LOST OBJECT SEARCH TECHNOLOGY (LOST)

By

Brittany Joy

Cecil Macgregor

Adithya Sairam

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TA: Daniel Gardner

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Abstract

This report details the creation and design of LOST, or Lost Objective Search Technology, an object finder specifically designed for visually and audibly-impaired people, but is usable by anyone. The user has a handheld receiver that is used to measure the strength of a radio-frequency signal from a one of three different transmitters, and provide feedback to the user to let them know how close they are to the selected transmitter based on the response rate of an LED, a speaker and a motor (collectively referred to as the feedback module). As the receiver gets closer the to the transmitter, the frequency of the response rate for the components of the feedback module increases. TILE, LOST's biggest competitor, relies on a Bluetooth connection with a phone app and the device attached to a lost object emits a noise, whereas the use of RF provides a larger range, can go through walls, and the receiver lets the user know the distance from an object without solely relying on how well one can hear how close they are to an object or see the approximate location on a phone screen.

Contents

1. Introduction

Lost Object Search Technology is designed to allow users with audio and visual impairment to easily detect and track down small lost objects. In every person's life, there are a handful of small objects which are critical for day to day life, such as car keys, cell phones, wallets, walking canes, etc. Thankfully, there are several products such as Tile which can be attached to these important objects and used to find them if they are misplaced. However, these products all share a common flaw: they are unusable by those with audio and visual impairments. The Tile's phone app is useless to the blind, and the deaf are unable to hear Tile's ringing. Nearly 15% of children experience low or high frequency hearing loss of at least 16-decibel hearing level in one or both ears [1]. Additionally, more than 3.4 million (3%) of Americans aged 40 years and older are either legally blind or are visually impaired [2]. These people are unable to use the existing lost object finders; clearly, something should be done.

The goal was to solve this clear and evident problem by creating LOST, or Lost Object Search Technology. We delivered a product which can be used easily and effectively by any user, regardless of any visual/audio impairments. LOST incorporates a receiver which connects to one of three transmitters (to be attached to up to three different objects). The receiver uses tactile, audio and visual feedback to guide the bearer to the selected transmitter using the classic "Hot or Cold" method of pathfinding. The use of analog switches and multiple forms of feedback will make LOST easily usable by the deaf and the blind.

Some of the key requirements considered for the creation and design of LOST are battery life, reliable radio-frequency communication between the transmitter and receiver, and portability of the project. Here are the high-level requirements which were achieved:

- Receiver must be able to connect to and evaluate the signal strength of up to three separate transmitters at a range of up to 300 feet with a resolution of >= 1 dB.
- Receiver must be able to report the signal strength (i.e., distance to transmitter) to the user using tactile feedback via a vibration motor, visual feedback via an LED, and audio feedback via speakers. Feedback will pulse at a rate proportional to received signal strength.
- Transmitters must be small (7cm x 7cm x 0.7cm), light (<50g), and able to operate on battery power for >30 days.

Below in Figure 1 is the block diagram that LOST was based off:

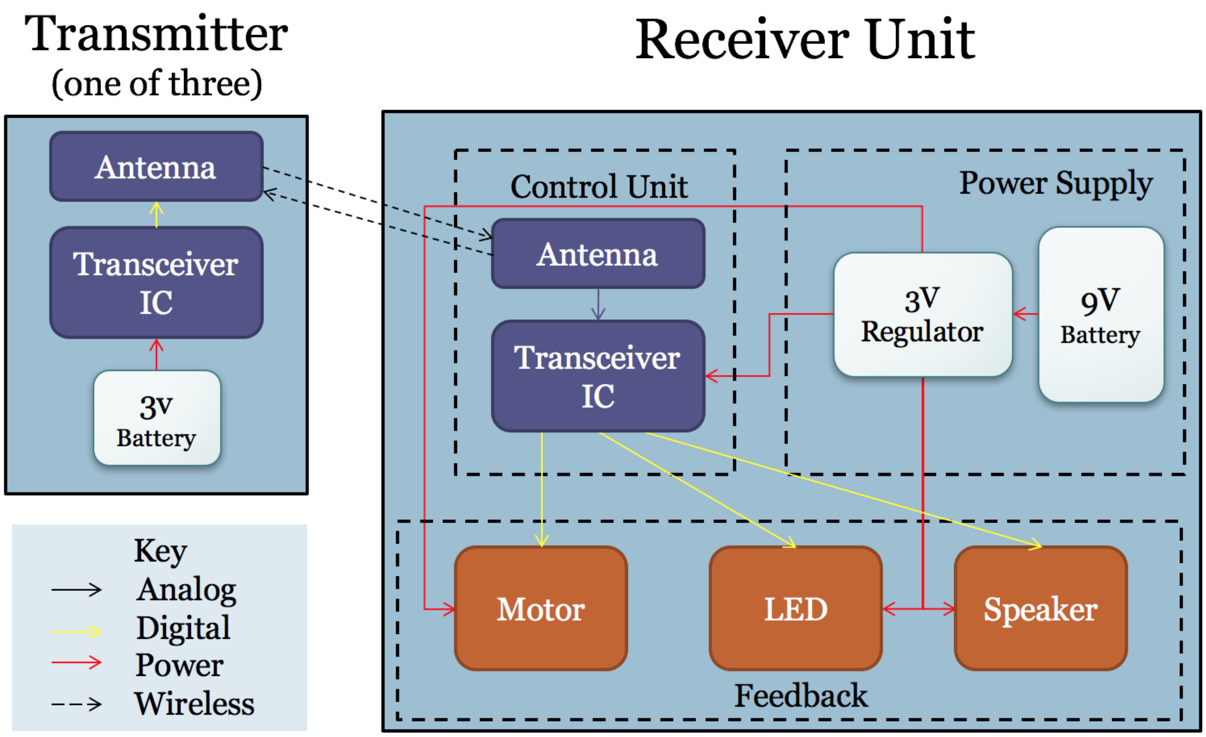

Figure 1: LOST Block diagram

2. Design

LOST has four major modules that are a part of its design: the transmitters, the control unit, the feedback module, and the power supply module. A block diagram of LOST is shown above in Figure 1. The receiver unit has a switch to turn off the power completely to the receiver when not in use, the transmitters will constantly remain in an on state, but will only transmit a signal when the user is actively searching for a lost object.

There are three RF transmitters, all transmitting signals in the 915 MHz industrial, scientific, and medical (ISM) band. The 915 MHz ISM band spans 902 MHz - 928 MHz, with the center frequency being 915 MHz, giving the radio band its name. 903 MHz, 915 MHz and 927 MHz were chosen as the operating frequencies for the transmitters merely to spread out along the band as much as possible. Each channel on this band occupies a width of 2 MHz, so that is the maximum bandwidth for signals we are transmitting. This ISM band is unlicensed in North America, and its most common use is industrial monitoring and home security. Each transmitter has its own small battery supply and listens periodically for when to begin transmitting a signal so the lost object can be found.

The control unit consists of the transceiver IC and an antenna. The transceiver IC is used to determine the RF signal strength and the on-chip microcontroller determines how to control the feedback module. The strength of the RF signal is calculated using RSSI, or Received Signal Strength Indicator. The transceiver IC gives the digital RSSI. RSSI is inversely proportional to distance [9] so we can correlate an increasing or decreasing trend in RSSI with decreasing or increasing distance, respectively.

The feedback module contains 3 different parts used to interact with the user. It receives signals from the output of the transceiver module that are fed into a speaker, a vibration motor, and an LED. Each of these indicates greater signal strength with an increased frequency of pulsation of sound from the speaker, vibration from the motor, and blinks from the light.

The power supply module consists of a 9V battery and a voltage regulator to step the 9V battery down to 3.5V to power the receiver and the feedback module components.

2.1 The Transmitters

The three transmitters send signals in the 915 MHz ISM band which is to be picked up by the receiver when attempting to locate lost objects. Each of them will has two antennas (for antenna diversity) and an integrated chip consisting of a transceiver and a microcontroller that will be powered by a 3V lithium battery. Each transmitter will operate at a different frequency corresponding to different channels within the 915 MHz ISM band. Operating frequencies of 903 MHz, 915 MHz, 927 MHz (2 MHz max BW) were selected. There are three transmitters included in this design and more cannot be added independently because the switch on the receiver unit has a limited number of locations it can toggle between (three in our design). The final transmitter is shown below in Figure 2.

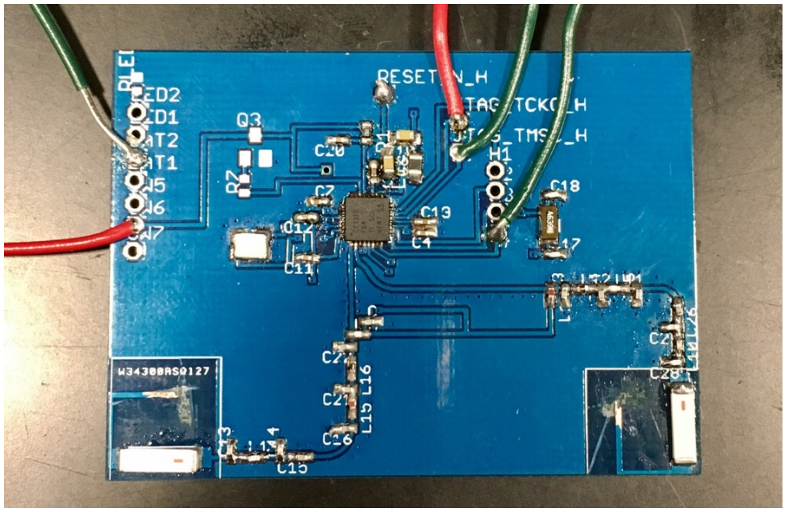

Figure 2: Transmitter

2.1.1 Transceiver IC

The RF transmitters (that are connected to objects the user wants to track such as keys or phones) are paired with a receiver that is kept on the user, and have operating frequencies of 903 MHz, 915 MHz, and 927 MHz. Texas Instruments' CC1310 SimpleLINK Ultra-Low-Power Sub-1 GHz Wireless MCU (CC1310F64RSMR package) was used. This transceiver IC was selected because the total cost of the chip and its development board was the cheapest of all the ultra-low-power transceiver ICs researched. This IC contains a very low power RF transceiver, used to receive and transmit signals, and a Cortex-M3 microcontroller that is used to program the transceiver with specific instructions. The transmitter is meant to be always turned on when connected to a frequently misplaced object and the transceiver will always be in transmit mode. In transmit mode, the transceiver is programmed to transmit an RF packet every single second. When its not transmitting, it will be in a standby mode, which consumes much less power. This way, the transmitter uses 11.2mA briefly for once a second. Rated power consumption in various operating modes is summarized in Table 1 below.

Receiving	5.5mA
Transmitting (10 dBm)	11.2 mA

Table 1: Transceiver Module Power Consumption

The microcontroller in the transceiver IC is an ARM Cortex-M3 processor with 16kB of RAM and 64kB of Flash. The microcontroller is used to control the transceiver so that it can operate in the desired modes described above. The package used in this design has 10 GPIO (General Purpose Input/Output) pins. This package contains the fewest number of GPIOs of the three available packages but has more than this design requires which is the reason it was chosen.

2.1.2 Antennas

The antennas are used to transmit and receive RF signals from the transmitters. A design utilizing antenna diversity was incorporated since LOST will be used primarily indoors. When indoors, there is not always a clear line-of-sight path between the antenna and the transceiver. The signal can be reflected along multiple paths before reaching the receiver and these signals can potentially destructively interfere. Having two antennas in this design has the potential to improve the quality and reliability of the RF wireless link since it reduces multipath interference. This is because the transceiver receives multiple observations of the same signal and if one of the antennas receive a bad signal, with optimal placement on the board the other antenna is likely in a position where it is receiving a much better signal [11]. The resonance of every antenna was tuned so that the antenna would resonate at the frequency of interest, 915 MHz. In order to achieve best functionality and reduce mismatch loss, antenna impedance matching circuitry was implemented [3]. See Appendix D - Antenna Tuning/Matching for more on the design of tuning the resonance and matching the antennas. Omnidirectional antennas were chosen since the transmitter can be in any direction away from the user. A chip antenna was selected over a copper PCB trace antenna so that the antenna would be physically smaller since LOST should be as small and compact as possible.

2.1.3 Battery

The transmitters will be powered with a CR 2032 3V coin battery. This will provide power to the internal transceiver and associated microcontroller.

2.2 Control Unit

The user will select one of the three transmitters using a switch on the receiver unit and the corresponding strength of the RF signal chosen by the user will be relayed to the feedback module. The schematic for the receiver unit that includes the control unit can be found in Appendix F – PCB Schematics and Layouts.

2.2.1 Transceiver IC

The physical part for this module is the same part used for the Transmitter Transceiver module. However, the transceiver has a different functionality in this module. When turned on, it will be in receive mode and consume a constant 5.5mA and look for an RF packet. When it receives a packet, it monitors the RSSI of the signal from the transmitter and uses it to determine the appropriate level of feedback to relay to the user. RSSI is used to output a single clock signal to the feedback module that controls all three components of the feedback module simultaneously. The frequency of this clock signal will vary directly with received signal strength to indicate proximity to the lost object.

2.2.2 Antennas

The antennas in the control unit of the receiver unit are identical to the antennas on each transmitter. Antenna diversity was also used in this design to reduce multipath interference. Antenna tuning and impedance matching was also performed on these antennas. See Appendix D - Antenna Tuning/Matching for more information.

2.3 Feedback

Since LOST is designed to work with people with audio/visual impairments, there are several methods of interacting with the receiver unit including sight, sound and touch. The schematic for the feedback module is shown below in Figure 3. L1 is the feedback LED, M1 is the vibration motor, and the speaker is labeled. An open-collector configuration was chosen to drive the modules since this topology is commonly used to drive devices that otherwise are not receiving enough current. It is also easy to make this transistor configuration work and turn on. Values for the resistors on the base of the transistors (R1, R2, and R3) and the values for the resistors in series with the LED and motor (R4 and R5) were calculated based off the gain of the transistor and the current requirements for each component. Once assembled, the values of these resistors were adjusted (by placing in different resistors) until the current requirements for each component were met. Each component receives input from a GPIO on the transceiver IC. When the GPIO is low, the components do not draw current.

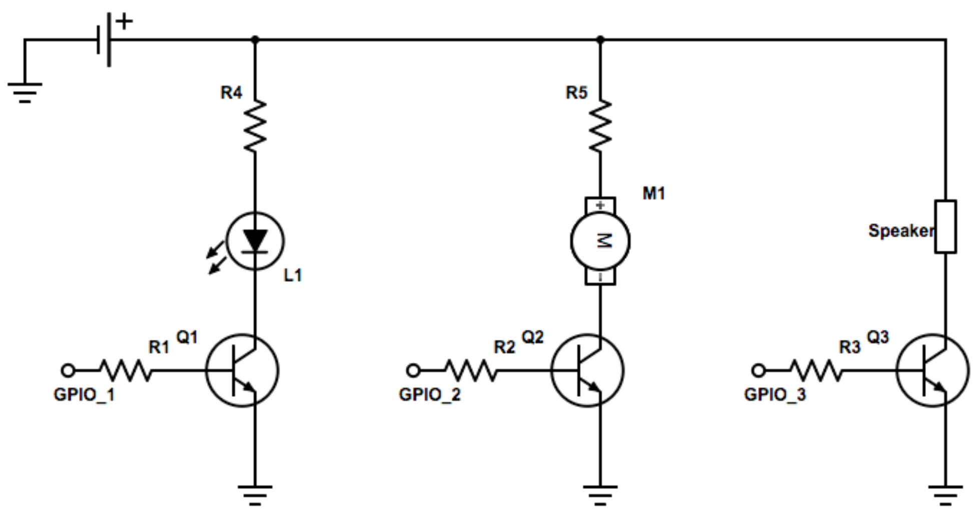

Figure 3: Feedback module schematic

2.3.1 The Vibration Motor

The vibration motor buzzes with faster frequency as the user approaches the transmitter of their choice, with constant intensity.

2.3.2 LED

The feedback LED blinks with increasing frequency as the user approaches the selected transmitter.

2.3.3 Speaker

The speaker beeps with faster frequency as the user approaches the transmitter. This will work in tandem with the LEDs and vibration motors so all three are in sync. The transceiver IC has the capability of outputting a PWM signal which is essentially a square wave. This can be output as a sound from the speaker. From testing, it was decided that a 400 Hz tone was audible enough and pleasant enough to be used.

2.4 Power Supply

The receiver unit is operated with a 9V battery with a buck converter to bring the voltage down to 3V so every part of the circuit can be powered without being overloaded. There is also a master power switch which will turn the power off for the receiver unit when not in use.

2.4.1 9V Battery

A 9V battery powers the receiver unit and will ensure a long-lasting life for the entire unit since the battery has more capacity than the small 3V coin battery in the transmitters. The implementation of the master switch will make sure that the battery isn't always draining.

2.4.2 Voltage Regulator

A voltage regulator is needed to step down the voltage from the 9V battery to 3.5V. The 3.5V supply is used to power the transceiver IC and the feedback module on the receiver unit. A buck converter was chosen over a linear voltage regulator because buck converters are more efficient and the receiver runs on battery power. The schematic for the buck converter circuit is shown below in Figure 4. Two resistors (R1 and R2 in the schematic) in the external circuitry of the voltage regulator control the output voltage supplied to the rest of the network.

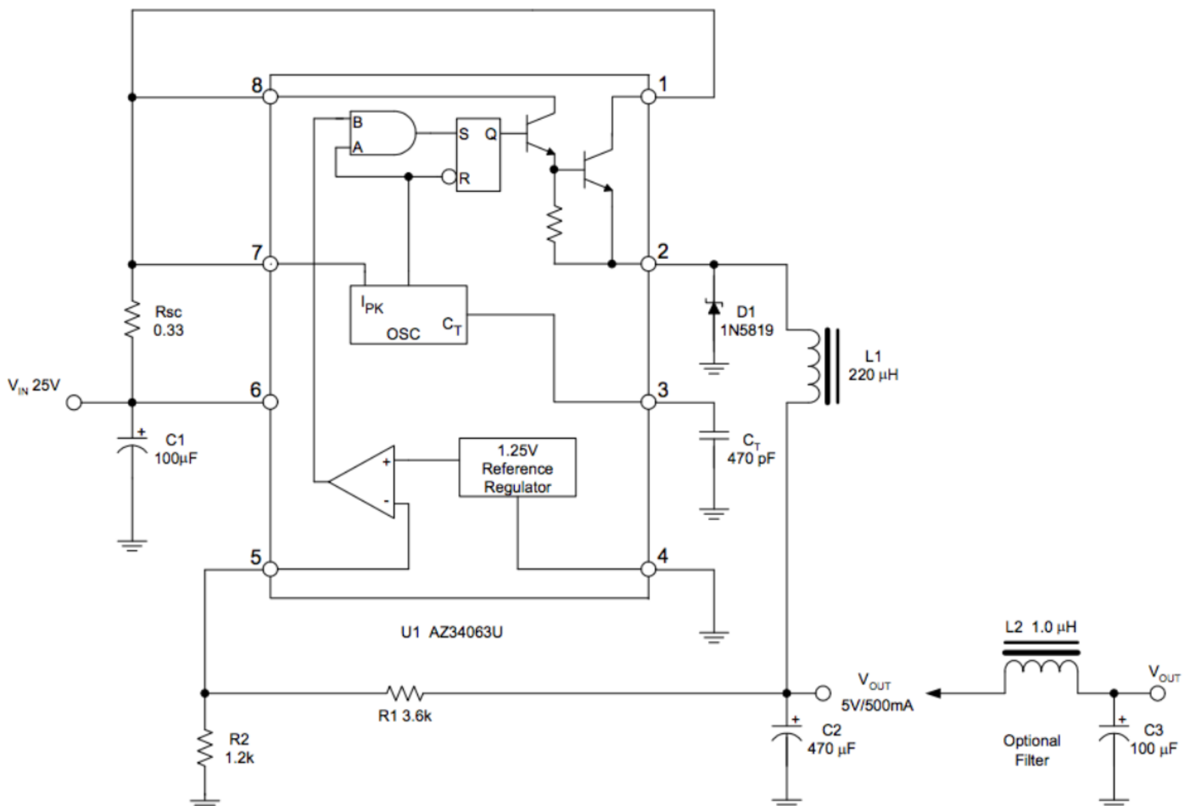

Figure 4: Buck Converter Schematic

2.5 PCB

This design required two PCBs, one for the receiver and one for the transmitters. The PCB for the receiver contains all the external circuitry required for the transceiver IC, spots for the two antennas and RF lines going from the antenna to the RF input of the transceiver IC (with matching networks in between), the buck converter and its associated external circuitry, and the circuitry required for the feedback module. The PCB for the transmitters is simply a stripped down version of the receiver PCB since the transmitter does not have a buck converter or any of the components associated with the feedback module.

Line widths for 50 ohm traces had to be computed for all the RF lines on the board. The ADS LineCalc tool was used for this. The PCB can be modeled as a grounded coplanar waveguide. Since the PCBs were ordered from PCBWay, specs for the PCBs were obtained from them.

There are two matching networks for each antenna on the board. The first matching network was designed before the PCB was made and it transformed 50 ohms to 44-j15 ohms at the RF input on the transceiver IC (specified on the datasheets as the optimal impedance). Space was left for a second matching network (pi-network) that would incorporate a matching network based on the values measured for the impedance looking into the RF lineup and transform the impedance to 50 ohms at the input of the antenna. The antennas themselves were placed optimally on the board according to documentation for the antenna. Careful measures were taken to follow specifications exactly for how the layout for and around the antenna should be done.

Placement of the resistors, capacitors and inductors were decided based on minimizing board size, short traces so there is no delay in reading and processing signals, and eliminating any current loops. One of the challenges in doing this was ensuring that the RF trace was never crossed by signal traces because that would create too much interference. To work around that, we used a via placed close to the chip so the RF trace was crossed at its thinnest.

The PCB layout and specifications for the transmitter and receiver are shown in Appendix F – PCB Schematics and Layouts.

2.6 Software

The software governs the activity of LOST, and is split into two major parts. The transmitter algorithm (Figure 5) governs the functionality of LOST's three transmitters, and is responsible for initializing and triggering broadcasts in the 915 MHz ISM band along with entering and exiting sleep mode. The receiver algorithm (Figure 6) is responsible for receiving, parsing, and evaluating packets, along with controlling output to the feedback module. Code samples are included in Appendix C – Code.

2.6.1 Transmitter Algorithm

The transmitter algorithm has two separate modes of functionality, low power sleep mode and active transmission. During active transmission, the code is generating and sending packets once per second. These packets are ordered sequentially and contain information identifying the transmitter responsible for sending the packet. With this information, the receiver can detect dropped packets as a break in the sequence, and can verify that received packed are coming from LOST's transmitter and not a third party. These packets are sent one at a time, with a one second pause between each packet.

For debugging purposes, buttons can be pressed to manually enter and exit sleep mode, which prevents the sending of further packets and deactivates the radio module to consume less power while idling.

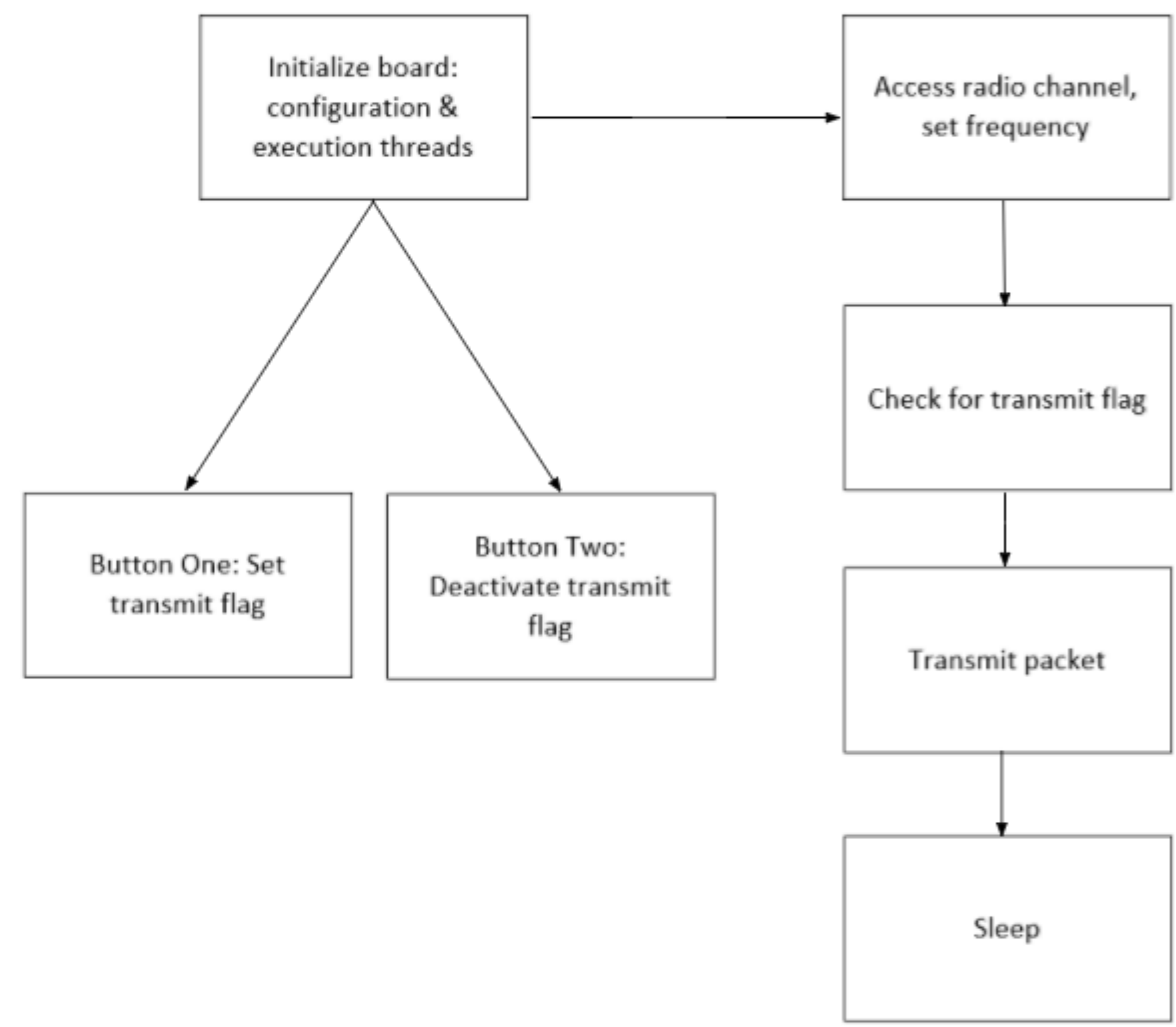

Figure 5: Transmitter logic flow

2.6.2 Receiver Algorithm

The receiver algorithm activates the radio and waits to receive packets on the frequency of the selected transmitter. Upon receiving a packet, it parses the packet and evaluates the Received Signal Strength Indicator (RSSI). RSSI is a measure of the radio frequency signal strength, measured in dBM. By convention, the strongest possible signal value is -14 dBM, while the weakest acceptable value is around -70. Using this value, it updates the response rate of the feedback module. This response rate is determined by the RSSI; the weaker the signal strength, the slower the response rate. The rate increases dramatically as the RSSI nears its maximum value, such that the feedback module buzzes extremely quickly once the receiver and transmitter are nearly touching. A display of our recorded RSSI values at varying distances is included in appendix C.

Simultaneously, the receiver algorithm is also controlling the feedback module in a simple fashion. It causes the module to pulse once (i.e., the LED flashes, the vibration motor vibrates, and the speaker beeps), then it sleeps for a period equal to the response rate.

See Appendix G – Distance vs RSSI for detailed graph.

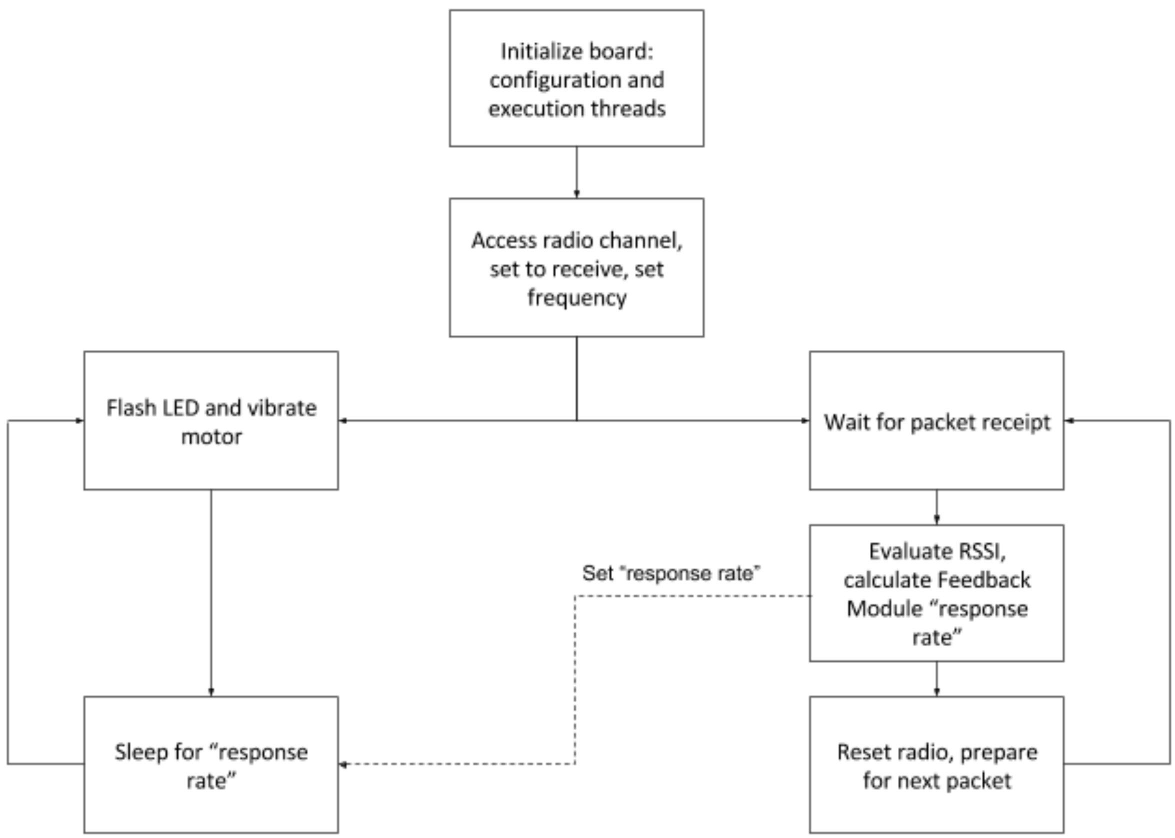

Figure 6: Receiver logic flow

3. Design Verification

Much of the design verification came from individual tests on separate modules since we were never able to get code onto the transceiver IC on the PCB. Because of this, the system incorporating the PCBs could not be tested.

3.1 The Transmitters

We were unable to test the transmitter as a whole since we couldn't get code onto our PCB.

3.1.1 Transceiver IC

To test the transceiver IC on the PCB, we attempted to program a simple program onto it which would turn on a preset GPIO. However, from the time of assembly on the PCB, we had trouble communicating with the CC1310 while trying to program the PCB from the development kit. There were three ways we tested why this error kept occurring: Ensure the JTAG connections were correct and secure, the memory mapping from different package sizes of the CC1310 was correct, and test the onboard PCB clock. The memory mapping discrepancies were taken care of in the software, while the test of the JTAG pin and clock were done by probing the pins and ensuring the outputs of each pin responded as expected. To circumvent this issue, we used another groups dev kit to transmit the RF signal, while our dev kit received the signal and manipulated the data.

3.1.2 Antennas

To match the antenna, all the components prior to the last matching network (pi-network before the antenna feed) were mounted onto the PCB. A pigtail was mounted on the input feed of the antenna to measure the impedance with a Network Analyzer. A network was then designed to match that impedance to 50 ohms at the input of the antenna. This process and the results are elaborated upon in Appendix D - Antenna Tuning/Matching. Unfortunately, even though careful design choices were made to implement antenna diversity and antennas were tuned for resonance as well as impedance matched, since we were never able to get code onto our PCB, we were unable to measure the performance of the antennas on our PCBs to see if all the design work that was put into them was truly helpful. The only verification that could be done with the antennas was verifying that they could at least receive and transmit at various frequencies along the 915 MHz ISM band (903, 915, 927 MHz) with a Signal Generator and a Spectrum Analyzer.

3.1.3 Battery

Given that code was completed sooner, batteries could have been tested to see how long they would be able to power the transmitters and how long the batteries on the transmitters would last. A theoretical calculation on the batteries based off typical current consumption of the transceiver ICs estimates that the transmitter battery should last for approximately 45 days. See Appendix E – Transmitter Battery Life Calculation for details on this calculation.

3.2 Control Unit

3.2.1 Transceiver IC

This module is identical to 3.1.1 with the added caveat that this is the receiver and has to communicate with the feedback module. After we decided that it was not possible to use the microcontroller on the PCB, we used another CC1310 dev kit from a different group, and did RSSI testing. One of the boards had the receiving RF code programmed while the other had the transmitter program, and we walked throughout ECEB and tested the strength and reliability of the RSSI. Once we had some solid data to work with, we created a response rate for the feedback module based on the signal strength.

3.2.2 Antennas

These antennas were matched in the exact same way as the antennas in 3.1.2 since the PCB was identical for the transmitter and receiver for this part. The rest of the design as well as the verification was also identical.

3.3 Feedback

The feedback module was unfortunately designed wrong for the PCB. A line that should have been brought to power was actually ground. Instead, the feedback module was successfully implemented and tested on the perf board. Components were connected to GPIOs on the transceiver IC dev board and driven by the driver circuit elaborated upon in section 2.3.

3.3.1 The Vibration Motor

A requirement of the motor was that it drew less than 22 mA. When the notor was connected directly to a DC power supply, it was found that the motor dissipates 0.8V when drawing 22mA of current. Since the motor will be receiving 3.5V supply, it needs a resistor in series to reduce the amount of current it draws. The value for this resistance was calculated as follows:

The resistor needs to dissipate 3.5-.8 = 2.7 V

$$V = IR, R = \frac{V}{I} = \frac{2.7V}{22mA} = 122.7\ ohms$$

It was found that a resistor of 120 ohms met this current requirement when implemented in the circuit.

3.3.2 LED

When tested with various values of resistance in series, the LED drew 3-6mA of current when turned on. A resistor of 330 ohms in series with the LED caused a current draw of 3mA which is well within the requirement of 22mA.

3.3.3 Speaker

The speaker was very quiet whenever it had series resistance added to it. Without any resistance in series, the Speaker drew less than 22 mA which met our power requirement. The speaker was tested using a sine wave and a square wave output from a mustimeter. This is hour the frequency of a 400 MHz tone was selected for the operation of the speaker.

3.4 Power Supply

The overall power supply was verified to provide enough power both to turn on the development board to act as the receiver as well as simultaneously power the feedback module that was implemented on the perf board.

3.4.1 9V Battery

The 9V battery provided 9.2V when measured brand new.

3.4.2 Voltage Regulator

The design equations for the output voltage of the buck converter are shown below.

$$V_{PIN5} = V_{OUT}\left(\frac{R2}{R1 + R2}\right) = 1.25\ (V)$$

$$V_{OUT} = 1.25\left(\frac{R1 + R2}{R2}\right)\ (V)$$

Initially, values of R1 = 3.6k ohms and R2 = 2.32k ohms were calculated to provide an output voltage of 3.19V. When measured, the actual output was slightly below 3V and it was not enough to turn on the development board. From values of SMT resistors we had available to us, we found values of R1 – 2.32k ohms and R2 = 1.2k ohms would theoretically give and output voltage of 3.7V but when measured gave 3.5V. This output was a smooth and constant 3.5V DC. This was enough voltage to turn on both the development board and the feedback module, so these were the final values used.

3.5 Software

Our software verification was performed on the development boards we used, the CC1310 Launchpad. This made it simple to demonstrate the sending and receiving of packets, switching between frequencies, and driving input/output pins on the CC1310. This all proved that our software worked as intended; the only issues arose when trying to move our software from the development board to the CC1310 package on our PCB, which rejected our attempts to do so.

4. Costs

We estimate a $54,000 and a parts cost of about $55 per LOST system.

4.1 Parts

A summarized table of costs is shown below. Parts such as the development board, UFL to SMA cable, and extra reactive components for designing the matching network are only development costs. The cost of rest of the parts that go into the final product are listed as a total under "final product." A full detailed list of parts costs can be found in Appendix B - Detailed Costs Table.

Part	Distributor	Cost
Final Product	Digikey (mostly)	$55.39
Development Costs	Digikey (mostly)	$42.77
Total		**$97.66**

Table 2: Costs Summary

4.2 Labor

The development costs in terms of labor are 40$/hr, 15 hrs/wk for three people. By the week of demos, we will have for approximately 12 weeks. Therefore, the total costs come out to:

$$2.5 * 3\ people * \frac{\$40}{hour} * \frac{15\ hours}{week} * 12\ weeks = \$54{,}000$$

5. Conclusion

5.1 Accomplishments

We were able to show independently that all of the hardware worked on the PCB excluding the microcontroller that we were unable to program. To be exact, we implemented the antennas and tune/impedance match them on the PCBs, the feedback module was implemented and worked as it should, and the buck converter properly stepped down the 9V battery to give a smooth, consistent 3.5V DC output.

From a software perspective, the transmitter and receiver code worked well with the hardware on the development kit and we were able to definitively show that a transmitter could be found by holding the receiver. The RSSI worked as expected, and the speaker, motor and LED were all driven the correct way. We eliminated any delays in receiving and processing the RF packets and RSSI by using multi-threading within the program, and triggering interrupts whenever an event occurs. This allowed for two threads to run simultaneously on the receiver and we experienced no performance or calculation delays.

5.2 Uncertainties

Although the hardware worked reliably and consistently, programming the on-PCB CC1310 did not. We tested the module rigorously for 5 days and attempted to find a solution to why it was not possible. Communication of the two JTAG connections from dev kit to the PCB worked accurately when probing with an oscilloscope, but even the simplest program did seem to work. We borrowed the development kit from another team to test if the program worked on that, and it did which led us to believe that there was some issue with the way the development kit communicated with the CC1310 on the PCB. We configured some of the pin and memory mappings to match the packages, but that did not work. The best way to eliminate this problem would be to use an Arduino Micro, which has a lot more technical support online with a similar cost/power ratio as the CC1310.

5.3 Ethical considerations

In accordance with the #1 of IEEE Code of Ethics, we “accept responsibility in making decisions consistent with the safety, health, and welfare of the public” and will “disclose promptly factors that might endanger the public or environment.” Our project is designed and intended to help people (especially those with audio/visual impairments) locate frequently misplaced objects easily and efficiently. The purpose of this section is to explain how we will commit to this.

Since our project has several transceiver chips and will be reprogrammable if tampered with, it is possible for someone to figure out a way to use components of our project maliciously. Attempting to track someone using this project would be difficult since the unlicensed band it operates on is heavily used over short ranges and signals are only transmitted when the user is looking for an object. Also, no sensitive information is ever transmitted. To prevent someone from tampering with the project, peripherals required to reprogram the devices will not be included and individual parts will not be easily accessible.

Our design for the project utilizes 9V batteries and Lithium coin batteries. There are safety hazards associated with both types of batteries. If metal or a conductive material connects the terminals on the 9V battery, it can cause a short circuit which can generate heat and possibly start a fire. During development, we took caution in storing any 9V batteries by either leaving them in their original packaging or storing them upright, and not storing them in contact with other batteries or metal objects as well as covering the terminals with masking, duct, or electrical tape [5]. Information on 9V battery safety will be included with our project so that the user does not unintentionally put themselves at risk.

Lithium coin batteries are less dangerous electrically than 9V batteries, but are a choking hazard for young children. If ingested, they can cause severe burns on the esophagus in as little as two hours and can cause ongoing medical concerns [6]. If the user removes the coin batteries they must be sure to keep out of reach of children and dispose of the batteries when they need to be replaced. We followed the safe practice guidelines for Lithium batteries provided by the course [7].

In accordance with #9 of the IEEE Code of Ethics, we will "avoid injuring others" by explicitly stating any hazards. To avoid any ethical breach, we will make clear any associated safety concerns with our project. In general, if the project is tampered with or taken apart, small pieces pose threat as a choking hazard to children and should be kept out of reach. There is also risk of electrical shock if the project is tampered with. This project will have RF emissions when on and in use. These RF emissions are lower power than emissions from cell phones or microwave ovens and do not pose a health risk.

Our project can be classified as a low-power non-licensed transmitter. Our project will comply with Part 15 of the FCC to avoid potential harmful interference with other RF signals. We intend to operate our project in the 902-928 MHz range which is a typical unlicensed part 15 band for devices of this type. Our project could potentially interfere with household devices such as cordless telephones, wireless toys, and baby monitors because these objects may also operate in this same frequency range [8]. Since the devices associated with our project are small and low-power, the field strength will not exceed the 30 dBm limit set by the FCC [10].

5.4 Future work

Despite several issues, we were pleased to produce a result which can do what we set out to do: track down lost objects. However, the product is far from finished. To continue our work, the first step needs to be switching out the CC1310, which generated a host of issues for our team, ranging from a severe dearth of documentation to a product which simply refused to be programmed on our PCB, despite all our efforts. With a different transceiver IC or different method of combining a transceiver and microcontroller, such as an Arduino Micro and a compatible transceiver, we could get our code running on our product as it should. We could redesign our PCB with minimal effort and produce a result which is as compact and lightweight as we originally intended, rather than having a bulky dev board strapped to our PCB. With that done, we could consider building a protective and elegant casing for our product, and possibly add in the ability to recharge our battery for ease of use. Additionally, the impedance matching networks we designed for our antennas need to be improved, as described in Appendix D – Antenna Tuning/Matching. With these changes made, we firmly believe a useful and impressive product that could improve the lives of those with audio and visual impairments could be created.

References

[1] "Data and Statistics." Centers for Disease Control and Prevention. Centers for Disease Control and Prevention, 05 Dec. 2016. Web. 07 Feb. 2017. <https://www.cdc.gov/ncbddd/hearingloss/data.html>.

[2] "The Burden of Vision Loss." Centers for Disease Control and Prevention. Centers for Disease Control and Prevention, 25 Sept. 2009. Web. 07 Feb. 2017. <https://www.cdc.gov/visionhealth/basic_information/vision_loss_burden.htm>.

[3] "3 Factors That Limit Range in RF Applications." Laird Technologies Wireless Connectivity Blog. Laird Wireless Blog, 03 Nov. 2015. Web. 08 Feb. 2017. <.http://www.summitdata.com/blog/3-factors-limit-range-rf-applications/>.

[4] "Small Loudspeaker Circuit Diagram Using IC LM386." Small Loudspeaker Circuit Diagram Using IC LM386. Circuit Digest, n.d. Web. 08 Feb. 2017. <http://circuitdigest.com/electronic-circuits/small-loudspeaker-circuit-diagram>.

[5] "9V Battery." NFPA. N.p., n.d. Web. 7 Feb. 2017. <http://www.nfpa.org/~/media/files/public-education/resources/safety-tip-sheets/9voltbatterysafety.p>.

[6] "Coin Lithium Battery Safety." Coin Lithium Battery Safety. Energizer, n.d. Web. 08 Feb. 2017. <http://www.energizer.com/responsibility/coin-lithium-battery-safety/preventing-coin-lithium-battery-injury>.

[7] Spring 2016 Course Staff. "Safe Practice for Lead Acid and Lithium Batteries." (n.d.): n. pag. *ECE 445 Senior Design Laboratory*. ECE Illinois, 13 Apr. 2016. Web. 8 Feb. 2017. <https://courses.engr.illinois.edu/ece445/documents/GeneralBatterySafety.pdf>.

[8] "ARRL." Part 15 - Radio Frequency Devices. ARRL, n.d. Web. 08 Feb. 2017. <http://www.arrl.org/part-15-radio-frequency-devices>.

[9] Parameswaran, Ambili T., Mohammad I. Husain, and Shambhu Upadhyaya. "Is RSSI a Reliable Parameter in Sensor Localization Algorithms – An Experimental Study." Web. <http://www.cse.buffalo.edu/srds2009/F2DA/f2da09_RSSI_Parameswaran.pdf>.

[10] "FCC Rules for Wireless Equipment Operating in the ISM Bands." N.p., n.d. Web. 08 Mar. 2017. <http://www.afar.net/tutorials/fcc-rules>.

[11] "Antenna Diversity." Wikipedia. Wikimedia Foundation, 05 Mar. 2017. Web. 2 May 2017. https://en.wikipedia.org/wiki/Antenna_diversity.

Appendix A - Requirement and Verification Table

A.1 Transceiver IC

Requirement	Verification	Status

1. The transceiver module must be able to receive signals over the 915 MHz ISM band.
2. The transceiver module must be able to transmit signals over the 915 MHz ISM band at selected frequencies (below) within the band (max bandwidth 2 MHz).
    a. 903 MHz
    b. 915 MHz
    c. 927 MHz
3. In listen mode the transceiver module consumes <.5mA on average
4. During transmission, it will consume <15 mA.
	1.
	    a. Use a Signal Generator with an attached antenna to generate signals at the desired operating frequencies and -10 dBm power.
	    b. Set transceiver to operate in receive mode
	    c. Monitor RSSI given by the transceiver at a distance of 5 and 10 m from the Signal Generator.
	2.
	    a. Set transceiver to operate in transmit mode at 1 of the desired frequencies.
	    b. Use a Signal Analyzer with an antenna attached to the input and measure the strength of the received signal at the desired frequency
	    c. Adjust transceiver and repeat at the other two operational frequencies
	3.
	    a. Put the transceiver in sleep mode and test how much current it is drawing. Use a 47 kohm resistor and measure voltage with a voltmeter to calculate current.
	    b. Put the transceiver in receive mode and test how much current is being drawn by the same method as in 2a.
	4. Put the transceiver in transmit mode and test it in the same way as step 2
		1. Y
		2. Y
		3. Y
		4. Y

A.2 Antenna

Requirement	Verification	Status
1. Antenna must be able to receive signals at 903, 915, and 927 MHz. 2. Antenna must be able to transmit signals at 903, 915, and 927 MHz	1. a. Use a Signal Generator with an attached antenna to generate signals at the desired operating frequencies (903, 915, and 927 MHz) at -10 dBm power. b. Set transceiver to operate in receive mode (with antenna attached) c. Monitor RSSI given by the transceiver and ensure signal with >-110 dBm is received. 2. a. Set transceiver (with antenna attached) to operate in transmit mode at -10 dBm at one of the desired frequencies (903, 915, or 927 MHz). b. Use a Signal Analyzer with an antenna attached to the input and measure the strength of the received signal at the desired frequency c. Adjust transceiver and repeat at the other two operational frequencies.	1. Y 2. Y

A.3 3V Battery

Requirement	Verification	Status
1. The battery will have a capacity of 225 ± 10 mAh at 3 ± 0.3 V.	1. Touch voltmeter probes to the positive and negative sides of the battery to measure voltage. Any value lower than 2.7V is considered dead.	1. Y

A.4 Vibration motor

Requirement	Verification	Status
1. The motor operates in the range of 1.2-1.8V, with a nominal voltage of 1.5V. 2. The maximum current draw should be less than 22 mA.	1. Connect the motor to a 1.5V power source and check that it is vibrating as expected. 2. Measure the current using an amp-meter and check that the draw	1. Y 2. Y

	doesn't exceed 22 mA +- 1 mA.	

A.5 LED

Requirement	Verification	Status
1. The LED turns on with 5V supply. 2. The maximum current draw should be less than 21mA.	1. Connect the LED to a 5V supply and check that it is bright and visible. 2. Check the voltage drop across the resistor and divide it by 1 kOhm to measure current. This should be under 20mA.	1. Y 2. Y

A.6 Speaker

Requirement	Verification	Status
1. The rated impedance is 8 ohms.	1. Use a multimeter to test impedance.	1. N

A.7 9V Battery

Requirement	Verification	Status
1. The battery will have a capacity of 500 ± 15 mAh at 9 ± 0.2 V.	1. Touch voltmeter probes to the positive and negative sides of the battery to measure voltage. Any value lower than 8.8V is considered dead.	1. N

Appendix B - Detailed Costs Table

The following is a table for full parts costs.

Part	Manufacturer	Retail Cost ($)	Quantity	Actual Cost ($)
RF Transceiver IC	Texas Instruments	$6.55	2	$13.10
RF Dev Board	Texas Instruments	$29.09	1	$29.09
Buck, Boost Switching Regulator	Diodes Incorporated	$0.47	1	$0.47
Antenna	Johanson Technology	$0.81	8	$6.51

diode for buck converter	ON Semiconductor	$0.41	1	$0.41
470uF capacitor	AVX Corporation	$1.94	1	$1.94
100uF capacitor	AVX Corporation	$0.80	1	$0.80
470pF capacitor	Murata	$0.03	1	$0.03
.33 ohm resistor	Panasonic Electronic Components	$0.38	1	$0.38
BJT for buck	Panasonic Electronic Components	$0.41	1	$0.41
22uF capacitor	Murata	$0.16	8	$1.27
2.7pF capacitor	Murata	$0.02	8	$0.18
.1uF capacitor	Murata	$0.01	76	$0.72
6.2pF capacitor	Murata	$0.03	8	$0.25
3pF capacitor	Murata	$0.02	8	$0.15
100pF capacitor	Murata	$0.01	12	$0.12
7pF capacitor	Murata	$0.03	8	$0.25
1uF capacitor	Murata	$0.03	4	$0.11
6.8uH inductor	TDK	$0.13	4	$0.50
7.2nH inductor	Abracon LLC	$0.10	8	$0.81
SMA to UFL connector	RF Solutions	$13.18	1	$13.18
24 MHz crystal	Epson Timing	$0.51	4	$2.04
32.768 kHz crystal	Epson Timing	$0.81	4	$3.24
220uH inductor	TDK	$0.27	1	$0.27
Speaker	Adafruit	$1.75	1	$1.75
2.7pF capacitor	Murata	$0.02	8	$0.18
6.2pF capacitor	Murata	$0.03	8	$0.25
3pF capacitor	Murata	$0.02	8	$0.15
7pF capacitor	Murata	$0.03	8	$0.25
6.8nH inductor	Johanson Technology	$0.04	8	$0.32
diode for buck converter	ON Semiconductor	$0.41	1	$0.41
470uF capacitor	AVX Corporation	$1.94	1	$1.94
100uF capacitor	AVX Corporation	$0.80	1	$0.80
Red LED	Cree Inc	$0.15	4	$0.60
Red LED	Cree Inc	$0.15	1	$0.15
Red LED	Cree Inc	$0.15	1	$0.15
White LED	Cree Inc	$0.20	1	$0.20
Speaker	Soberton Inc	$2.05	1	$2.05
Vibration motor	Adafruit	$1.95	1	$1.95
PN2222 Transistor npn (through-hole)	Fairchild/ON Semiconductor	$0.18	4	$0.72
NPN Surface Mount SOT-23	ON Semiconductor	$0.10	4	$0.41
STRAP BATT ECON 9V I STYLE 4"LD	Keystone Electronics	$0.60	1	$0.60

2X2032 COIN BATT HOLDER W/SWITCH	Adafruit	$1.95	3	$5.85
Panasonic BATTERY LITHIUM 3V COIN 20MM	Panasonic	$0.29	3	$0.87
9V battery	Energizer	$1.80	1	$1.80
1.2kohm (for buck)	Samsung	$0.01	1	$0.01
2.32kohm (for buck)	Stackpole Electronics	$0.02	1	$0.02
Total				$97.66

Table 3: Parts Cost

Appendix C - Code

C.1 Transmitter Pseudocode

```
static void transmitThread()
{
    /* Request access to the radio */
    rfHandle = RF_open(&rfObject, &RF_prop,
(RF_RadioSetup*)&RF_cmdPropRadioDivSetup, &rfParams);

    /* Set the frequency */
    RF_postCmd(rfHandle, (RF_Op*)&RF_cmdFs, RF_PriorityNormal, NULL,
0);

    /* Get current time */
    curtime = RF_getCurrentTime();
    while(1)
    {
        if(transmit == 1)
        {
            /* Create packet with incrementing sequence number and
random payload */
            packet[0] = (uint8_t)(seqNumber >> 8);
            packet[1] = (uint8_t)(seqNumber++);
            uint8_t i;
            for (i = 2; i < PAYLOAD_LENGTH; i++)
            {
                packet[i] = (uint8_t)(915);         //Add identifying
information to the body of the packet
            }
```

```
            /* Set absolute TX time to utilize automatic power
management */
            curtime += PACKET_INTERVAL;
            RF_cmdPropTx.startTime = curtime;

            /* Send packet */
            RF_EventMask result = RF_runCmd(rfHandle,
(RF_Op*)&RF_cmdPropTx, RF_PriorityNormal, NULL, 0);
            if (!(result & RF_EventLastCmdDone))
            {
                /* Error */
                printf("Error in transmit\n");
                while(1);
            }
        }
        else
        {
            sleep(1);
        }
    }
}
```

C.2 Receiver Code

```
static void receiveThread()
{
    rfc_propRxOutput_t rxStatistics;

    RF_Params rfParams;
    RF_Params_init(&rfParams);

    if( RFQueue_defineQueue(&dataQueue,
                            rxDataEntryBuffer,
                            sizeof(rxDataEntryBuffer),
                            NUM_DATA_ENTRIES,
                            MAX_LENGTH + NUM_APPENDED_BYTES))
    {
        /* Failed to allocate space for all data entries */
        printf("Error, line 161\n");
        while(1);
    }

    /* Modify CMD_PROP_RX command for application needs */
    RF_cmdPropRx.pQueue = &dataQueue;           /* Set the Data Entity
queue for received data */
```

```
    RF_cmdPropRx.rxConf.bAutoFlushIgnored = 1;  /* Discard ignored
packets from Rx queue */
    RF_cmdPropRx.rxConf.bAutoFlushCrcErr = 1;   /* Discard packets
with CRC error from Rx queue */
    RF_cmdPropRx.maxPktLen = MAX_LENGTH;        /* Implement packet
length filtering to avoid PROP_ERROR_RXBUF */
    RF_cmdPropRx.pktConf.bRepeatOk = 1;
    RF_cmdPropRx.pktConf.bRepeatNok = 1;

    /* Request access to the radio */
    rfHandle = RF_open(&rfObject, &RF_prop,
(RF_RadioSetup*)&RF_cmdPropRadioDivSetup, &rfParams);

    /* Set the frequency */
    RF_postCmd(rfHandle, (RF_Op*)&RF_cmdFs, RF_PriorityNormal, NULL,
0);

    // Set up RX command to output statistics data
    RF_cmdPropRx.pOutput = (uint8_t*)&rxStatistics;

    // Read RSSI after a packet has been received
    rssi = &rxStatistics.lastRssi;

    /* Enter RX mode and stay forever in RX */
    RF_runCmd(rfHandle, (RF_Op*)&RF_cmdPropRx, RF_PriorityNormal,
&callback, IRQ_RX_ENTRY_DONE);
    while(1);
}

void callback() //called upon receipt of a packet
{
    if (packetSuccess)
    {
        /* Toggle pin to indicate RX */
        PIN_setOutputValue(ledPinHandle,
Board_PIN_LED2,!PIN_getOutputValue(Board_PIN_LED2));

        /* Get current unhandled data entry */
        currentDataEntry = RFQueue_getDataEntry();

        /* Handle the packet data, located at &currentDataEntry->data
*/
        packetLength      = *(uint8_t*)(&currentDataEntry->data);
        packetDataPointer = (uint8_t*)(&currentDataEntry->data + 1);
```

```
        /* Copy the payload + the status byte to the packet variable
*/
        memcpy(packet, packetDataPointer, (packetLength + 1));

        RFQueue_nextEntry();
    }
}
```

Appendix D - Antenna Tuning/Matching

D.1 Resonance Tuning

Tuning the resonance of an antenna insures that the impedance at the input of the antenna is purely real, but this does not necessarily mean the antenna is matched to a 50-ohm system. However, tuning the antenna reduces power reflections between the antenna and the rest of the system to improve power transfer. The steps taken in tuning the resonance of the antenna are outlined below.

First, one-port SOLT calibration was performed on a Network Analyzer. Then, a pigtail was soldered onto a blank PCB with only the chip antenna soldered down. S11 was views in log-mag format on the Network Analyzer. Before any tuning was done, the antenna resonated at 844MHz as seen below in Figure 5.

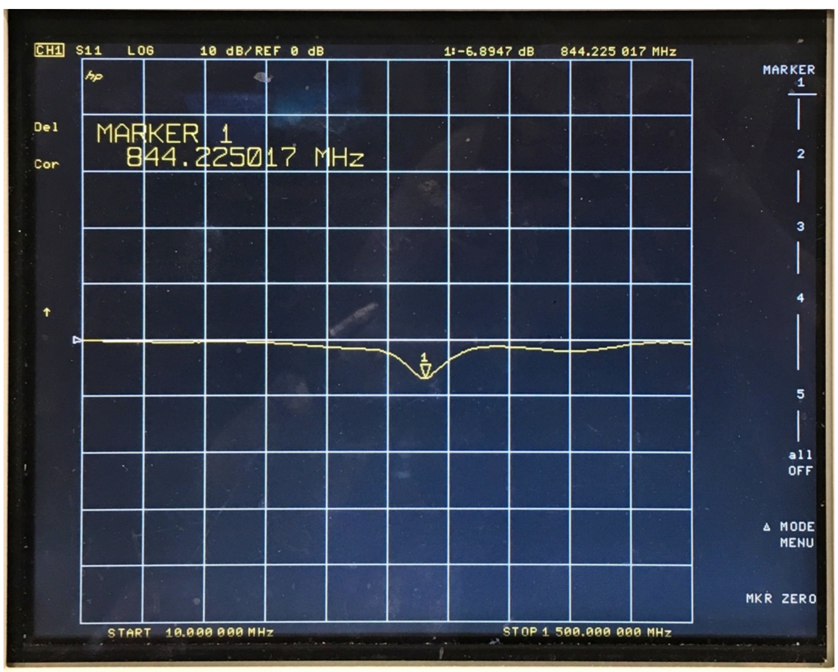

Figure 5: Antenna resonance before tuning

Next, the copper trace that extended from the end of the antenna (effectively increading the length of the antenna) was scraped away until the antenna resonated at 915MHz as seen below in Figure 6. Also, this tuning had an added benefit of improving S11 by about 5 dB at its frequency of resonance, which also means the antenna has a better match to the system.

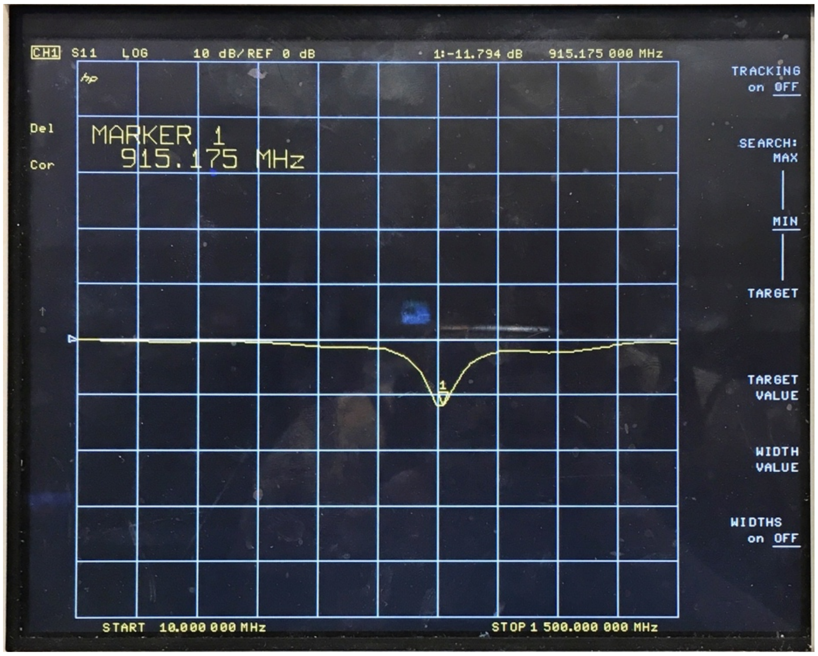

Figure 6: Antenna resonance after tuning

D.2 Impedance Matching

There are two matching networks on every PCB in LOST. The first network transforms 50 ohms to the optimal 44-j15 ohms at the RF input on the transceiver IC. The schematic of this network is shown below in Figure 7.

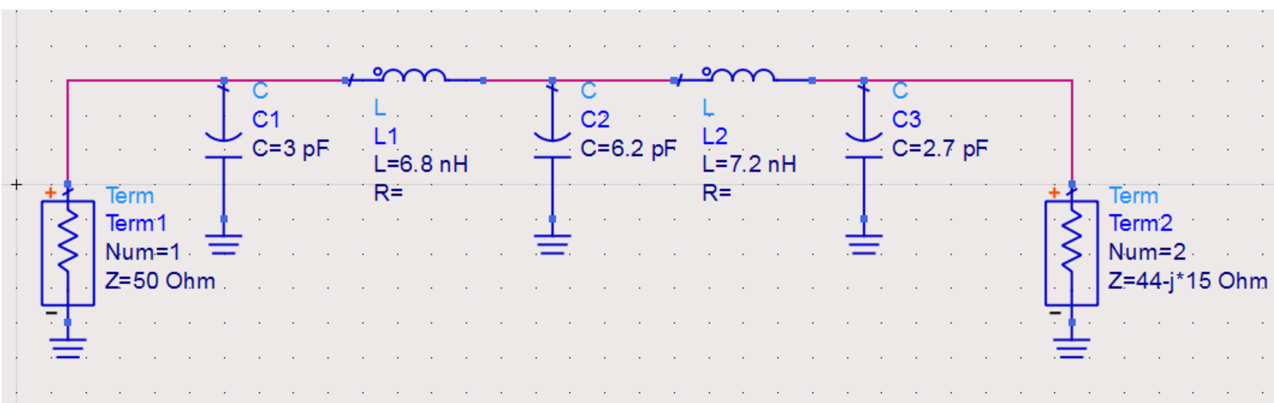

Figure 7: Matching network to transform 50 ohms to 44-j15 ohms

The second matching network is a pi-network intended to match the measured impedance of the network seen in front of the antenna to 50 ohms at the input of the antenna. To measure the impedance that the antenna needs to be matched to, the entire circuit for the transceiver IC was soldered down onto the PCB (the chip antenna was not connected) and then a pigtail was soldered to where the antenna input would be. This impedance was measured on the Network Analyzer to be 28.6-j17.7ohms. This corresponds to a mismatch factor of .881, where 1 corresponds to a perfect match. Figure 8 shows this measurement. This would need to be transformed to 50 ohms to present 50 ohms of impedance to the input of the antenna.

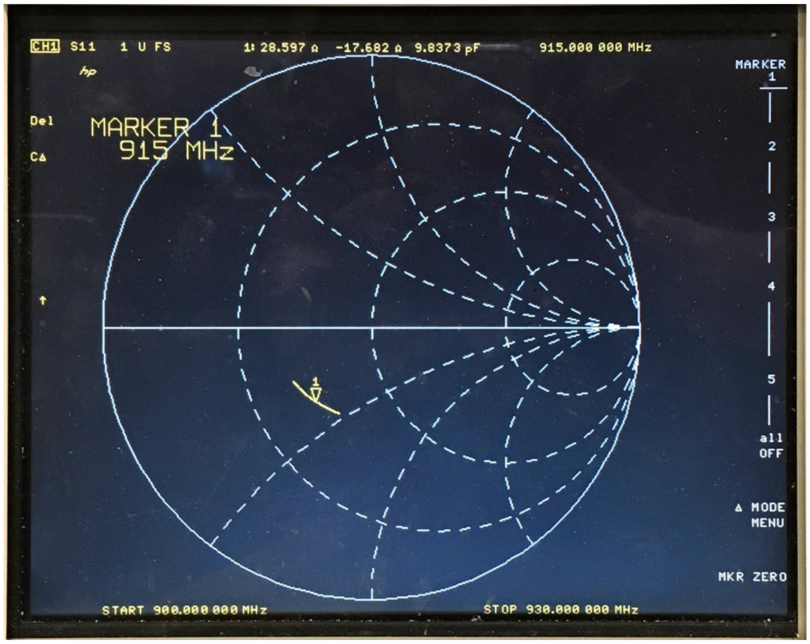

Figure 8: Measured impedance before matching network

ADS was used to calculate the values of components needed to transform this impedance. The results from the Smith Chart Tool in ADS are shown below in Figure 9. As can be seen in Figure 9, this network should theoretically give a 50 ohm match. The schematic for this corresponding matching network is shown below in Figure 10. The results of this mounting this network on the PCB are shown below in Figure 11. The calculated mismatch factor is now .930, which is closer to 1, which means we have an improvement in the match; however, a perfect match was not achieved. The mistake in calculating this matching network was realized too late to go back and correct it. The flaw in this calculation is that the network that was designed should transform 50 ohms to the complex conjugate of the impedance that was measured to achieve maximum power transfer by reducing reflections between the antenna and the rest of the system. This means the network should have been designed to transform 50 ohms to 28.6+j17.7ohms. If the network was designed to transform to this value instead, a match much closer to 50 ohms should be achieved.

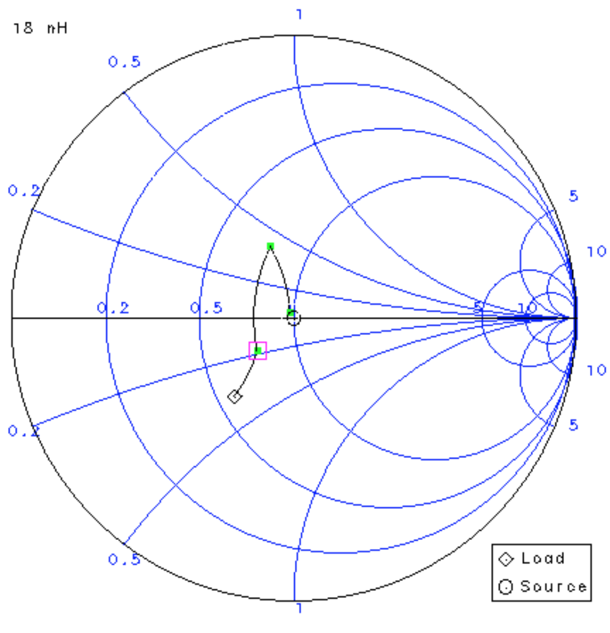

Figure 9: ADS Smith Chart Tool

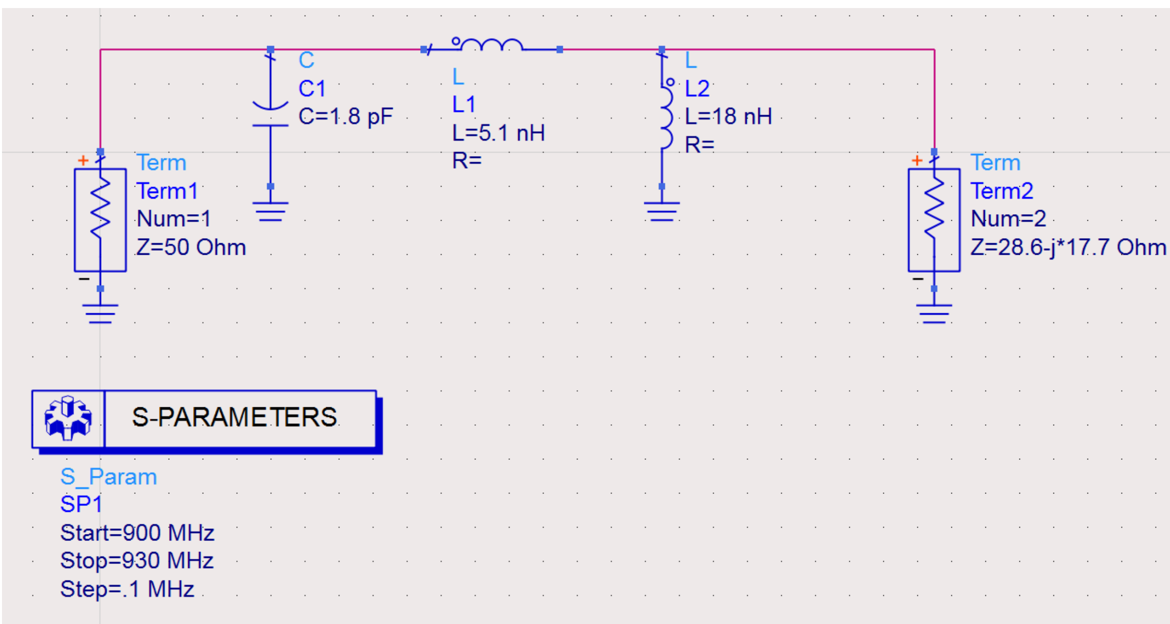

Figure 10: Matching Network schematic

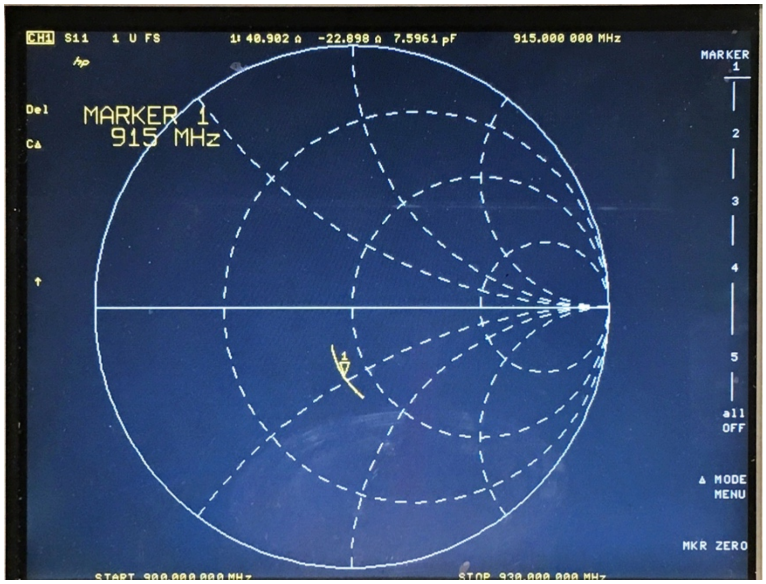

Figure 11: S11 After matching network

Appendix E – Transmitter Battery Life Calculation

The most important aspect of our project which can be calculated prior to building and testing is the transmitter's battery life. To adhere with our high level requirements, it must be able to function on battery power for >30 days, using a 3V battery with a 225 mAh capacity.

To verify this, we first calculated the transmitter's power consumption if it is never activated and used to broadcast to the receiver. In this case, it will only be in the standby mode cycle as described in section 2.1.1: 14.75 seconds of standby mode, 0.25 seconds of receive mode to check if the receiver is trying to contact it.

According to the data sheet, the Texas Instruments CC1310 package used in the transmitter has the following current consumption, seen in Table 4.

Receiving	5.5mA
Transmitting	11.2mA

Table 4: Transceiver IC power consumption

Thus, the following calculation can be made to determine average current consumption in the standby mode cycle:

$$\frac{(14.75\, s * 0.0007\, mA) + (0.25\, s * 5.5\, mA)}{15\, s} = 0.1020\, mA$$

Which can be used to estimate how long the battery will last.

$$\frac{225\ mA * h}{0.1020\ mA} = 2205.88\ h = 91.91\ days$$

This simplistic estimation shows a battery life which is well within the >30 day battery life requirement. However, it is important to include the effects of active transmission when LOST is activated to track down the transmitter when it's attached to misplaced objects.

Our usage model allows for the transmitter to be active <=1% of the time. This corresponds to roughly 14 minutes of active use each day, which is far more than we would expect the typical user to need.

Thus, we graph charge consumption assuming a current draw 0.1020 mA for the first 99% of each day, then 11.2 mA for the remaining 1%. This is shown in Figure 12.

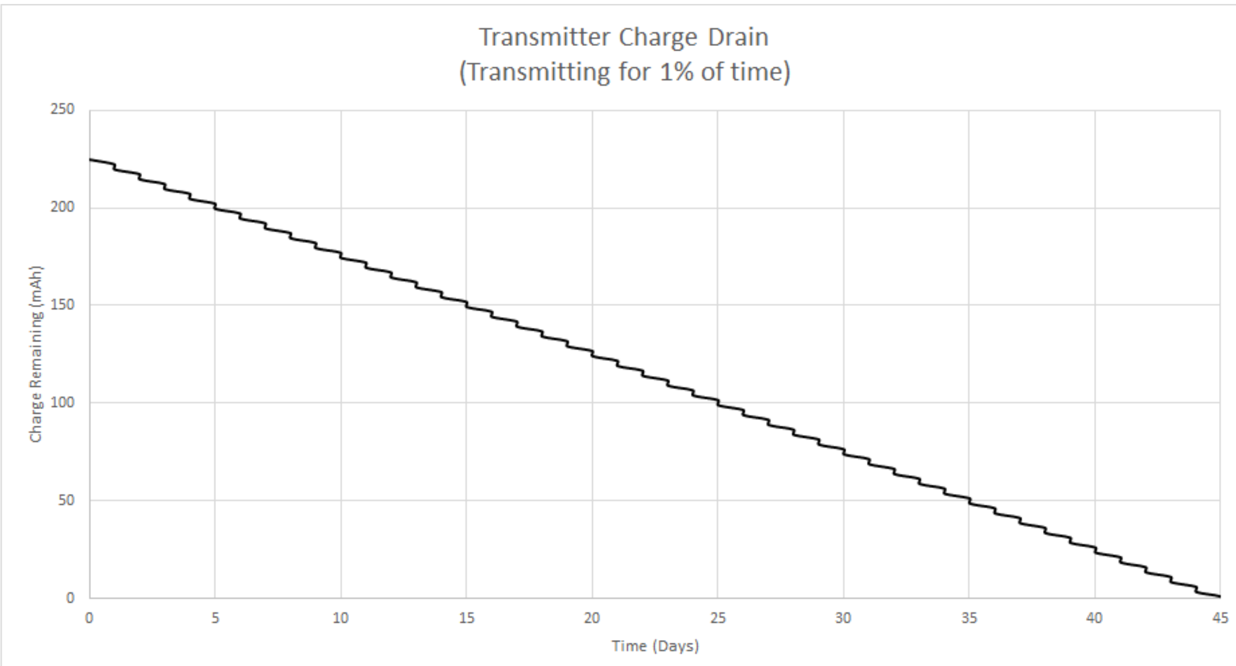

Figure 12: Transmitter charge drain

Plotting this data shows the battery draining after 45 days, which is within our high level requirement of >30 days.

Appendix F – PCB Schematics and Layouts

Shown below in Figure 13 is the transmitter schematic and shown below in Figure 14 is the PCB layout for the transmitter.

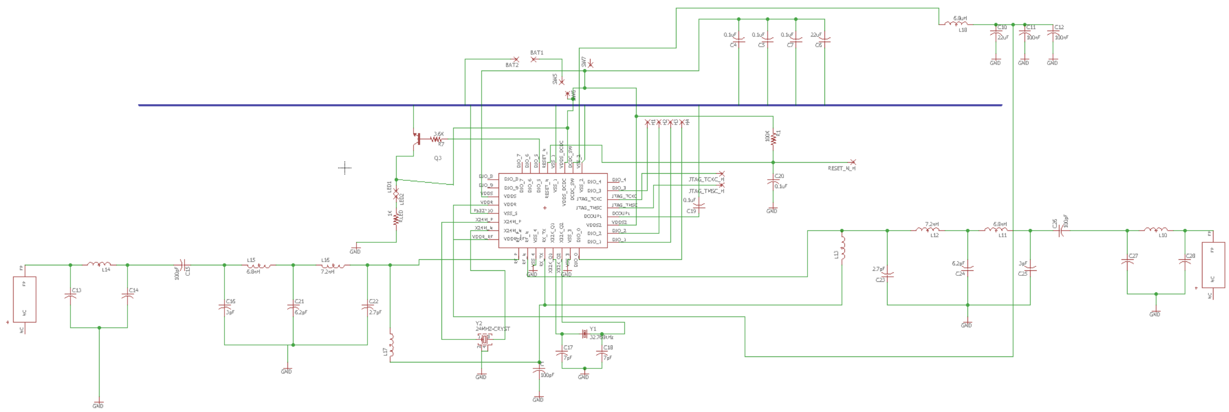

Figure 13: Transmitter Schematic

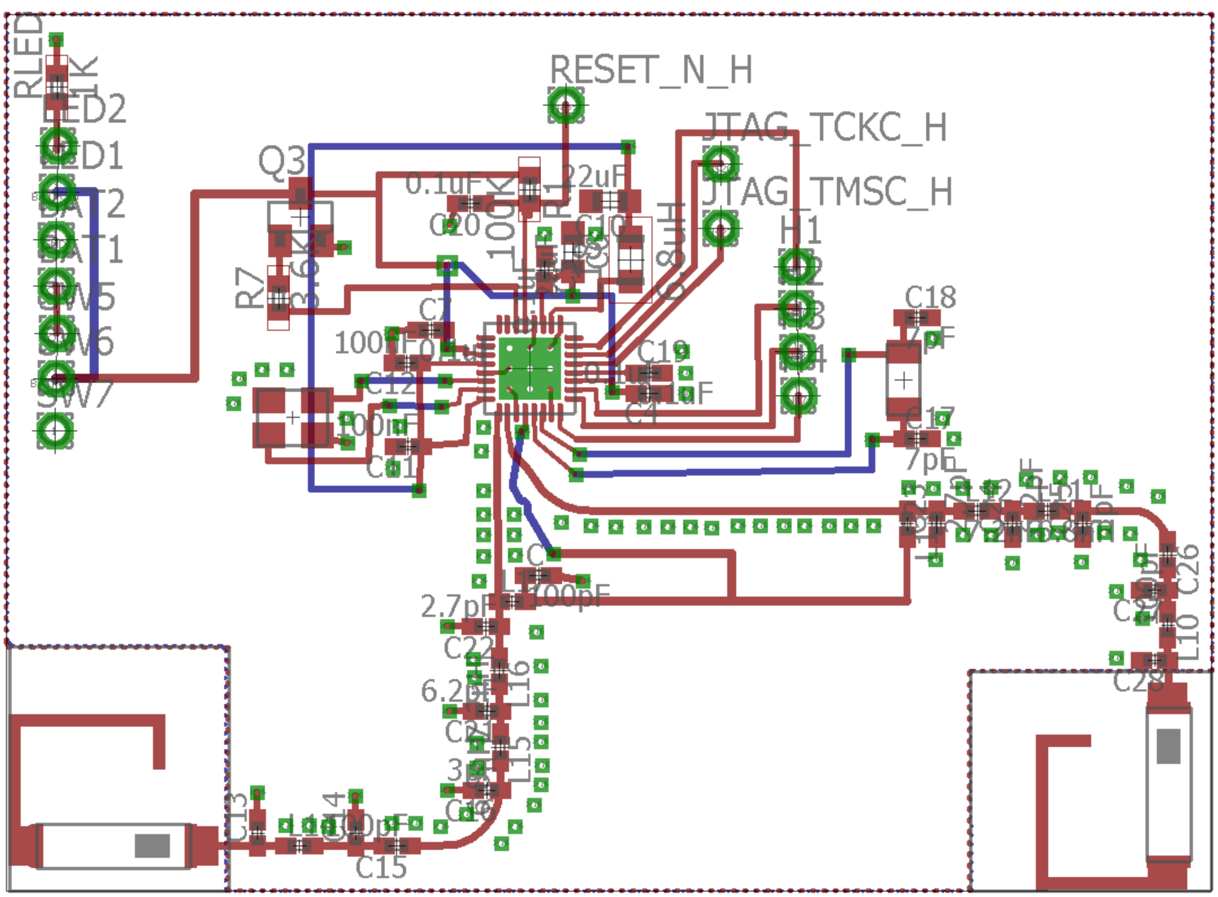

Figure 14: Transmitter layout

Shown below in Figure 15 is the receiver schematic and shown below in Figure 16 is the PCB layout for the receiver.

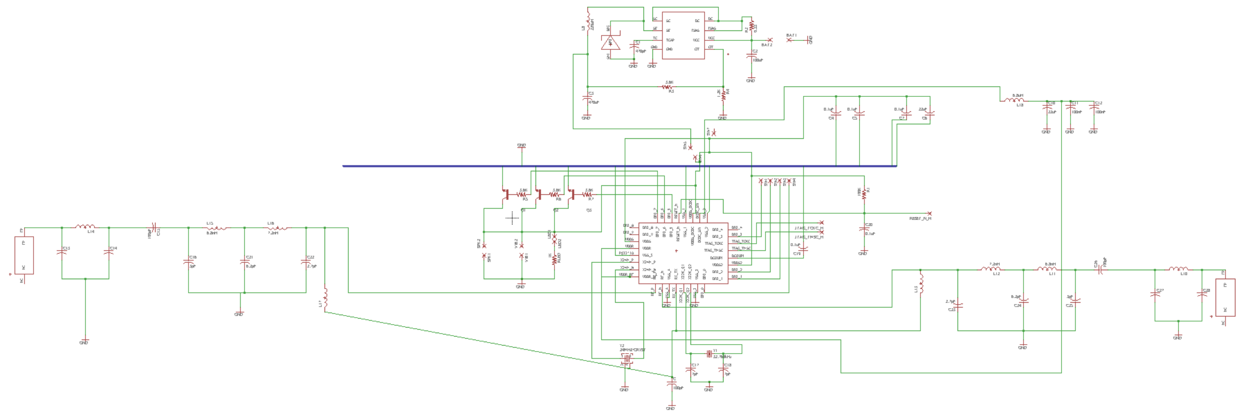

Figure 15: Receiver schematic

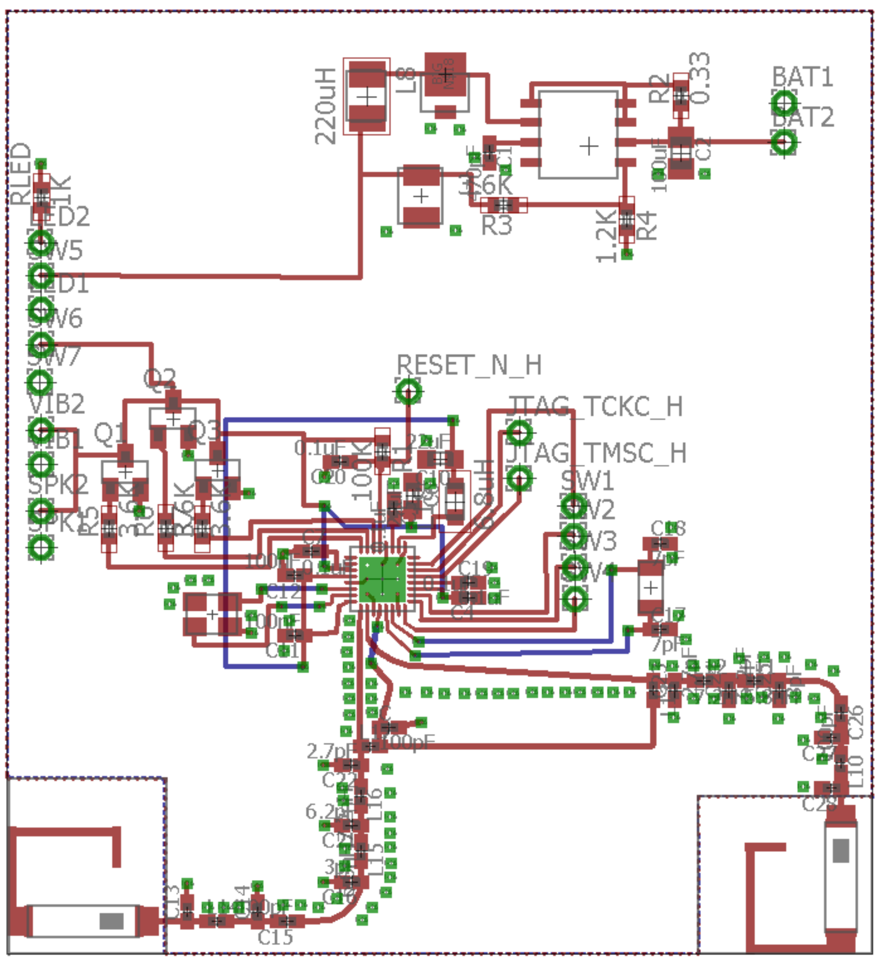

Figure 16: Receiver Layout

F.1 PCB Specifications

<u>PCB Specifications for Receiver</u>
Width (X-dimension) (mm): 55
Height (Y-dimension) (mm): 60
Quantity: 10
Layers: 2
Layer Order from Top to Bottom (if more than 2-Layers): N/A
Thickness: 0.6 mm
Solder Mask Color: Red
Copper Weight (1, 2, 3, or 4 oz): 1oz

<u>PCB Specifications for Transmitter</u>
Width (X-dimension) (mm): 55
Height (Y-dimension) (mm): 40
Quantity: 10
Layers: 2
Layer Order from Top to Bottom (if more than 2-Layers): N/A
Thickness: 0.6 mm
Solder Mask Color: Blue
Copper Weight (1, 2, 3, or 4 oz): 1oz

Appendix G – Distance vs RSSI

Here is the graph for Distance vs Received Signal Strength Indicator (RSSI).

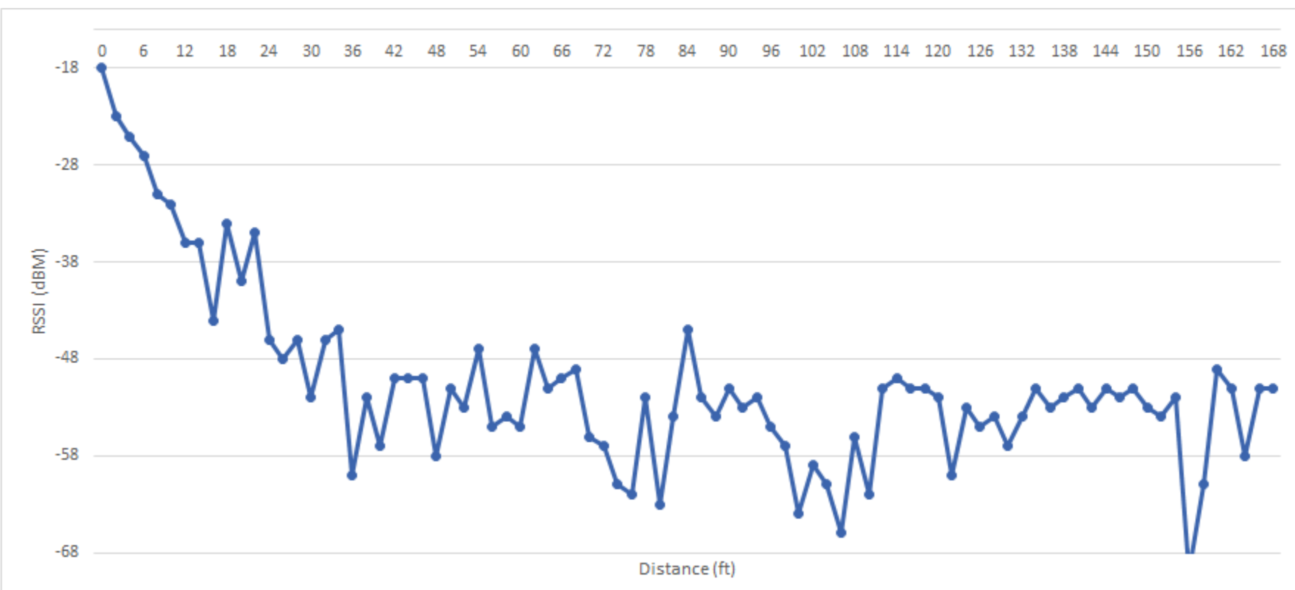

Figure 17: Distance vs Received Signal Strength Indicator (RSSI)