost for mass production. The total cost for the production of 10,000 units came out to be **$585,124.36**. This is equivalent to approximately **$58.31** per unit, which is almost $30 less than the production of a single unit. The detailed estimation is shown in Figure A-3 of Appendix A. Production cost can be reduced even more if the wave soldering method, which is a form of mass soldering, is used to solder all of the PCB components. Several other existing processes of mass production can also be used to reduce the cost of each unit. The detailed calculation of costs for manufacturing 10,000 units is also shown in the appendix. Also, there was no results for finding the total cost of ordering the antenna in mass quantities, which could have a significant impact on the unit cost.

Future Work

In this section you should offer suggestions as to how the project might be improved or expanded upon if a future group of students wished to create a new project based upon yours. You should consider difficulties that were no foreseen at the beginning, and offer advice on pitfalls to watch for.

There are many ways this project could be further worked upon or expanded. First, it is possible to significantly reduce the size of the device; the 4.7 x 2.75 in area of the board was larger than was needed for the parts, and was selected to accommodate easy fitting into the case. There are also ways to implement Spi-Bi-Wire without the full JTAG shroud, as only a few pins are used. A surface mount variant of the MSP430 could be used to further reduce space. All test points could be removed. The use of a custom case, perhaps 3D printed, would facilitate a far smaller board area.

Secondly, a secondary power input for USB could be implemented, connecting directly into the 5V stage that the first regulator steps down from. Clearly, additional protective circuitry would be needed in this case to protect the power circuit in the event both the USB power connection and the barrel power connection were hot simultaneously.

Finally, a second Si4713 could be added to the board. They could both be on the same I2C bus by changing the logic on the SEN pin, which can function as a chip select. This would allow one chip to be dedicated to receiving, and the other would be dedicating to transmission. The transmission dedicated one could easily be fitted with a power amplifier without the need for RF switches for parallel RX/TX pathways. There is no need to put an LNA on the receiving chip because we are not receiving any signal, but merely measuring average power present on different frequencies.

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Appendix

Appendix A

Calculations of Costs

First Part order			
Part #	Quantity	Cost/Unit	Total
1	1	$ 2.69	$ 2.69
2	1	$ 0.18	$ 0.18
3	1	$ 0.32	$ 0.32
4	1	$ 0.29	$ 0.29
5	1	$ 13.42	$ 13.42
6	4	$ 0.25	$ 1.00
7	1	$ 0.17	$ 0.17
8	1	$ 1.61	$ 1.61
		TOTAL COST	$ 19.68

Second Part Order			
Part #	Quantity	Cost/Unit	Total
1	1	$ 13.95	$ 13.95
2	1	$ 0.71	$ 0.71
3	2	$ 0.25	$ 0.50
4	3	$ 1.70	$ 5.10
5	2	$ 0.67	$ 1.34
6	1	$ 0.84	$ 0.84
7	4	$ 0.50	$ 2.00
8	2	$ 0.67	$ 1.34
9	2	$ 0.48	$ 0.96
10	6	$ 0.45	$ 2.70
11	2	$ 4.07	$ 8.14
12	2	$ 1.93	$ 3.86
13	2	$ 0.67	$ 1.34
14	2	$ 0.25	$ 0.50
15	2	$ 6.19	$ 12.38
16	2	$ 2.46	$ 4.92
17	2	$ 0.45	$ 0.90
18	2	$ 0.55	$ 1.10
19	2	$ 0.27	$ 0.54
20	2	$ 0.27	$ 0.54
		TOTAL COST	$ 63.66

Third Part Order			
Part #	Quantity	Cost/Unit	Total
1	2	$ 0.10	$ 0.20
2	4	$ 0.51	$ 2.04
3	2	$ 0.10	$ 0.20
4	2	$ 0.27	$ 0.54
5	4	$ 0.59	$ 2.36
6	2	$ 0.10	$ 0.20
7	2	$ 0.27	$ 0.54
8	2	$ 0.26	$ 0.52
9	2	$ 0.55	$ 1.10
10	2	$ 0.38	$ 0.76
11	2	$ 0.10	$ 0.20
12	2	$ 0.10	$ 0.20
13	2	$ 0.46	$ 0.92
14	2	$ 4.81	$ 9.62
15	2	$ 0.27	$ 0.54
		TOTAL COST	$ 19.94

Fourth Part Order			
Part #	Quantity	Cost/Unit	Total
13	1	$ 19.95	$ 19.95
14	1	$ 25.45	$ 25.45
15	1	$ 1.21	$ 1.21
16	1	$ 0.58	$ 0.58
17	1	$ 13.42	$ 13.42
		TOTAL COST	$ 60.61

Seventh Part Order			
Part #	Quantity	Cost/Unit	Total
1	2	$ 0.29	$ 0.58
2	6	$ 0.10	$ 0.60
3	3	$ 0.24	$ 0.72
4	8	$ 0.35	$ 2.80
5	2	$ 1.99	$ 3.98
6	3	$ 0.63	$ 1.89
7	2	$ 1.24	$ 2.48
8	4	$ 0.10	$ 0.40
9	6	$ 0.17	$ 1.02
10	9	$ 0.20	$ 1.80
11	3	$ 0.72	$ 2.16
12	9	$ 0.10	$ 0.90
13	1	$ 2.69	$ 2.69
14	4	$ 0.18	$ 0.72
15	4	$ 0.32	$ 1.28
16	4	$ 0.10	$ 0.40
17	4	$ 0.10	$ 0.40
18	10	$ 0.23	$ 2.30
19	4	$ 0.11	$ 0.44
20	4	$ 0.71	$ 2.84
21	2	$ 1.54	$ 3.08
22	2	$ 2.85	$ 5.70
23	4	$ 0.28	$ 1.12
24	4	$ 0.17	$ 0.68
25	2	$ 1.08	$ 2.16
26	2	$ 1.21	$ 2.42
27	1	$ 2.12	$ 2.12
28	1	$ 8.74	$ 8.74
29	1	$ 2.15	$ 2.15
30	1	$ 19.95	$ 19.95
31	1	$ 13.42	$ 13.42
		TOTAL COST	$ 91.94

Figure A- 1: Estimation of Costs for Each Part Order

As it can be seen in the tables above, the estimated costs for each part order was calculated. The total for all five parts orders, as mentioned in the report in the cost section was estimated to be about **$255.83.** The estimation for each part order is highlighted as below:

- First Part Order: $19.68
- Second Part Order: $63.66
- Third Part Order: $19.94
- Fourth Part Order: $60.61
- Seventh Part Order: $91.94

Cost Of Single Device			
Part #	Quantity	Cost/Unit	Total
1	1	$ 0.29	$ 0.29
2	2	$ 0.10	$ 0.20
3	1	$ 0.24	$ 0.24
4	5	$ 0.35	$ 1.75
5	1	$ 0.63	$ 0.63
6	1	$ 1.24	$ 1.24
7	1	$ 0.10	$ 0.10
8	2	$ 0.17	$ 0.34
9	3	$ 0.20	$ 0.60
10	3	$ 0.10	$ 0.30
11	1	$ 2.69	$ 2.69
12	1	$ 0.18	$ 0.18
13	1	$ 0.32	$ 0.32
14	1	$ 0.10	$ 0.10
15	1	$ 0.10	$ 0.10
16	4	$ 0.23	$ 0.92
17	1	$ 0.11	$ 0.11
18	1	$ 0.71	$ 0.71
19	1	$ 1.54	$ 1.54
20	1	$ 2.85	$ 2.85
21	1	$ 0.28	$ 0.28
22	1	$ 0.17	$ 0.17
23	1	$ 1.08	$ 1.08
24	1	$ 1.21	$ 1.21
25	1	$ 1.99	$ 1.99
26	1	$ 2.12	$ 2.12
27	1	$ 8.74	$ 8.74
28	1	$ 2.15	$ 2.15
29	1	$ 25.45	$ 25.45
30	1	$ 13.42	$ 13.42
31	1	$ 13.99	$ 13.99
		TOTAL COST	$ 85.81

Figure A- 2: Cost of Short-Range FM Transmitter

Above shows the detailed calculation for the production of a single unit of the short-range FM transmitter. For the device that was used during the final demonstration at the end of the semester, approximately 31 different parts were used, along with there quantities. The unit cost of each part was found on Digikey and Mouser. Based on the quantities of each part that is necessary for the operation of the product, the totals for each part were calculated then summed together to get **$85.81**, the cost for production of a single unit.

Finally, the total cost for manufacturing 10,000 units is shown in Figure A-3. A couple of parts were removed since they are not necessary for the final product. This includes the test pins since they are not necessary for testing, and the internal tactile switch. The detailed calculation of the final cost is shown below.

Approximate Cost of 10,000 Units		
Part #	Quantity	Cost for Total Units
1	10000.00	$ 1,248.00
2	20000.00	$ 126.96
3	10000.00	$ 952.20
4	10000.00	$ 3,344.00
5	10000.00	$ 8,008.00
6	10000.00	$ 270.38
7	20000.00	$ 658.00
8	30000.00	$ 1,244.70
9	30000.00	$ 526.50
10	10000.00	$ 11,843.00
11	10000.00	$ 1,204.00
12	10000.00	$ 63.48
13	10000.00	$ 54.76
14	10000.00	$ 546.20
15	40000.00	$ 880.80
16	10000.00	$ 5,192.00
17	10000.00	$ 6,512.50
18	10000.00	$ 13,317.60
19	10000.00	$ 672.80
20	10000.00	$ 322.20
21	10000.00	$ 4,738.30
22	10000.00	$ 6,698.20
23	10000.00	$ 12,703.50
24	10000.00	$ 59,375.00
25	10000.00	$ 111.28
26	10000.00	$ 194,610.00
27	10000.00	$ 110,000.00
28	10000.00	$ 139,900.00
	TOTAL COST	$ 585,124.36
	COST/UNIT	$ 58.51

Figure A- 3: Manufacturing Cost for 10,000 Units

The total cost for manufacturing 10,000 units was estimated to be **$585,124.36**, which is about **$58.51** per unit.