University of Southern Indiana
Pott College of Science, Engineering, and Education
Engineering Department

8600 University Boulevard
Evansville, Indiana 47712

Electronic Whistle Transmitter and Receiver

Wyat Harmon, Erica Schmidt, Presley Warren
ENGR 491 - Senior Design
Spring 2022

Approved by: ____

Faculty Advisor: Arthur Chlebowski, Ph.D. Date

Approved by: ____

Department Chair: Paul Kuban, Ph.D. Date:

ACKNOWLEDGEMENTS

We would like to acknowledge all the organizations and individuals which aided us in the completion of this project in its entirety:

- University of Southern Indiana Engineering Program & Department
- Dr. Arthur Chlebowski, Project Advisor
- Dr. Julian Davis, Project Liaison
- Jamie Curry, Senior Administrative Assistant
- HomeValet, Nick Daniels
- Richard Pflanz

ABSTRACT

American football players often have trouble hearing the whistle due to high intensity play, physical contact, adrenaline, and extremely loud crowds; so, they continue to throw, run, and/or tackle without realizing the referee(s) has stopped the play. This presents an added danger to the game and results in avoidable injuries that occur after the play is over. To increase player safety, this project consists of designing a secondary tonal system, placed in helmets, that alerts football players that a play has ended. The electronic whistle transmitter and receiver system uses low frequency wireless communication between two custom printed circuit boards that delivers an audible tone close to the players' ears when the electronic whistle is activated. The electronic whistle transmitter and receiver system acts as an additional safety measure for the athletes.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

ELECTRONIC WHISTLE TRANSMITTER AND RECEIVER IMPLEMENTATION

1. PROJECT PURPOSE

Concern regarding the risks of sports-related injuries, specifically concussions, has grown in recent years. According to the National Safety Council, being struck by another person or object is the leading cause of injury for young adults ages 15 to 24, and sports-related concussions play a significant role in this statistic [1].

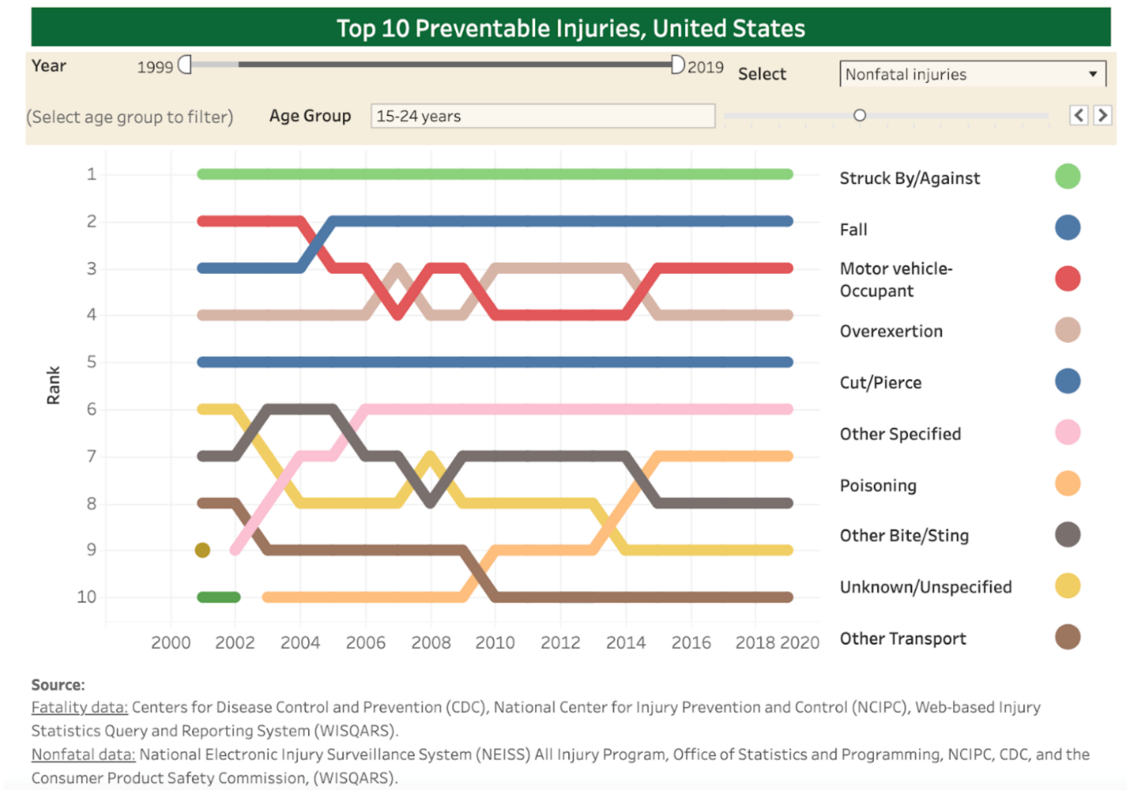

Figure 1: Preventable Injury Statistics [1]

According to the Brain Injury Research Institute (BIRI), brain injuries cause more deaths than any other sports injury. In American football, brain injuries account for 65% to 95% of all fatalities, brain injuries occur at the rate of one in every 5.5 games, and in any given season, 10%

of all college players and 20% of all high school players sustain brain injuries [2]. Many athletes, especially football players due to the nature of the sport, are concussed more than once in their careers. It is known that after a single concussion, there is greater susceptibility to sustaining another and that subsequent concussions may occur from less force and involve longer recovery time. Also, the young brain is more susceptible to concussion than the adult brain and requires more time to resolve the injury [3].

The exact mechanism of a concussion is unknown, but it is likely that they are caused by rotational acceleration of the brain. It is still uncertain where in the brain concussion occurs or the exact origin of the symptoms; however, it is now apparent that direct impact to the head is not required. Concussion can occur with a blow to the chest that causes a whiplash effect on the brain. Whiplash of the neck and concussion frequently co-exist [3].

With mounting concern for players' safety, the National Football League (NFL) has begun collecting data using various technologies, such as innovative helmets, sensors, and video analysis to better understand how and where injuries occur [4]. Since 2002, the NFL has used this gathered data to implement more than 50 changes and additions to contact rules to protect players from potential injury [5]. A couple major changes include a rule made in 2018 which states that a player cannot lower his head to initiate and contact his helmet against an opponent; this applies to all players and all areas of the field, and in 2009, a rule was added to make it an illegal hit on a defenseless receiver if the initial force of the contact by the defender's helmet, forearm, or shoulder is to the head or neck area of the receiver. Although much has been done already, it has not proven enough to drastically decrease the injury rate [6]. The NFL analyzes and shares injury data as a part of ongoing efforts to advance the health and safety of players. This data is compiled and analyzed by IQVIA, the largest healthcare data science organization and global leader in human data science technologies. The injury data below includes statistics from 2015 to 2021 for the incidence of reported concussions, ACL tears, and MCL tears during the preseason and regular season.

Concussions: Preseason and Regular Season

2015-2021

Year	Preseason			Regular Season			Preseason + Regular Season		
	Game	Practice	Total	Game	Practice	Total	Game	Practice	Total
2015	54	29	**83**	183	9	**192**	237	38	**275**
2016	45	26	**71**	166	6	**172**	211	32	**243**
2017	46	45	**91**	178	12	**190**	224	57	**281**
2018	34	45	**79**	127	8	**135**	161	53	**214**
2019	49	30	**79**	136	9	**145**	185	39	**224**
2020*	N/A	30	**30**	129	13	**142**	129	43	**172**
2021**	22	30	**52**	126	9	**135**	148	39	**187**

*2020 was markedly different from other seasons due to the COVID-19 pandemic. There were no preseason games in 2020.
**The NFL season structure changed in 2021 to include three preseason games and 17 regular season games. Prior to 2021, the NFL season included four preseason games and 16 regular season games.

Figure 2: NFL Injury Data - Concussions [6]

Incidence of ACL Tears – 2015-2021

Year	Preseason			Regular Season			Preseason + Regular Season		
	Game	Practice	Total	Game	Practice	Total	Game	Practice	Total
2015	16	13	**29**	25	5	**30**	41	18	**59**
2016	11	9	**20**	29	7	**36**	40	16	**56**
2017	16	15	**31**	21	2	**23**	37	17	**54**
2018	18	10	**28**	24	5	**29**	42	15	**57**
2019	10	7	**17**	25	7	**32**	35	14	**49**
2020*	N/A	11	**11**	36	4	**40**	36	15	**51**
2021**	13	9	**22**	43	6	**49**	56	15	**71**

*2020 was markedly different from other seasons due to the COVID-19 pandemic. There were no preseason games in 2020.
**The NFL season structure changed in 2021 to include three preseason games and 17 regular season games. Prior to 2021, the NFL season included four preseason games and 16 regular season games.

Figure 3: NFL Injury Data- ACL Tears [6]

Incidence of MCL Tears – 2015-2021

Year	Preseason			Regular Season			Preseason + Regular Season		
	Game	Practice	Total	Game	Practice	Total	Game	Practice	Total
2015	38	12	**50**	104	6	**110**	142	18	**160**
2016	21	15	**36**	87	3	**90**	108	18	**126**
2017	20	17	**37**	98	9	**107**	118	26	**144**
2018	23	14	**37**	94	1	**95**	117	15	**132**
2019	23	7	**30**	76	3	**79**	99	10	**109**
2020*	N/A	16	**16**	95	8	**103**	95	24	**119**
2021**	18	12	**30**	92	6	**98**	110	18	**128**

*2020 was markedly different from other seasons due to the COVID-19 pandemic. There were no preseason games in 2020.
**The NFL season structure changed in 2021 to include three preseason games and 17 regular season games. Prior to 2021, the NFL season included four preseason games and 16 regular season games.

Figure 4: NFL Injury Data - MCL Tears [6]

Although the NFL's efforts to promote players safety has improved upon the injury rate in the last 7 years as shown in Figures 2, 3, and 4 above, there is nothing currently in place to stop the issue of continuation of play. Meaning the referee blows the whistle to signal the end of a play, but the players continue because they either don't hear it or claim they don't hear it. This causes preventable injuries that occur when the athletes should have been stopped. This project aims to correct the issue by creating a device and implementing the technology necessary to stop the continuation of play altogether.

2. ENGINEERING DESIGN CONSIDERATIONS

In this section, the engineering design considerations are discussed. The important design considerations are public health, safety, and welfare, global, cultural, environmental, economic, and professional standards. The goal of this section is to set expectations for the electronic whistle transmitter and receiver system to meet. Each section highlights important components of the project to be considered when designing. Table 6 located in the Appendix details where each of the following considerations are implemented in each portion of this project.

2.1. *Public Health, Safety, and Welfare*

The electronic whistle transmitter and receiver system does influence safety. The goal of this project is to attempt to improve the safety of football players after the whistle is blown. Many injuries occur after the whistle is blown because the players are not able to hear it. With the electronic whistle receiver in the helmets, injuries will be prevented and eliminated. Therefore, it will increase safety. The electronic whistle receiver will influence welfare. More importantly the health aspect of welfare. Football players can play without worry of an injury after the whistle. The health of players will increase with the decrease of injury.

When considering the design of the electronic whistle receiver, the safety of players was taken into consideration. The receiver will be electrically powered, so there is a need to avoid the chance of shock or the chance of abrasion. In the chance of head exposure, there must not be a sharp edge on the receiver capable of injuring the player. The receiver must also be designed to dissipate heat so that it does not reach temperatures north of 100 degrees Fahrenheit. Skin burns at 116 degrees Fahrenheit, so the receiver should be kept cooler than this in case there is skin exposure to the system. On the other hand, if one of the receiver devices loses power, the player will have no secondary alert and will be at more risk of injury after a play has ended. If there is a failure in the system, the player should immediately report to a referee and have the helmet replaced.

2.2. *Global*

The electronic whistle transmitter and receiver are being prototyped for American football in the United States. Design considerations will be made to meet global standards if the product first succeeds in the United States. The idea to implement this design in other countries that participate in American football and even implement it into other sports is not in the immediate future.

2.3. Cultural/Social

If the electronic whistle transmitter and receiver system were to be implemented into high school football programs, there could be social factors to consider, such as income and education level of the programs able to afford the devices. Smaller schools or private schools without state funding may not have the opportunity to utilize the device, whereas larger schools in specific areas would. Additionally, a tone must be emitted from the electronic whistle transmitter and receiver. The tones may sound slightly different from normal whistles used in sports today. Additionally, since the sport chosen for this project was American football, the instructions manual must be written in English for both the electronic whistle transmitter and receiver.

2.5. Environmental

The transmitter must be capable of withstanding exposure to moisture. A protective waterproof covering may be added to the transmitter, and the IP rating must stand at IP54 (protected from limited dust and from water spray in any direction) [7]. This IP rating is given because American football can take place in the rain/snow. The handheld electronic whistles may be exposed to more moisture than the receivers; the receivers are placed in the helmets of players. The receivers must be able to withstand moisture from the players' helmet.

2.6. Economic

The transmitter and receiver implementation must be priced so that each player and referee can have the same system. The whistle transmitter will be marketed as one product while the helmet receiver can be marketed as another. The whistle price may increase more dramatically but there are only a few whistles needed per game. The additional price to the helmet should be negligible since there are many more helmets used in a game and helmets are already an expensive item.

2.7. Professional Standards

Based on FCC standards a transmitter cannot have a maximum output power greater than 30 dBm (1 Watt) or an Effective Isotropic Radiated Power (EIRP) of 36 dBm (4 Watts). More powerful devices can cause unwanted interference with other radio frequency devices and could create a safety hazard. The formula for EIRP is shown in Equation 1 below.

$$EIRP = Pt - LC + Ga$$

Equation 1: Effective Isotropic Radiated Power

The electronic whistle transmitter and receiver modules must meet the IP rating of IP54 discussed in section 2.6 [7]. Additionally, the transmitter and receiver modules must communicate over an open FCC frequency [8].

3. PROJECT INTRODUCTION

To further improve upon injury prevention in American football, we have created a transmitter and receiver device that will send a tonal alert via radio frequency from an electronic whistle to a speaker inside the players' helmets alerting them when the whistle has been activated, i.e., when the play is over. Many football players have a challenging time hearing the whistle blow due to high intensity play, physical contact, adrenaline, and extremely loud crowds in NFL stadiums; so, they continue to throw, run, and/or tackle without knowing the play has been stopped. This presents an added danger to the game, and results in players being injured after the play is over or "dead." There is currently no protocol in place to stop this issue. The electronic whistle transmitter and receiver system will eliminate the continuation of play by giving the players a loud enough tone close to their ears in addition to the whistle blow.

The overall goal for the electronic whistle transmitter and receiver is to act as an additional safety measure for the athletes. Many needs must be met for the device to serve its purpose and perform effectively. Because the transmitter and receiver are to communicate via radio frequency, the receiver must be able to pick up the same signal sent from the transmitter. The device must then be capable of producing an audible tone in the players' ears using two buzzers connected to the receiver. Both the receiver and the buzzers must be compact enough to fit inside the helmet. The device must also have a long enough range to encompass the entire playing field. The receivers and buzzers should be designed and implemented so that they are durable enough to withstand hard jolts and tackles; the transmitter should be water resistant to withstand exposure to moisture, such as precipitation and sweat. Lastly, the device must utilize minimal power to last the full duration of a football game.

3.1. Project Goals

- Transmitter and receiver wirelessly communicate.
- Electronic whistle activates the transmitter.
- Receiver connects to two buzzers.
- Receiver and buzzers fit inside a football helmet.
- Transmitter fits inside an electronic whistle.
- Range of the devices encompasses the entire playing field.

4. DESIGN CONCEPTS

Throughout the research and preliminary design stages of the project, various decisions had to be made that would determine the main design concepts of the electronic whistle transmitter and receiver system. The objective was to make informed design decisions that would then lead to a first level architecture of the system. Some of these concepts include the type of alert the players would receive, as well as how the transmitter and receiver would communicate. This section discusses the considerations that went into these decisions and the ultimate reasons for choosing a tonal alert and a low radio frequency for communication.

4.1. Type of Alert

There are many ways to alert a player during a game. It can be looked at as each of the five senses. American football utilizes the sense of hearing to alert players currently. Some options that were discussed were to utilize an LED, vibration, or tonal alert. LEDs would utilize the sense of sight, vibration would utilize the sense of touch, and a sound would utilize the sense of hearing.

4.1.1. LED Alert

Light could be used to alert a football player that the play is over. The idea was discussed as placing LED lights inside the brim of each player's helmet and would flash or turn on when the electronic whistle was activated. Some issues that arise when discussing this option are concussions and light blindness. Lights are something to stay away from when a concussion occurs. Over 300,000 concussions occur per year in football [9]. Football has the most concussions out of all sports. With lights attached to the helmet it may be harder to see obstacles around the player. For these reasons, a visible alert was not chosen.

4.1.2. Vibration Alert

Vibration could be used to alert the football player that the play is over, also. A device that creates the vibration could be placed somewhere on a player's uniform. An issue with this is that with football being a full contact sport, will the players be able to feel the vibrations? The concussion rate is high enough to say that football is an extreme contact sport, and it is likely that players will struggle to feel the vibrations [9]. For this reason, the vibration alert was not chosen.

4.1.3. Tonal Alert

A secondary audible tone could be used to alert the football player that the play is over. This idea was discussed as placing buzzers on each side of players' helmets that would sound a tone when the electronic whistle is activated. An audible alert has been used for many years [10]. Football stadiums are very loud. They can sometimes get over 100dB. The safe range of sound intensity for humans in 85 dB [11]. Oticon performed a study on hearing on a football field. "When Oticon audiologists measured sound levels with a regulation helmet, using KEMAR, an acoustic research mannequin, sound levels were virtually the same with and without the helmet" [11]. The helmet does not provide any sort of protection to the sound levels of stadiums. Furthermore, since the players are having problems hearing the whistle, bringing the sound closer to their ears would eliminate the player's inability to hear the whistle blow. When comparing these three options, a tonal alert closer to the football player's ear was chosen.

With a tonal alert chosen, buzzers placed in helmets to alert players need to meet a safe maximum decibel level of 85dB [11]. Due to the maximum decibel level, buzzers were found to sound a tone of a maximum of 80dB. This meets the safety regulation was met [11].

4.2. Wireless Communication

After choosing the type of alert for the customized system, the type of wireless communication between the transmitter and receiver modules needed to be discussed and chosen. The two options that were discussed were to utilize either Wi-Fi or low radio frequency. Both options are a spectrum of radio frequency. Radio frequency was chosen because it is already being used by coaches to communicate with one player on offense and one player on defense through a one-way speaker in each of the players' helmets [12].

4.2.1 Wi-Fi (GHz)

An option that was discussed for wireless communication between the transmitter and receiver modules was to utilize Wi-Fi. Wi-Fi bases its connection on electromagnetic waves known as radio waves. A router and adapter are used to send and receive the waves in a two-way process. Access points can also be used in place of a router. The devices send and receive the radio waves at 2.4GHz and 5GHz and can encode/decode the signals to then perform the tasks [12].

A key factor when considering Wi-Fi as a wireless connection option is its range capability. In general, a 2.4GHz signal has a range of 150 feet indoors and 300 feet outdoors, while a 5GHz signal has around a 50 feet indoor and 100 feet outdoor range. 5GHz signals are faster than 2.4GHz but have less range and are obstructed easier. The range of Wi-Fi can be maximized by not obstructing the signal and obtaining a good standard, but increasing the range is an expensive task [13].

The cons of Wi-Fi outweigh the benefits. Limited range, possibility of "black spots" in coverage, and the possibility of hacking are all negatives. In addition to that, the project would be much more expensive if Wi-Fi were used [12]. This option was not chosen for the wireless communication method.

4.2.2. Low Radio Frequency (kHz to MHz)

The other option discussed for wireless communication was to utilize low radio frequency. Its frequency spans from kHz to MHz. A benefit to this option is that signals travel farther at low frequencies. Therefore, the range of communication is much larger than the range of Wi-Fi and can be increased more with high powered antennas. Additionally, unlike Wi-Fi, interruptions are unlikely to occur. The only issue found with low radio frequency was security. Lastly, the NFL already has technology in place for coaches to communicate with their quarterbacks during a game.

To do this, low radio frequency is used with speakers inside the quarterbacks' helmets. The coaches are permitted to talk to their players; however, the quarterback is unable to talk back. This system uses a protected frequency band to keep the communication secure. When comparing the two options for communication, low radio frequency was chosen.

After selecting a low radio frequency range, a frequency needed to be specified. With further research, a frequency of 433MHz was chosen. According to the Federal Communication Commission, this is an open frequency that is widely used by alarm systems, key fobs, remote controls, garage door openers, etc. [8]. Additionally, the 433MHz frequency was chosen because an evaluation kit that proved the project concept utilized 433MHz frequency for communication between its transmitter and receiver modules.

5. DESIGN SOLUTION

This section discusses the design solution process. An off-shelf test kit was purchased to test in parallel with the customized electronic whistle transmitter and receiver design. After, gaining knowledge from the off-shelf test kit, the first and second level architectures were designed to layout the structure of the customized system.

5.1. Off-Shelf Test Kit

A DigiKey Evaluation Kit was purchased to gain knowledge of a similar performing system. It consists of a transmitter module, encoder/decoder module, and receiver module. The modules work together to communicate and encode/decode data packets that tell the system which output to activate. Figure 5 is a visual of the various components of the test kit.

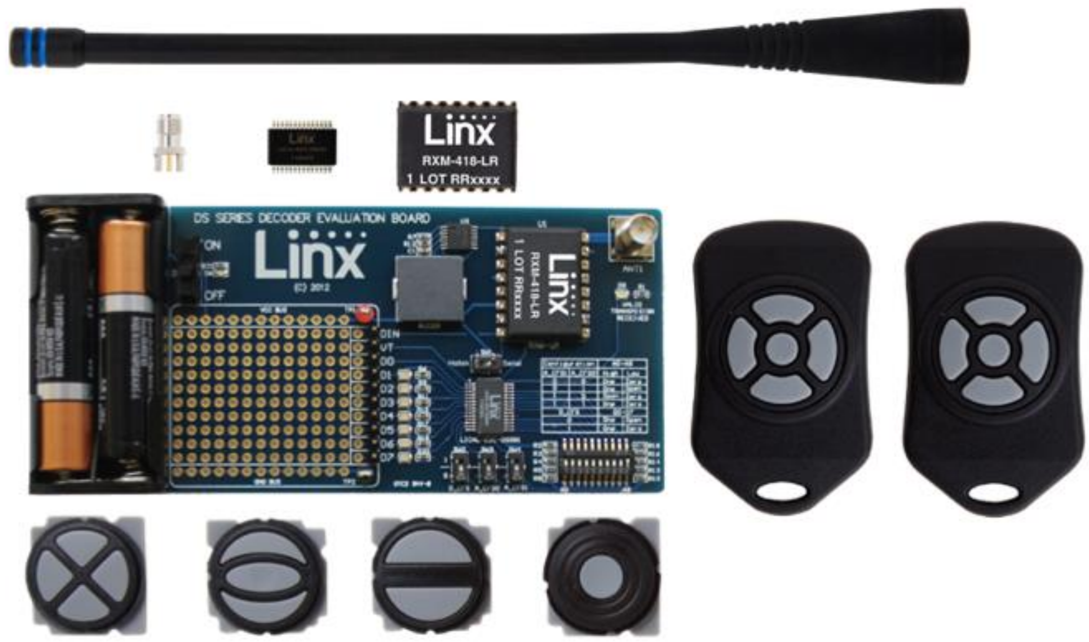

Figure 5: DigiKey Evaluation Kit [15]

The operation of the transmitter is straightforward. When a button(s) is pressed on the transmitter, the states of D0 to D4 are formatted into packets by an on-board encoder integrated circuit [15]. These encoded packets are sent to a transmitter that, through the antenna, conveys the data into free space. The receiver board is powered by two AAA batteries. A Linx LR Series receiver is used for reception of the transmitted signal. This receiver provides exceptional sensitivity, allowing the transmitter and receiver to operate at distances of up to 750 feet (depending on signal conditions) [15]. The data recovered by the receiver is decoded by the DS Series set as a decoder. If the settings of the 10-position DIP switch on the receiver board match the address setting of the transmitter, the data line outputs are updated to match the states of the buttons on the transmitter. In this evaluation kit, one data line on the evaluation board is used to drive a buzzer while the other lines activate LEDs.

To explain the functionality of the encoder/decoder module in the test kit, the encoder/decoder utilizes serial protocol. In encoder mode, it monitors the state of the TE line. When the line is high the encoder records the states of the data and address lines, assembles them into a packet and outputs the packet three times [16]. The serial protocol encodes the address and data lines as binary bits that follow logic low and logic high voltage levels [16]. The logical states of each line are recorded and placed into bytes. Then, the data lines can be connected to switches or contacts [16]. The address lines can be set with DIP switches or cut traces on the PCB [16]. In other words, the encoder reads data and address lines, assembles a data packet, creates an output packet, and repeats but with an inverted packet. In decoder mode, the decoder receives packets and validates them. The validation includes checking the bit timings and comparing the received address to the local address line settings [16]. Two matching packets must be received consecutively. If the timings are good and the addresses match, the decoder sets its data lines to match the received states [16]. In other words, the decoder validates that data was received, checks that the address was matched, receives a valid first and second data packet, then activates the corresponding data lines.

To analyze the evaluation kit system further, a set of tests were performed. Each test performed on the evaluation kit will be tested in the customized project design.

5.1.1. Evaluation Kit Tests

- Transmitter communicates with the receiver.
- One key fob transmitter communicates with the receiver module.
- All buttons on the single key fob transmitter activate a LED/Buzzer.
- For the duration of the button push, the duration of buzzer tone matches.
- Two key fob transmitters communicate with the receiver module.
- Both key fobs activate the buzzer when buttons are pressed simultaneously.

When testing the evaluation kit, it was noted that when simultaneously pressing the same button on each transmitter key fob, the buzzer would flip to a 0/Off. Ideally, when one transmitter activates the buzzer, any additional transmitter communicating over the same address should not switch the buzzer activation data. This was not the case. Many causes can explain this issue that are discussed in Section 6.4.6. Therefore, the only test not passed for the DigiKey Evaluation Kit was the activation of both transmitters/key fobs simultaneously.

Again, the goal of utilization of the evaluation test kit was to help concrete the idealized design solution of the electronic whistle transmitter and receiver system. The test kit proved the project concept and gave insightful information of the structure of the circuit board design in future revisions of the project's customized design.

5.2. Project System Architecture

The first level architecture of the electronic whistle transmitter and receiver system shown below in Figure 6 was laid out to gain a simplified visual understanding of how each device will be powered and how the transmitter will communicate with the receiver.

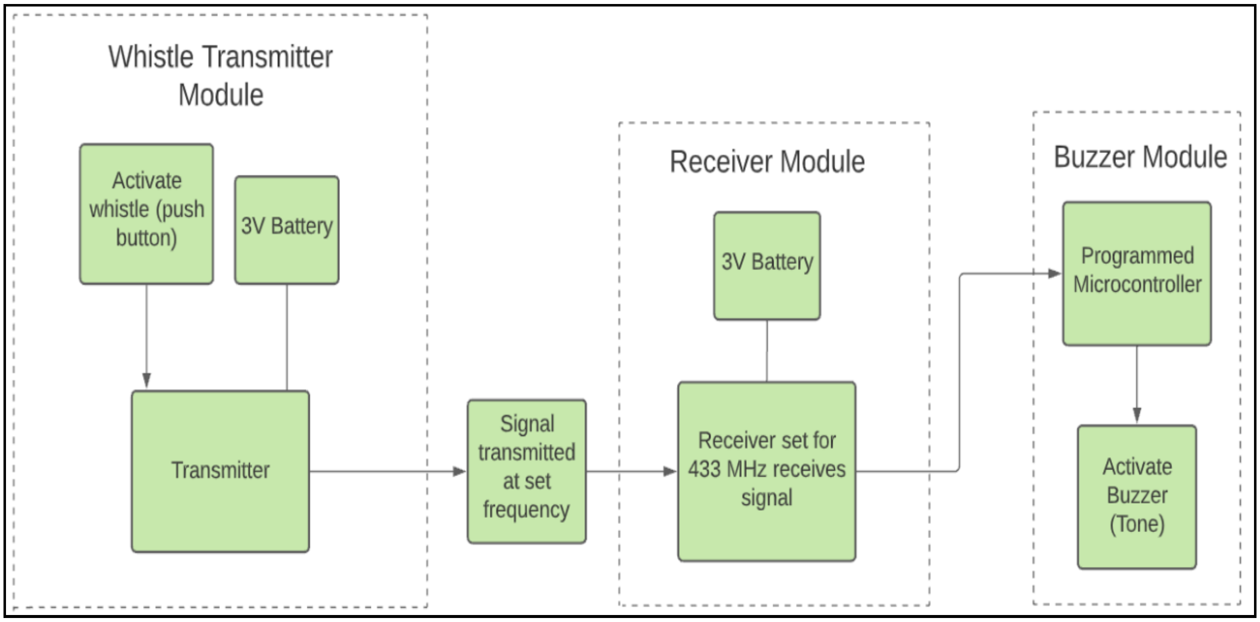

Figure 6: First Level Architecture

The second level architecture in Figure 7 was built to detail the main ideas that would be implemented into a formal schematic design. The initial design idea for Revision 1 was to have both the receiver and transmitter powered by a 3V battery placed on the boards. The receiver was also to be designed to alternately receive power from the whistle. The detailed design was determined to need an encoder and decoder along with the transmitter, receiver, and antennas. The components needed were decided after reviewing the evaluation kit's schematics. Upon activation, the encoder would send its inputs to the transmitter. The transmitter would then send the input data packets through the antenna and out the device at the 433 MHz signal. The data packets that would be received through the receiver's antenna and sent to the receiver module itself. Finally, the signal would be passed along to the decoder and output from the decoder to the two buzzers as an audible alert.

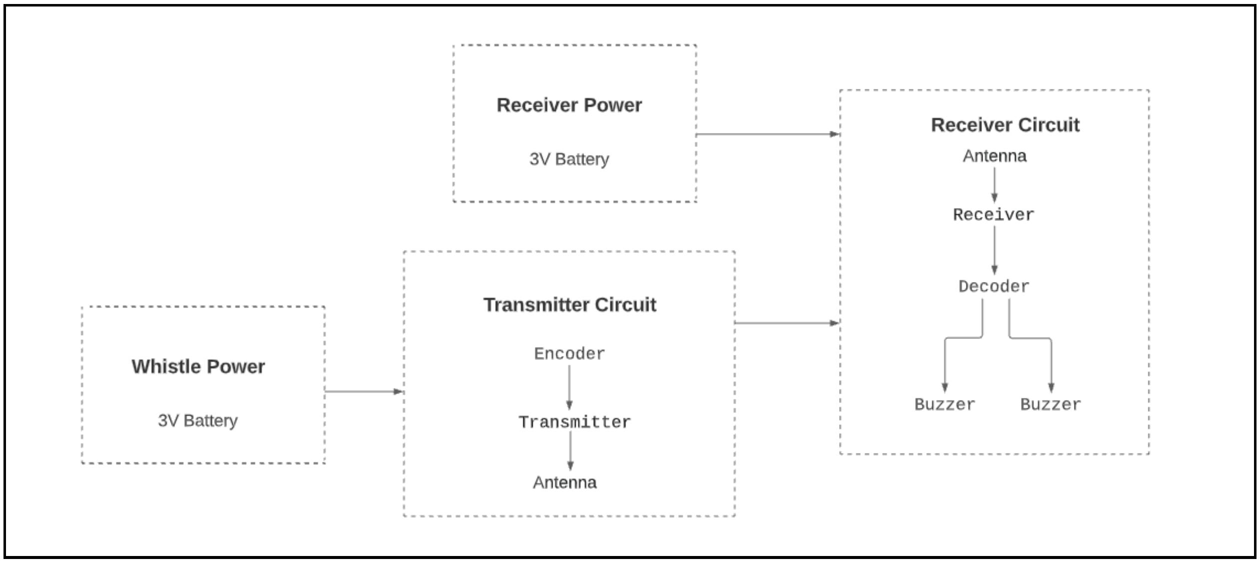

Figure 7: Second Level Architecture

6. REVISION 1 FORMAL DESIGN

This section discusses the specific aims, schematic design, fabrication, and testing for the formal design of Revision 1. The formal Revision 1 design began with setting specific aims. Then, with design inspiration from the off-shelf test kit (Section 4.1), the schematic design of the transmitter and receiver circuit boards were completed. Lastly, this section discusses the fabrication of the transmitter and receiver modules and the series of tests that were performed to meet the specific aims.

6.1. Specific Aims for Revision 1

- All necessary components are soldered onto PCBs.
- Both boards are getting power.
- Neither of the boards have shorts.
- Transmitter and receiver communicate at 433 MHz.
- Buzzers play an audible tone when the signal is received.

6.2. Transmitter 1.0

This section discusses the transmitter 1.0 schematic and board design. The transmitter 1.0 design is large due to Revision 1 being utilized for functionality testing. With the boards being large, it made testing easily performed. Furthermore, the implementation of transmitter 1.0 PCB design is discussed.

6.2.1. Transmitter 1.0 Schematic and Board Design

After researching the necessary components and their dimensions, a detailed schematic and board design for the transmitter was done in EAGLE, an electronic computer-aided design (ECAD) program. Once the design was finalized and approved, the printed circuit board (PCB) was ready to be fabricated. The schematic design for the transmitter in Revision 1.0 can be found in Figure 43 of the Appendix. The following image in Figure 8 is a snippet of the PCB design for the Revision 1.0 transmitter created in EAGLE.

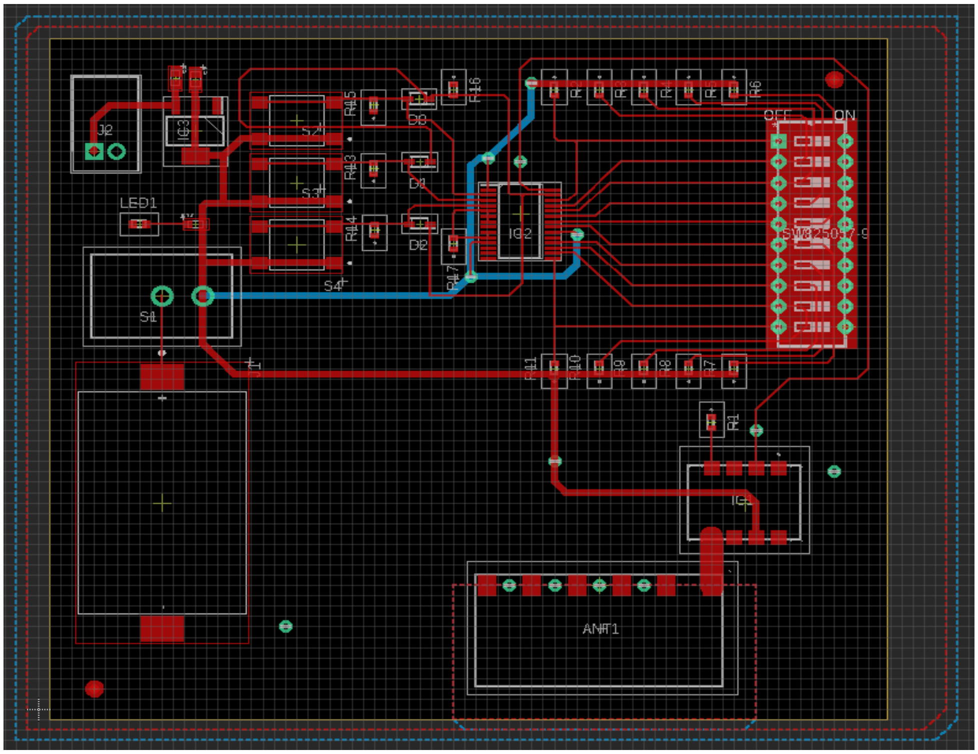

Figure 8: Transmitter 1.0 EAGLE Board Design

6.2.2. Transmitter 1.0 PCB

Originally, the PCBs were fabricated in-house using a milling machine on FR-4 laminate boards. In Figure 9, the transmitter 1.0 PCB fabricated from the milling machine at the AEC is shown. Unfortunately, the boards that were fabricated from the milling machine never functioned correctly. While the components were being placed, it was difficult to navigate part outlines and keep the solder from spreading outside of the desired areas. The boards were made from the FR-4 material and had no solder mask, so the entire top layer was exposed copper that is conductive and attracts the solder. Therefore, the boards had issues with solder connecting components/pads to other sections where a connection was not meant to be made. The main issue this created was a short from the power rail (VCC) to the ground plane (GND). A short between power and GND could cause damage to all the electronics on the board as well as the board itself. Only some of the parts were populated because of the electrical shortage. The specific location of the short on the boards could not be found and populating the boards with all the components was halted.

After further discussion, it was decided that the schematic and board designs would be sent to a PCB fabrication company, JLCPCB, for them to print the bare boards. The boards were then delivered and populated in-house by soldering on the respective components. The transmitter PCB that was fabricated by JLCPCB is shown in Figure 10.

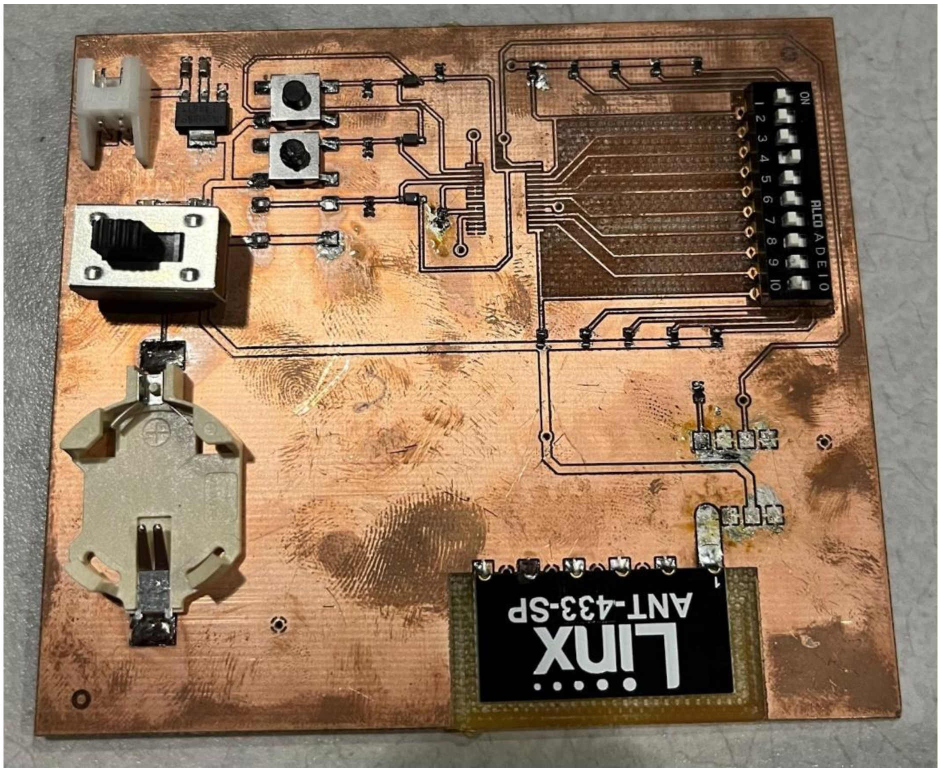

Figure 9: In-House Fabricated Transmitter 1.0 PCB

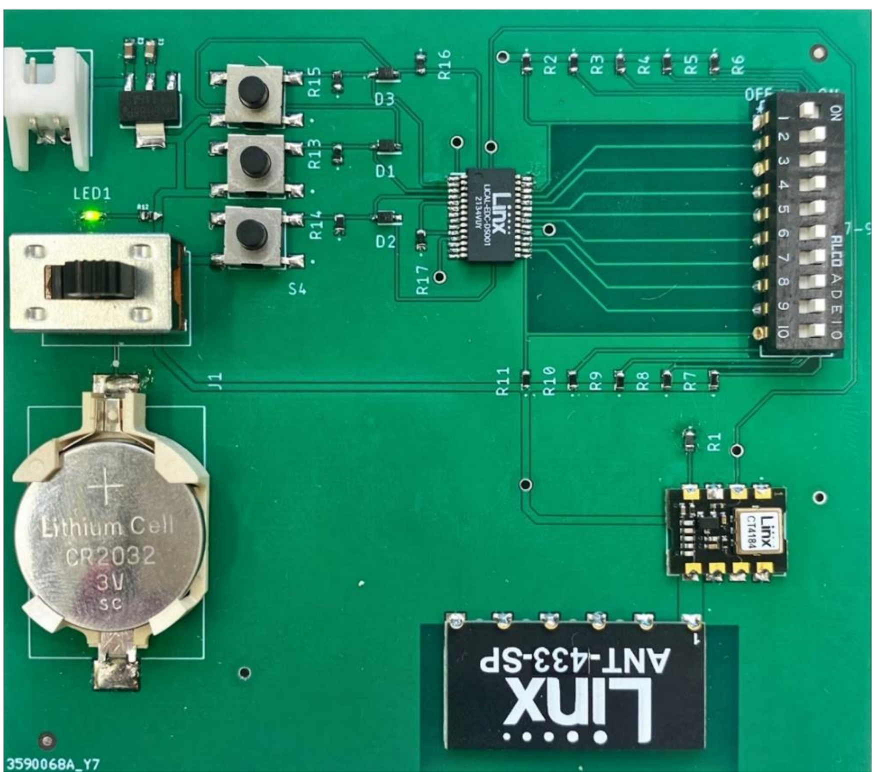

Figure 10: Transmitter 1.0 PCB

When reviewing Figure 10 above, there are several small and large electronic components to be seen. At the top left, a linear regulator with 2 bypass capacitors is seen next to a right-angle connector. The components here are designed to connect to the whistle's power, regardless of the voltage, and regulate it down to 3.3V to power the transmitter PCB. On the bottom left, the battery holder with its CR2032 Lithium-Ion battery in place is designed to provide power to the board in the case of no external whistle power. Above the battery holder is a simple on off single pull single throw (SPST) slide switch designed to connect/disconnect the other electronics to power. A green LED and 220Ω resistor are also there to indicate when the board is on or off. The encoder and its inputs are found in the upper center of the PCB. Three momentary pushbutton SPST switches, each with Schottky diode protection, are connected to the encoder's input data pins. The pushbutton switches are the inputs to the Revision 1 transmitter, and the diodes are tied to each to ensure that one input does not activate another. 100kΩ pull down resistors are spread around the top center/right side of the board. Pull down resistors are designed to set a state of a pin or switch to low (GND) until pulled high (Power) manually by an external change. A 10 switch DIP switch can be found on the top right side of the board. The DIP switch is used to set the address pins on the encoder to increase safety of the design against intentional/unintentional interruption or interference. The transmitter board can only communicate with a receiver module that has its decoder set to the same address. Under the DIP switch, the transmitter itself is connected to a 750Ω resistor to set the power level of the transmitter. Under the transmitter is the surface mount antenna used to send out the transmitted signal.

6.3. Receiver 1.0

This section discusses the receiver 1.0 schematic and board design. Like transmitter 1.0, the receiver 1.0 design is large due to Revision 1 being utilized for functionality testing. With the boards being large, it made testing easily performed. Furthermore, the implementation of receiver 1.0 PCB design is discussed.

6.3.1. Receiver 1.0 Schematic and Board Design

Similarly for the receiver module, after researching the necessary components and their dimensions, a detailed schematic and board design for the receiver was done in EAGLE. Once the design was finalized and approved, the PCB was ready to be fabricated. The schematic design for the receiver in Revision 1.0 can be found in Figure 44 of the Appendix. The following image in Figure 11 is an image of the PCB design for the Revision 1.0 receiver created in EAGLE.

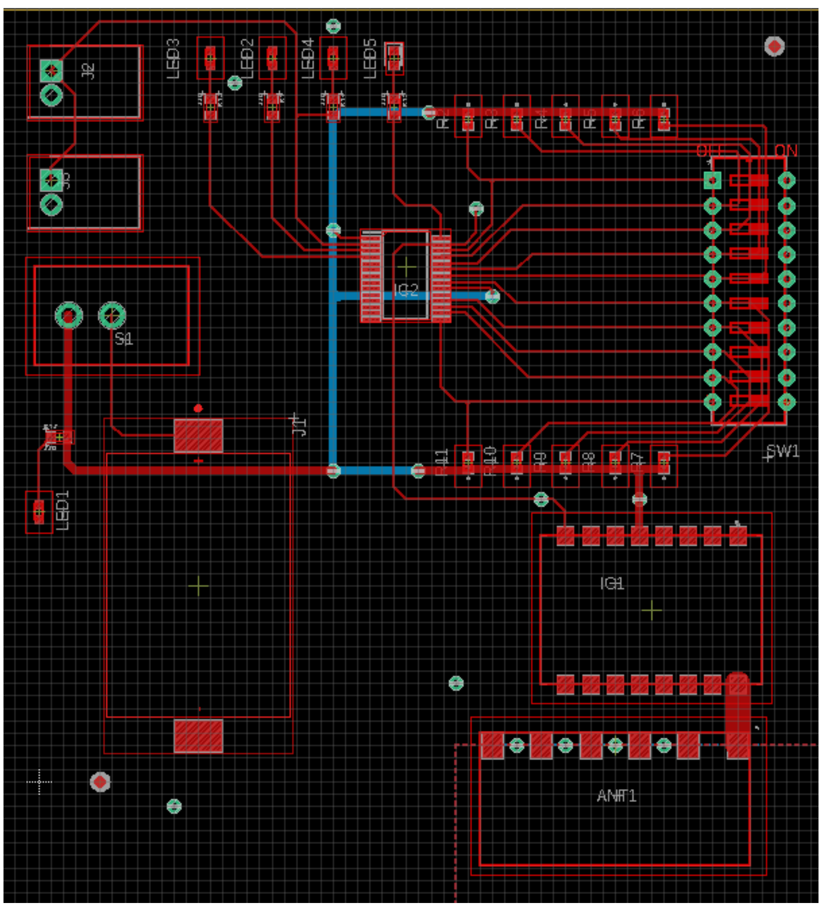

Figure 11: Receiver 1.0 EAGLE Board Design

6.3.2. Receiver 1.0 PCB

The fabrication of the receiver PCB using an in-house milling machine presented the same issues with shorts (Section 5.2.2). Figure 12 shows the in-house receiver PCB. Because of the short issue, the receiver PCB design was sent to JLCPCB to fabricate the bare boards. The boards were then delivered and populated in-house by soldering on the respective components. The receiver PCB that was fabricated by JLCPCB is shown in Figure 13.

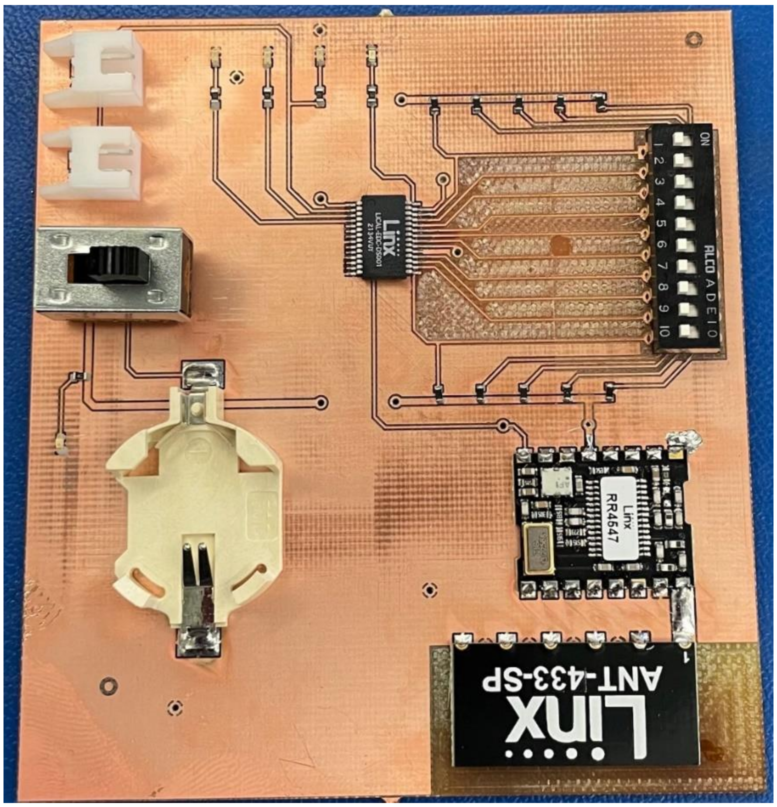

Figure 12: In-House Fabricated Receiver 1.0 PCB

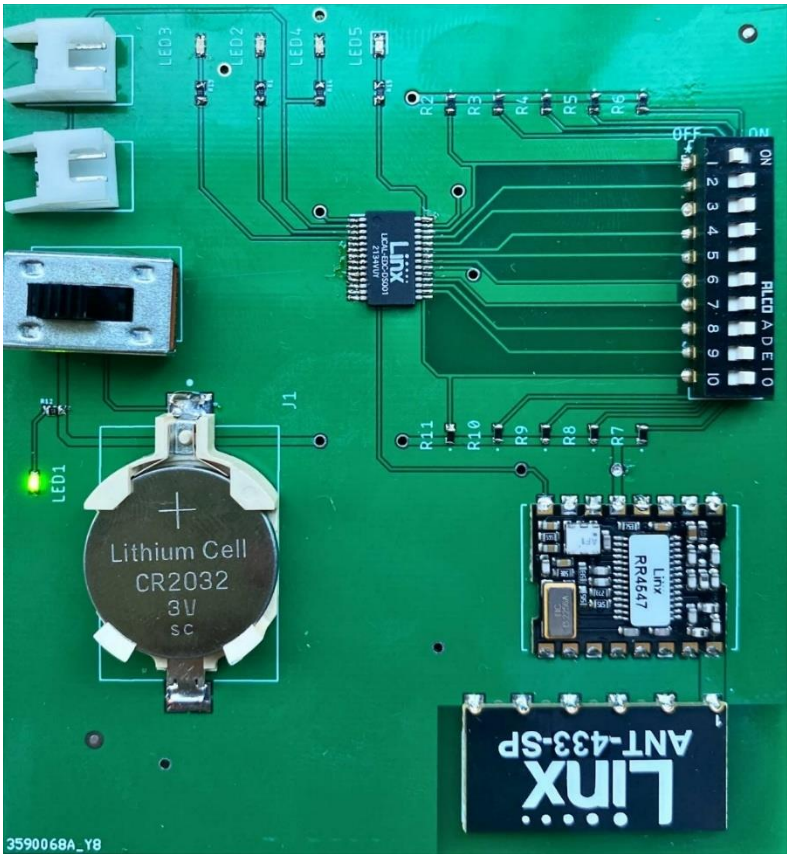

Figure 13: Receiver 1.0 PCB

The Revision 1 receiver PCB shown in Figure 13 above has many of the same electrical components as the Revision 1 transmitter PCB discussed in Section 6.2.2. To begin, a battery holder, power switch, and green LED with a 220Ω resistor are in the same vicinity as in Transmitter 1.0. Also, a 10 switch DIP switch for address setting is in the same upper right location. The antenna in the bottom right is the same part, this is where the transmission is received from the transmitter. The receiver module is located above the antenna and takes the transmission after reception from the antenna and transfers it to the decoder located in the upper center. At the top left of the receiver PCB there are two connectors for the buzzers. The connectors are tied to one output data pin (D0) of the decoder. Above the decoder there are also 3 green LEDs each tied to its own 220Ω resistor and a blue LED with its own 220Ω resistor. The green LEDs are linked to different output data pins of the receiver to indicate which input was pressed on the transmitter. The blue LED was used to indicate a transmission was received. Lastly, there were also 100kΩ pull down resistors spread around on this board.

6.4. Tests and Results

A series of six tests were performed on the Revision 1 system. These tests were done to verify the operation of the transmitter, receiver, and buzzers and ensure the specific aims of Revision 1 were met.

6.4.1. Short Test

A short test was performed to ensure the Revision 1 fabrication did not create any shorts on the board. Checking for shorts in the transmitter and receiver boards was done to make sure that the board was fabricated correctly, proper connections were made between components, and when power was applied to the boards it would not cause damage to the components. Additionally, if the boards did not pass this test, then the following tests could not be completed.

To test for shorts in the boards a digital multimeter (DMM) was used. The continuity function of the DMM was used for this test. The continuity function sends a small current through the probes and creates this tone when one probe receives the current from the other. The probes (+/-) were placed between the ground plain and the voltage source line. If the DMM sounded a long buzzer tone, then the probes were connected meaning there was a short present. If the DMM did not create a long tone, then there was no connection between the probes meaning a short was not present.

When the test was executed the DMM did not indicate that there were any shorts throughout the transmitter and receiver boards. The Revision 1 boards passed the short test.

6.4.2. Communication Test

A communication test was performed to check that the transmitter and receiver were communicating. This test would ensure that the transmitter was sending signals properly and that the receiver was able to capture the signal and respond accordingly. Additionally, if this test was not passed, then the following tests could not be completed.

To test communication between the transmitter and receiver, both modules were turned on. The transmitter module is equipped with three input buttons. When any of the three buttons are pressed, the encoder outputs to the transmitter telling it to send a signal over 433 MHz frequency. Simultaneously, the receiver module receiver component is looking for a signal being transmitted over 433 MHz frequency. When a signal is received, the decoder will respond by outputting to the "DOUT" pin connected to LED5. If LED5 turned on, then this indicated that the transmitter was communicating with the receiver and operating properly.

When this test was executed, LED5 turned on. Figure 14 is an image of the receiver module with the circled blue LED, LED5, turned on. The transmitter and receiver communicate. The Revision 1 boards passed the communication test.

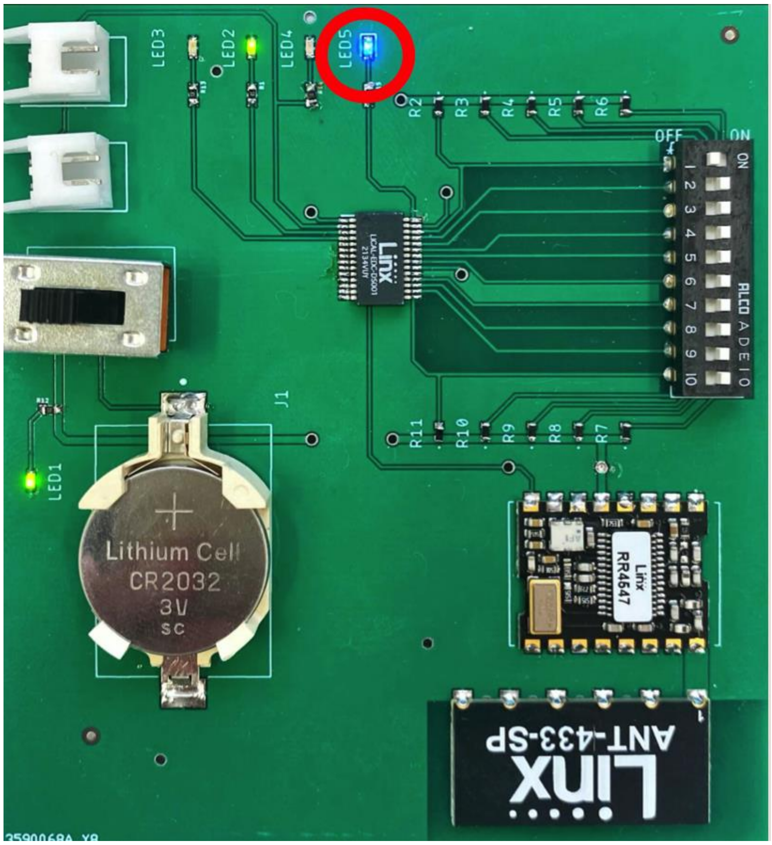

Figure 14: Communication Test LED Verification

6.4.3. Buzzer Test

A buzzer test was performed to check to see if the buzzers activated when the correct input (D0) was pressed on the transmitter. To perform this test both boards needed to be turned on. The push button switch near the top of the board with the LEDs was tied to the D0 pin so pressing this should turn on LED 4 and LED 5 as well as the buzzers. The LEDs and buzzers did activate when the transmission was received, but the buzzers sounded much quieter than 80dB. A multimeter was used to check the voltage output at the decoder pin (D0) to ensure that the buzzers were receiving the correct voltage. The voltage at the pin would output 3V when the buzzers were not attached versus 1.5V when the buzzers were attached. The voltage drop was causing the buzzers to not completely turn on because they were rated for 3V.

6.4.4. Range Test

A range test was performed on Revision 1 to check if the signal could be transmitted across the minimum required range. First, the range was calculated using the dimensions of a regulation football field and the Pythagorean Theorem.

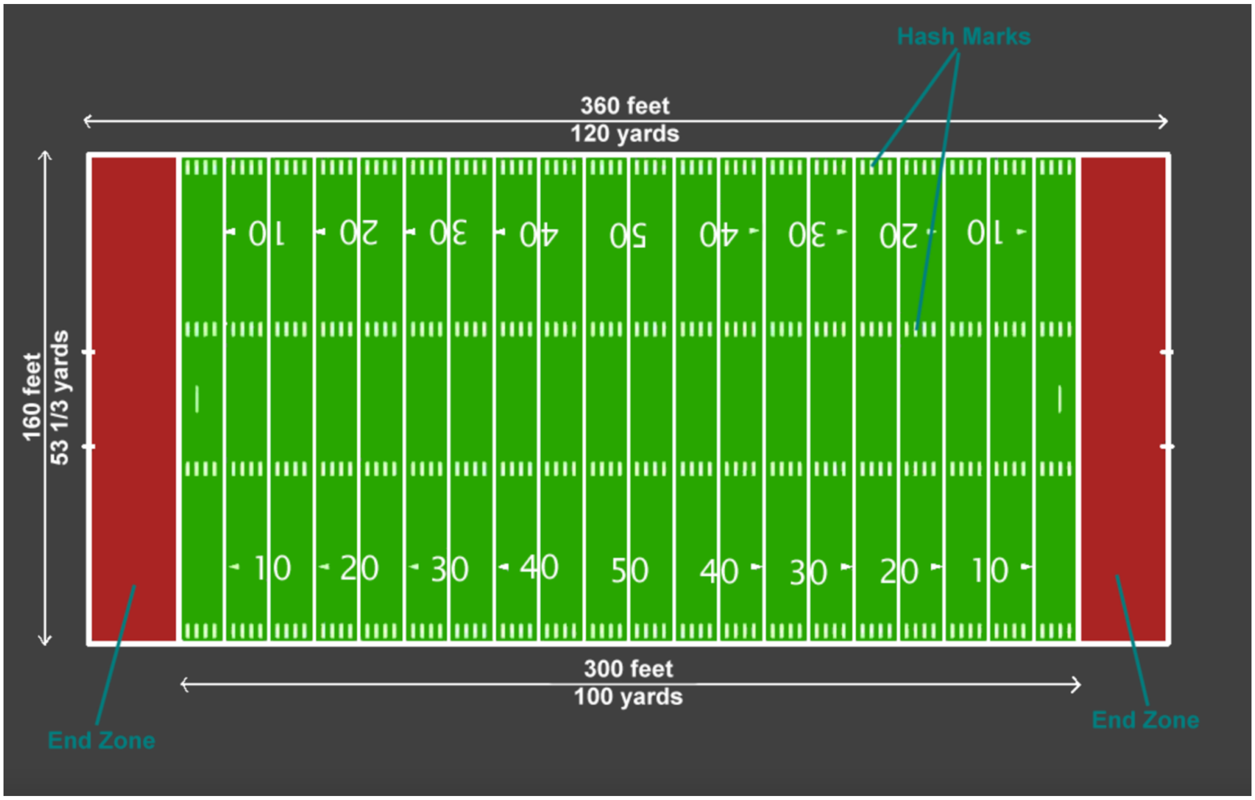

Figure 15: Regulation Football Field Dimensions [17]

Figure 15 above shows the dimensions used to calculate the range:

$$c = \sqrt{a^2 + b^2} = \sqrt{(360\ ft)^2 + (160\ ft)^2} = 393.95\ ft$$

Equation 2: Pythagorean Theorem

This range of approximately 394 ft is the diagonal distance from corner to corner of a football field, including the endzones. Ideally, the range would allow for extra room on the sidelines for when players run out of bounds; however, all NFL stadiums are different in that case, so there is not a standard distance to factor in. Therefore, a minimum range requirement for the system was set for 394 ft.

To perform the test, the Revision 1 transmitter and receiver were taken out to an open field where 394 ft was measured out using a measuring wheel device. The transmitter and receiver were turned on and the addresses were set on the DIP switches to send and receive the signals. Transmitter 1.0 was unable to send a signal across the 394 ft range. Therefore, transmitter 1.0 failed the range test. It is believed that this failure could be attributed to issues with the overall functionality of transmitter 1.0. Throughout the testing portion of Revision 1, inconsistencies were observed in the transmitter; it was sensitive to the way it was held or positioned when attempting to send a signal to the receiver. This issue was later corrected in Revision 2 with a new transmitter model.

6.4.5. Multi-Receiver Communication with One Transmitter Test

A multiple receiver communication with one transmitter test to verify that multiple receivers could communicate with one transmitter. This is a significant test that indicates all 22 football players (11 offensive players and 11 defensive players) on the playing field would have a working secondary tonal alert in their helmets. Multiple receivers communicating with one transmitter means that multiple players will receive an alert when one referee activates their whistle.

To perform this test, the Revision 1 receiver and DigiKey Evaluation Kit receiver were used. Once both receivers were turned on, the Revision 1 transmitter was activated by pressing one of three activation buttons. When the transmitter activated, both receiver modules responded. The blue LEDs on each receiver module connected to the “DOUT” pin of the decoders turned on. This indicated that both receivers had received a transmission at the 433MHz frequency when one transmitter was activated. Therefore, the multi-receiver communication test passed. Figures 16 and 17 illustrate the circled blue LEDs on the Revision 1 and Evaluation Kit receiver modules.

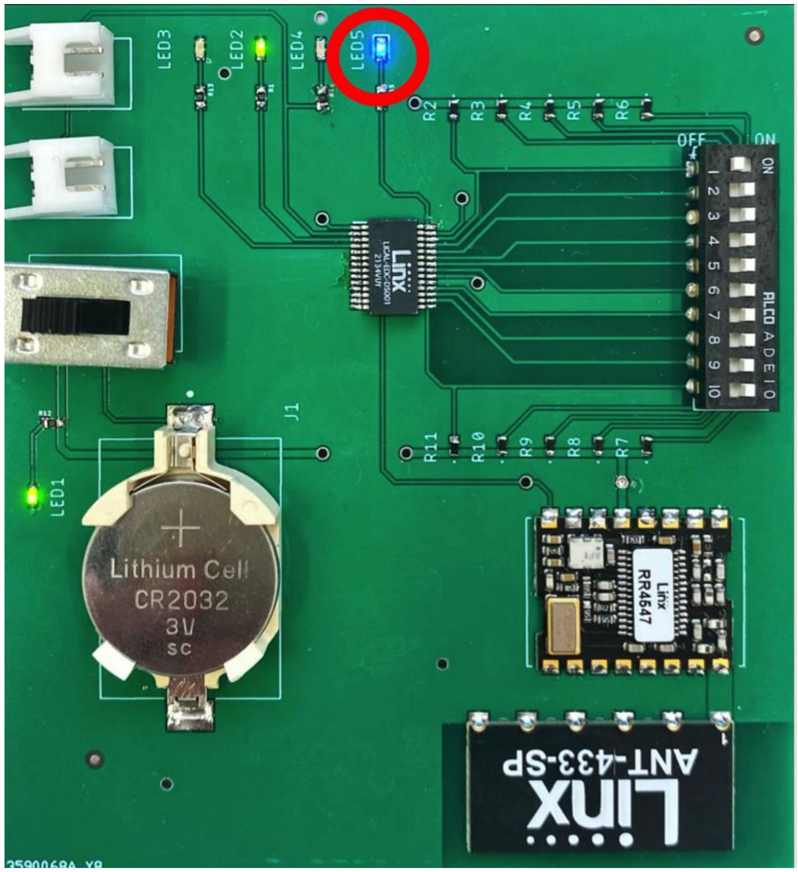

Figure 16: Receiver 1.0 LED Verification

Figure 17: Evaluation Kit Receiver LED Verification

6.4.6. Multi-Transmitter Communication with One Receiver Test

The last test done to the Revision 1 board design was to verify that multiple transmitters could communicate with one receiver. Again, like the previous test, this is a significant test that indicates multiple referees could activate their whistle simultaneously, while activating one player's secondary alert in their helmet.

This test was completed by utilizing the Revision 1 receiver and two transmitters. Once the receiver and transmitters were turned on, both transmitters were activated. When this occurred, the Revision 1 receiver did not respond correctly by turning LED5 on. Figure 18 illustrates Revision 1 receiver with LED5 (circled) not turned on. This indicated that the receiver did not receive a transmission when two transmitters were activated. Therefore, the Revision 1 design did not pass the multi-transmitter communication test. The failure of this test was analyzed.

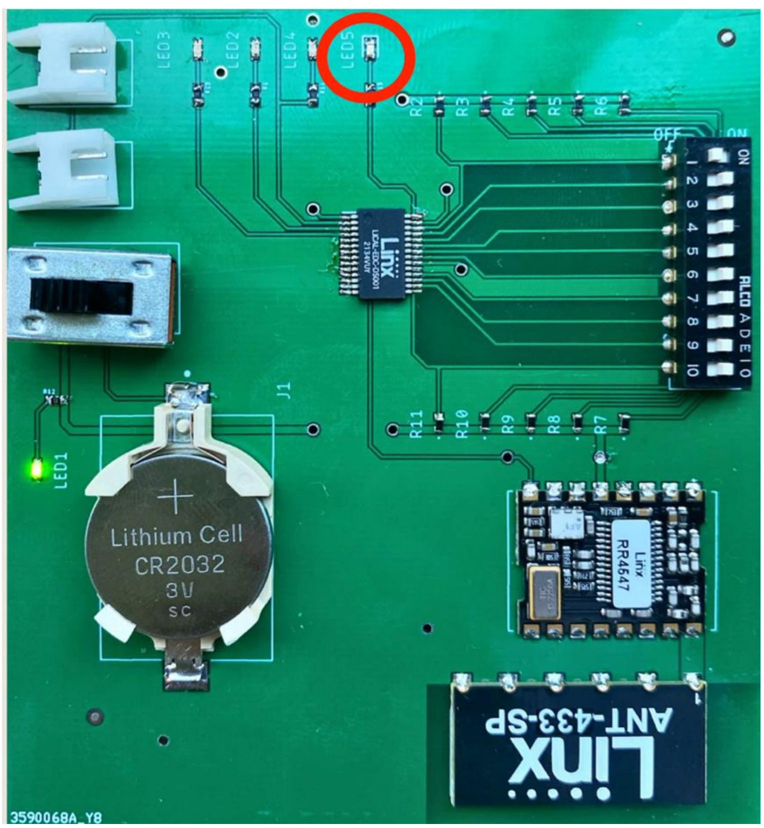

Figure 18: Receiver 1.0 LED Failure

To begin the analysis of the failure of the multi-transmitter communication test, a spectrum analyzer was used to ensure that an input signal was transmitted over 433MHz when two transmitters were activated simultaneously. A spectrum analyzer measures the magnitude of an input signal versus frequency. The frequency spectrum was centered at 433MHz to better visualize the magnitude. Figure 19 contains the spectrum analyzer plot centered at 433MHz when two transmitters were activated. The peak in the center of the spectrum verifies that when two transmitters were activated, a signal was being transmitted at 433MHz frequency.

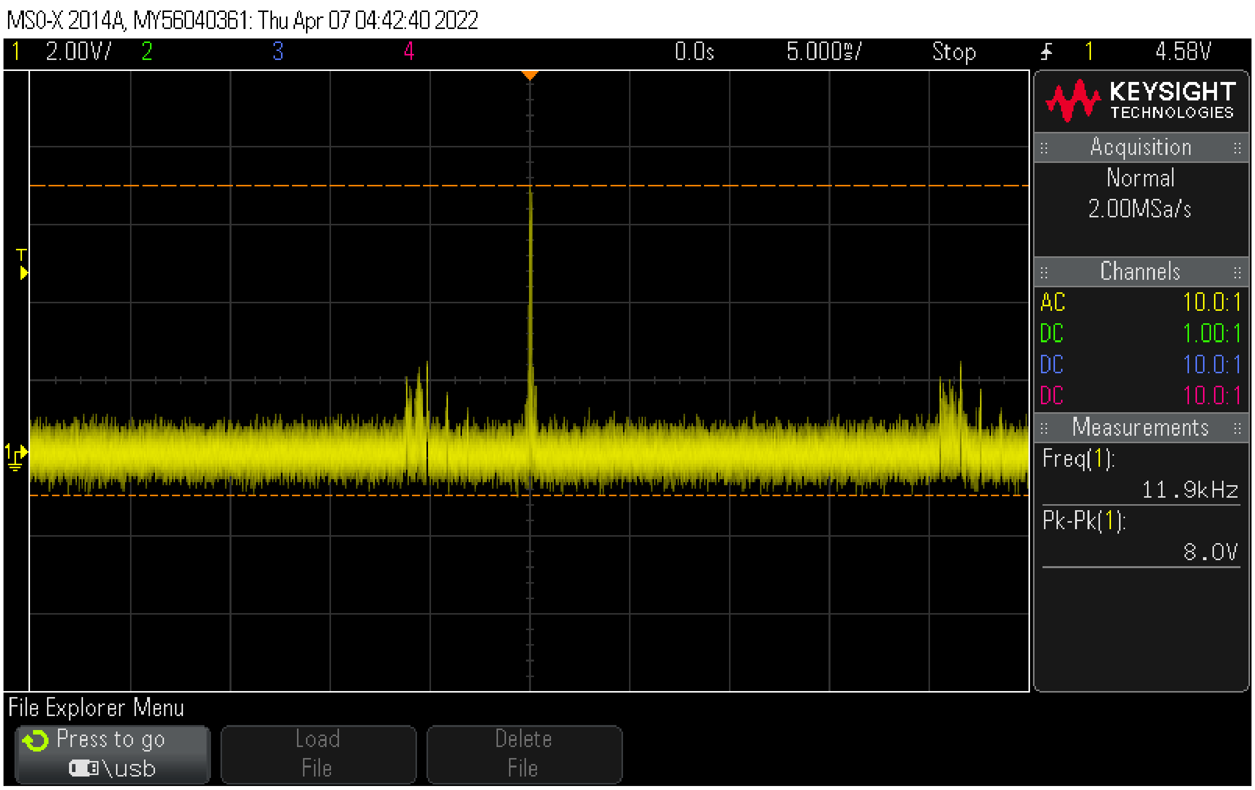

Figure 19: Frequency Spectrum with 433MHz Centered Peak

The next step taken was to focus the spectrum analyzer on 433MHz and change the bandwidth from 100MHz to 0Hz. When the bandwidth is set to zero, the time signal sent at 433MHz frequency can be analyzed using an oscilloscope. With the oscilloscope, the time signal when one transmitter is activated was analyzed along with the time signal when two transmitters are pressed simultaneously.

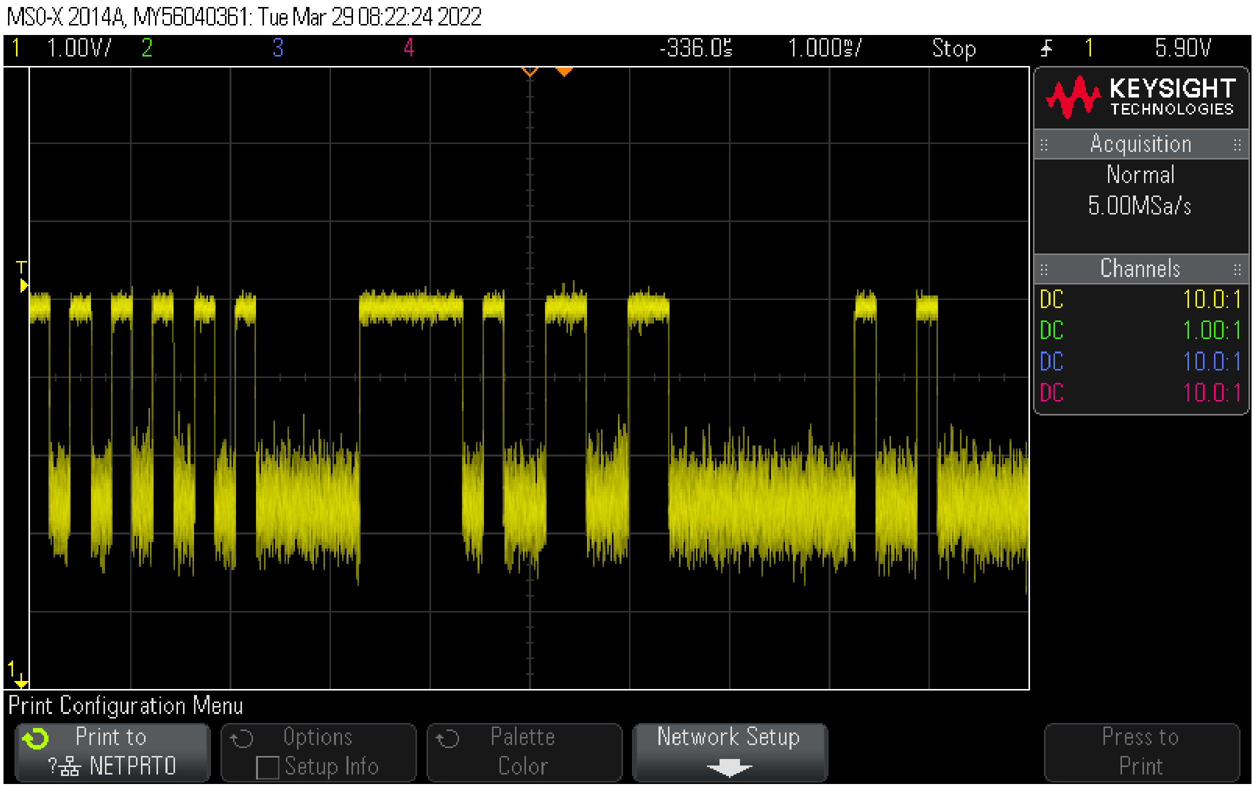

Figure 20: One Transmitter Time Signal

When one transmitter is activated, the input signal transmitted at 433MHz represented in Figure 20 is a square wave containing data information. Since the transmitter and receiver modules used for this project utilize on-off keying, it represents digital data as the presence or absence of a carrier wave [8]. The presence of a carrier for a specific duration represents a binary one, while its absence for the same duration represents a binary zero [8]. Therefore, the decoder was able to decode the square wave, match the data packet from its input to output pin, and turn on the corresponding output pin in the receiver module.

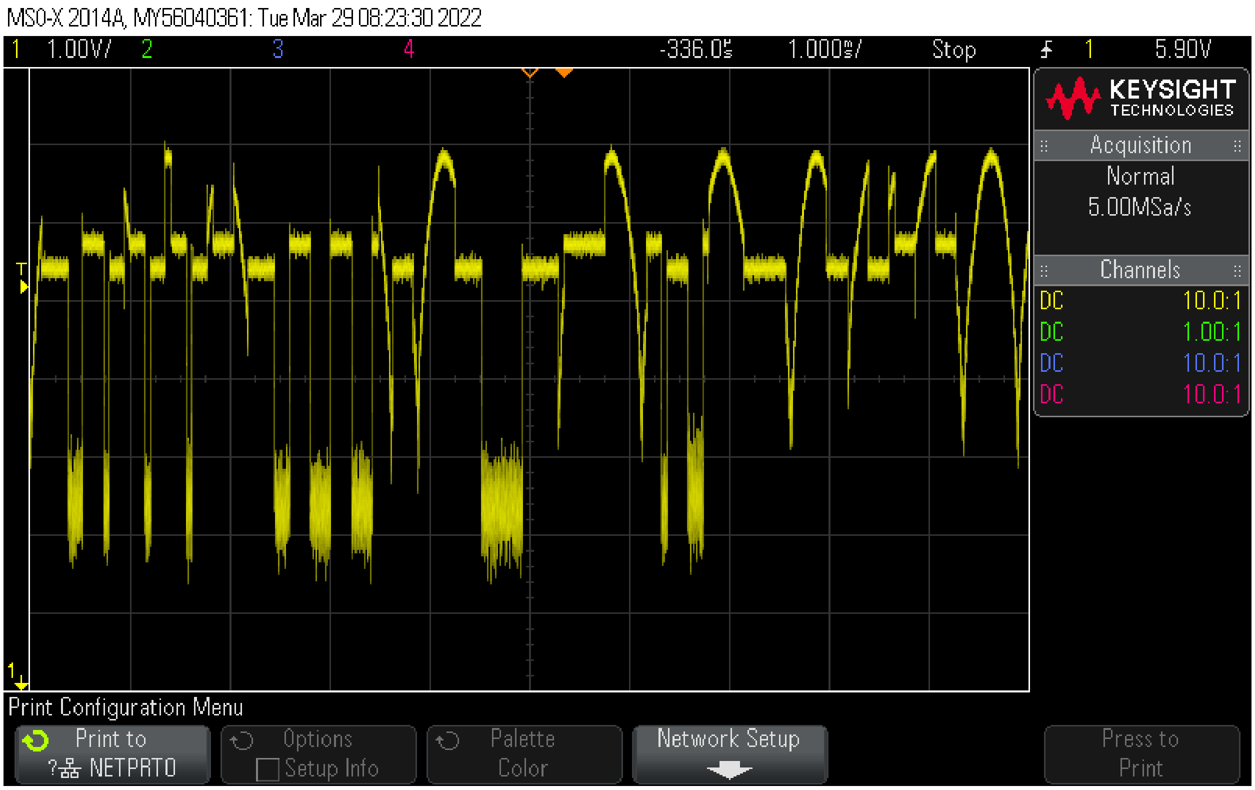

Figure 21: Multi-Transmitter Time Signal Corruption

When two transmitters are activated, the presence or absence of a carrier wave becomes distorted, which is represented in Figure 21 above. This is caused by the two transmitted signals overlapping with one another creating peaks in the amplitude of the time signal. The distortion of the time signal eliminates the decoder's ability to decode the signal into a data packet. The corruption of the time signal when two transmitters are activated is the cause of failure.

6.4.7. Summary of Test Results

Table 1 below displays the previously discussed Revision 1 tests along with their pass or fail results.

Table 1: Revision 1 Test Results

Test	**Result (P/F)**
Short Test	Pass
Communication Test	Pass
Buzzer Test	Pass
Range Test	Fail
Multi-Receiver Communication with One Transmitter	Pass
Multi-Transmitter Communication with One Receiver	Fail

7. FORMAL DESIGN REVISION 2

A second revision of the electronic whistle transmitter and receiver system was completed. This section discusses the specific aims, design changes, schematics, fabrication, and testing for the formal design of Revision 2. The formal Revision 2 design began with setting specific aims based on what the system accomplished in Revision 1 and the original goals set for the project (Section 2.1). Using the formal design from Revision 1, the schematic and board design were edited and improved to meet these goals. Lastly, a series of tests were performed to see if the Revision 2 design met the specific aims laid out below.

7.1. *Specific Aims for Revision 2*

- Transmitter and receiver communicate at 433 MHz.
- Transmitter is powered by an electronic whistle.
- Transmits 433 MHz signal across the minimum range requirement.
- Transmitter PCB fits inside an electronic whistle.
- Receiver PCB and buzzers fit inside a football helmet.

7.2. *Design Changes from Revision 1 to Revision 2*

The most notable changes made from Revision 1 to Revision 2 include the size reduction of the PCBs, the use of a new transmitter model, linking the transmitter to the electronic whistle, and removing many unnecessary components.

Table 2 below lists the PCB dimensions from both Revision 1 and Revision 2. The size reduction of the PCBs from Revision 1 to Revision 2 is needed to meet the specific aims of the transmitter fitting in the whistle casing and the receivers fitting into the helmets. The football helmet donated to the project had an accelerometer located in it. The accelerometer size was used as the initial size estimate for Revision 2. Then, the electronic whistle PCB was measured and confirmed to be smaller in length, width, and height when compared to the accelerometer. The measurements taken from the whistle PCB were 10.16cm x 3.18cm x 3.18cm. The Revision 2 transmitter and receiver dimensions were chosen based on these measurements. The width of both boards was not able to be reduced to 3.18cm due to the size of the electronic components required. See Section 5.6.7 for more information about the receiver fitting into the helmet. See Section 5.6.8 for more information on the transmitter fitting into the whistle casing.

The first revision of the boards did not have size considerations factored in, so they were made larger to be more easily tested, but the reduction in size was also made possible by removing components that were solely needed for testing and not for proper functionality of the system. For the receiver boards, 7 of the 100kΩ resistors and all five of the 220Ω resistors were removed. The 4 green LEDs were removed along with the blue LED. The buzzer connectors were switched from right angle mount to normal mount to preserve space. The new buzzers rated for 1.5V were an external change to the receiver design. The final change to the receiver from Revision 1 to Revision 2 was reducing the dip switch from 10 switches to 3.

For the transmitter, 2 new designs were generated. Transmitters 2.0 and 2.1 saw a decrease from 15 100kΩ resistors down to 6. In addition, 20Ω resistors were added at the expense of a 750Ω and 220Ω resistor. Both capacitors on the Revision 1 transmitter were removed because the linear regulator was no longer needed. All three diodes were removed since there was only one input to the system and no need for diode protection. The power LED was removed along with the linear regulator since power was being drawn from a 3V whistle. Power coming from the whistle also allowed the battery holder to be removed. The connector for the whistle was removed and the connection was instead made via pads on the new design. All three push button switches were removed, and a single pad was added to the PCBs to take the input from the whistle and activate the encoder. The dip switches on the transmitters were also reduced from 10 switches down to 3. The difference between transmitter 2.0 and 2.1 was the transmitter module. Transmitter 2.1 incorporated the LR series transmitter module to replace the LC series module used in Revision 1. The LR series module would have been used in Revision 1, but it was out of stock at the time parts were purchased. The LR series module was purchased in hopes that it would increase the range of the design and act more consistently than the Revision 1 design. The LR series module has a higher data rate and lower supply voltage than the LC series module.

Table 2: PCB Dimensions

	Transmitter Dimensions	**Receiver Dimensions**
Revision 1	8.38 cm9.49 cm Area=79.52 cm2	9.27 cm8.51 cm Area=78.89 cm2
Revision 2	4.89 cm3.27 cm Area=16.00 cm2	8.38 cm3.81 cm Area=31.93 cm2

7.3. Transmitter 2.0

This section discusses the transmitter 2.0 schematic and board design. The transmitter 2.0 design implements changes mentioned in section 7.2. Furthermore, the implementation of transmitter 2.0 PCB design is discussed.

7.3.1. Transmitter 2.0 Schematic and Board Design

After implementation of the changes discussed in section 6.1, a detailed schematic and board design for the transmitter was done in EAGLE. Once the design was finalized and approved, the printed circuit board (PCB) was ready to be fabricated. The schematic design for the transmitter in Revision 2.0 can be found in Figure 45 of the Appendix. The below image in Figure 22 is a snippet of the printed circuit board design for the Revision 2.0 transmitter made in EAGLE.

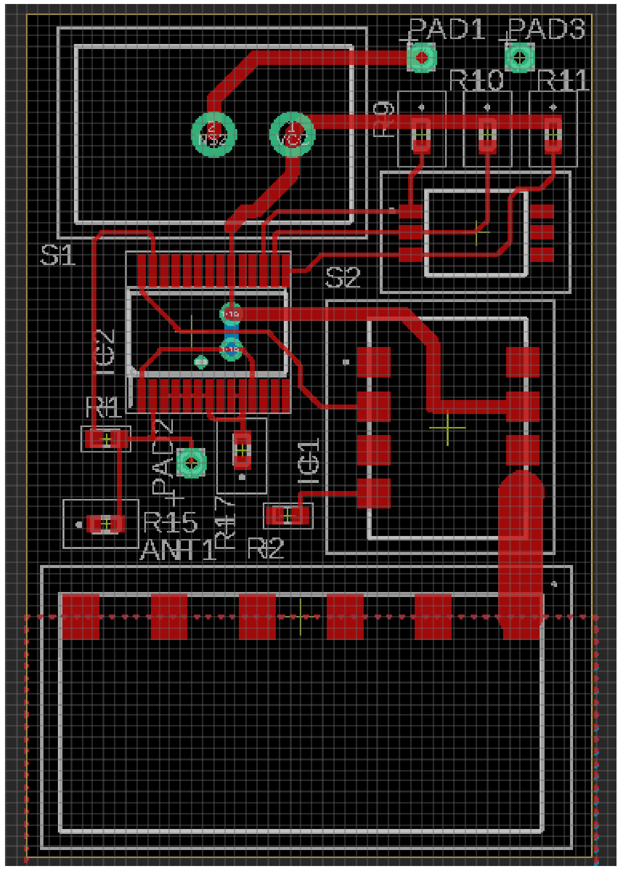

Figure 22: Transmitter 2.0 EAGLE Board Design

7.3.2. Transmitter 2.0 PCB

As discussed in Section 5.2.2, the schematic and board designs would continue to be sent to a PCB fabrication company, JLCPCB. The boards were then delivered and populated in-house by soldering on the respective components. The Revision 2.0 transmitter PCB that was fabricated by JLCPCB is shown in Figure 23.

Figure 23: Transmitter 2.0 PCB

Since the Revision 2.0 transmitter module was designed to obtain power from the electronic whistle, the transmitter was wired from its source and ground pads to the source and ground pads of the electronic whistle circuit board. The electronic whistle was disassembled to gain access to the positive and negative terminals of the internal PCB. Wires between the two PCBs were soldered onto their respective pads. PAD1 was the power pad and PAD2 was the GND pad. The whistle button press connection was made at PAD2. The whistle connection was tested and is discussed in Section 6.6.2. Figure 24 contains an image of the electronic whistle PCB wired to the Revision 2.0 transmitter.

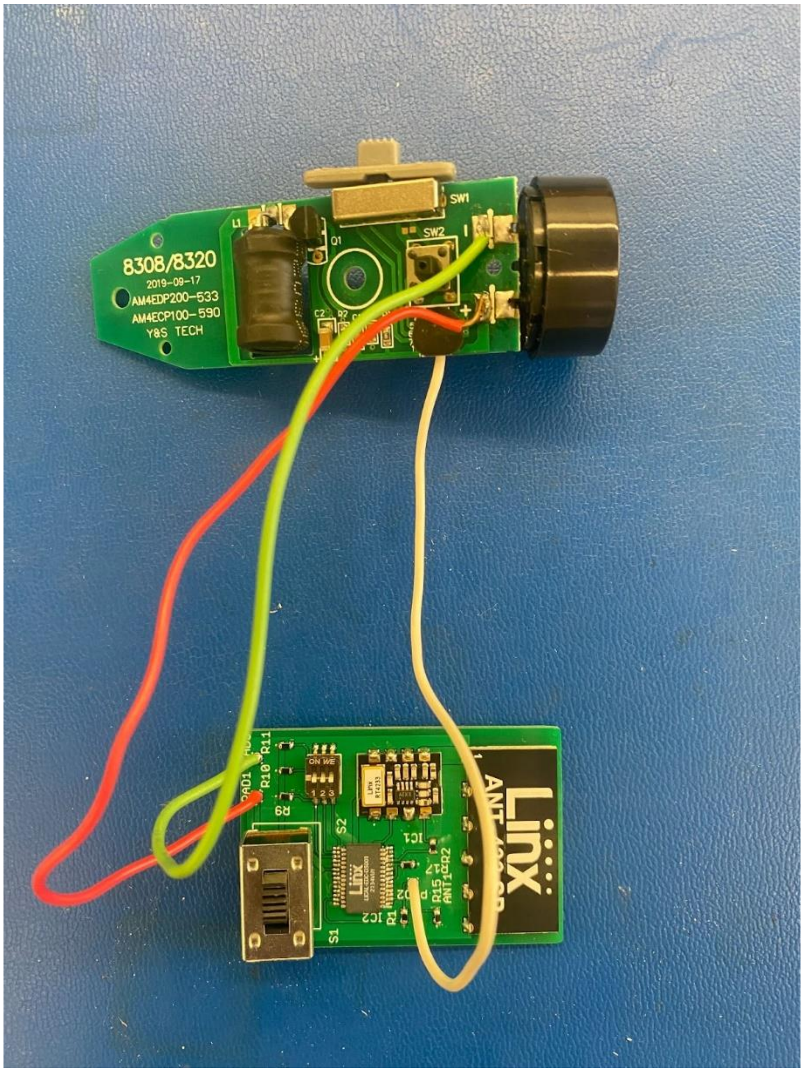

Figure 24: Whistle to Transmitter Connection

7.4. Transmitter 2.1

This section discusses the transmitter 2.1 schematic, board design, and PCB design. The transmitter 2.1 design implements changes are discussed throughout. Furthermore, the reasoning behind changes made from transmitter 2.0 to transmitter 2.1 are discussed.

7.4.1. Transmitter 2.1 Schematic and Board Design

As noted in Section 3.4.4, the LC series transmitter module in Revision 1.0 did not pass the range test. Due to this reason, the LR series transmitter was purchased to see if the range test result could change. This transmitter is improved with a data rate of almost double that of the LC series transmitter used in Revision 1.0. Additionally, the supply voltage of the LR series transmitter is less than the LC series transmitter. Since the receiver in Revision 1.0 is LR series, the LR series transmitter will perform with a higher efficiency than the LC series. Therefore, the only change made from Revision 2.0 to 2.1 was the transmitter. The schematic for the transmitter in Revision 2.1 can be found in Figure 46 of the Appendix. The following image in Figure 25 is an image of the printed circuit board design for the Revision 2.1 receiver made in EAGLE.

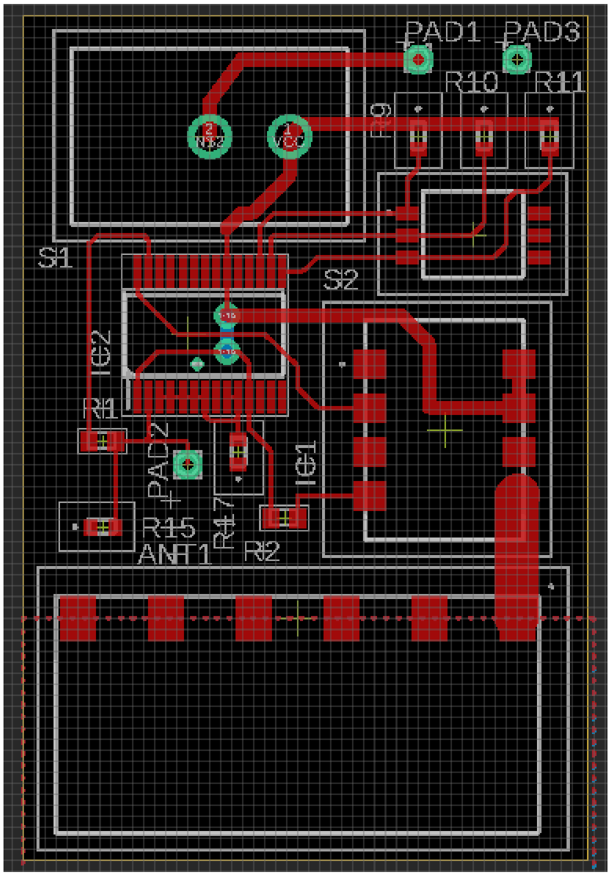

Figure 25: Transmitter 2.1 EAGLE Board Design

7.4.2. Transmitter 2.1 PCB

Again, the transmitter boards were sent to JLCPCB for fabrication of the bare boards. The boards were populated in-house by soldering on the respective components. The Revision 2.0 transmitter PCB that was fabricated by JLCPCB is shown in Figure 26 below.

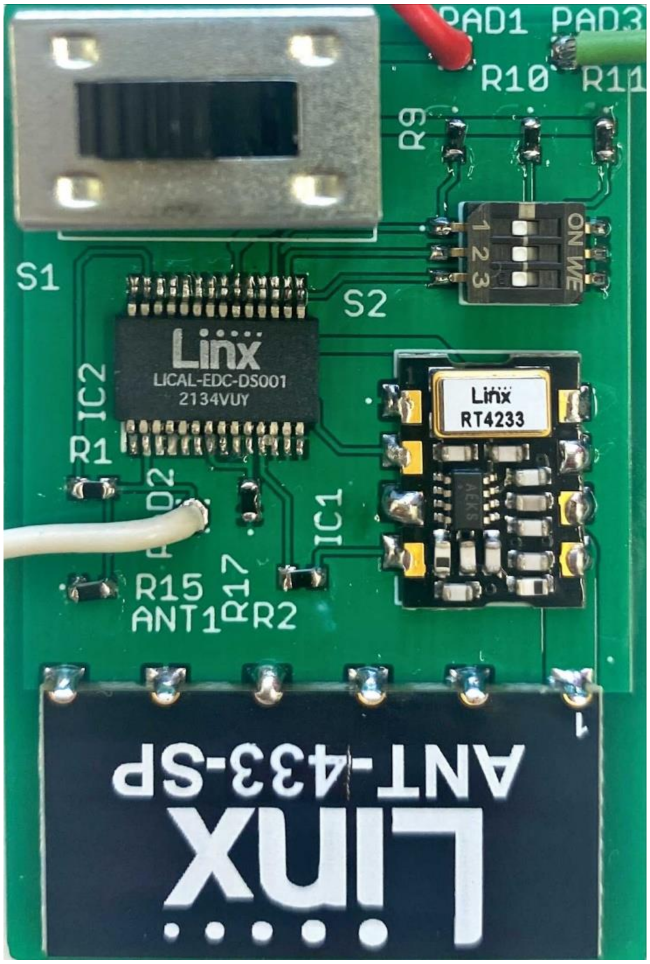

Figure 26: Transmitter 2.1 PCB

The Revision 2 transmitter changes were discussed in Section 7.2 but can again be seen in Figure 26 above. Less 100kΩ pull down resistors are present, and the DIP switch is now only 3 switches. The 3 pads are used for the external whistle power, ground, and input. The transmitter modules on both 2.0 and 2.1 are now tied to 0Ω resistors for max transmission power. The only difference in board design between transmitter 2.1 and 2.0 (Section 7.3.2) is that the adjustable pin on the transmitter module is tied to VCC in 2.1 and GND in 2.0.

The max transmission power of the two transmitter modules was investigated to meet one of the safety engineering design considerations mentioned in Section 2.7. Refer to Equation 1 from Section 2.7, Pt = max transmitter power, Ga = antenna gain, and Lc = cable loss. Pt for the LR series transmitter is 9 dBm. The Pt for the LC series transmitter is 5 dBm. The Ga for the antenna used in both designs is -6.4 dBm. The cable loss is unknown but since it is a power loss and not a gain, it can be assumed that both transmitter modules do not exceed the power max output power requirements.

7.5. Receiver 2.0

This section discusses the receiver 2.0 schematic and board design. The receiver 2.0 design implements changes mentioned in section 7.2. Furthermore, the implementation of receiver 2.0 PCB design is discussed.

7.5.1 Receiver 2.0 Schematic and Board Design

After implementation of the change discussed in section 6.1, a detailed schematic and board design for the receiver was done in EAGLE. Once the design was finalized and approved, the printed circuit board (PCB) was ready to be fabricated. The schematic design for the receiver in Revision 2.0 can be found in Figure 47 of the Appendix. The following image in Figure 27 is an image of the printed circuit board design for the Revision 2.0 receiver made in EAGLE.

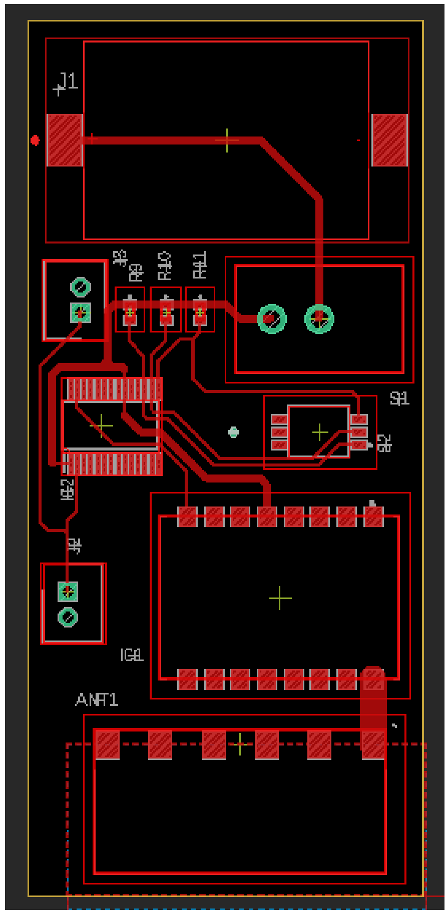

Figure 27: Receiver 2.0 EAGLE Board Design

7.5.2. Receiver 2.0 PCB

Similarly, the receiver boards were sent to JLCPCB for fabrication of the bare boards. The boards were populated in-house by soldering on the respective components. The Revision 2.0 receiver PCB that was fabricated by JLCPCB is shown in Figure 28.

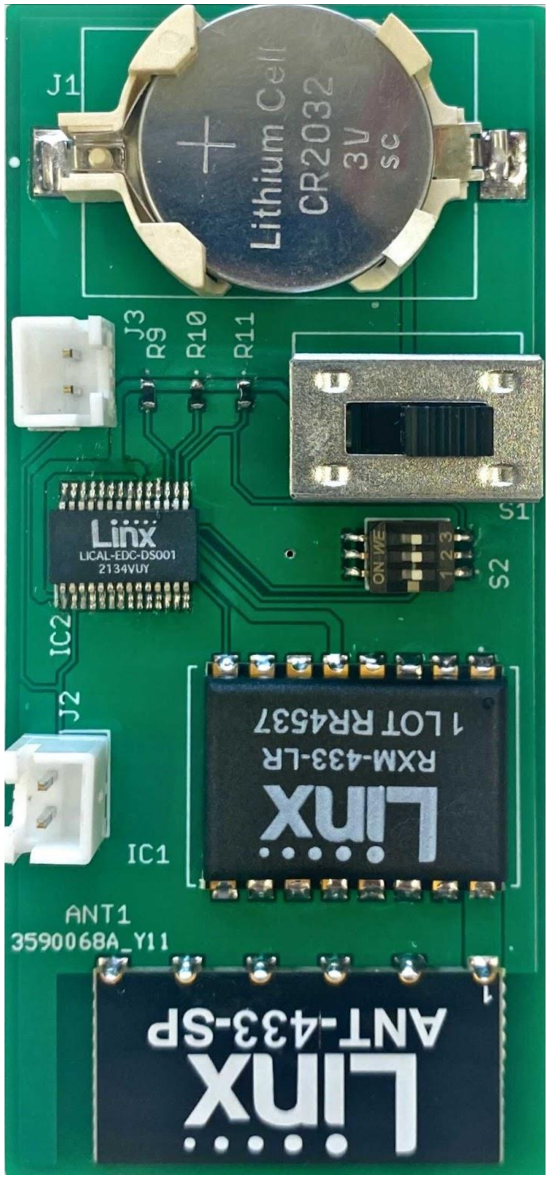

Figure 28: Receiver 2.0 PCB

The Revision 2 receiver board is designed with many of the same components discussed in Section 6.3.2 and had some of the components removed as discussed in Section 7.2. From top to bottom of Figure 28, the battery holder and power switch can be seen. No green power LED is present which also meant the 220Ω resistor could be removed. To the left of the power switch the decoder and the two new connectors for the buzzers are placed. The new 3 switch DIP switch can be found under the power switch.

7.6. Tests and Results

A series of eight tests were performed on the Revision 2 system. These tests were done to verify the operation of the original transmitter module, the new transmitter module, the receiver, and the buzzers. These tests ensured the specific aims of Revision 2 were met and the expected improvements were observed.

7.6.1. Short Test

The same short test procedure from Revision 1 (Section 4.4.1) was performed on the Revision 2 transmitter and receiver modules. No shorts were indicated by the DMM. Therefore, the Revision 2 boards passed the short test.

7.6.2. Communication Test

The communication test procedure from Revision 1 (Section 4.4.2) was performed slightly differently on the Revision 2 transmitter and receiver modules to verify that the transmitter and receiver were communicating over 433MHz frequency. The receiver board could still be turned on with the 3V battery and power switch, but the new transmitter boards do not have battery inputs. Power and GND needed to be supplied to the transmitter boards externally as well as the input to the encoder. Instead of LED5 indicating communication between the transmitter and receiver, the buzzers were connected to the disconnect able crimp style connectors (J2 and J3). The emission of a tone from the buzzers would indicate communication.

To perform this test, the Revision 2 receiver board was turned on. 3V was supplied to PAD 1 on the transmitter PCB and GND was supplied to PAD 3. 3V was supplied to PAD 2 to activate the encoder and send the transmission. The buzzers emitted a tone upon reception of the signal. Therefore, the Revision 2 design passed the communication test.

7.6.3. Buzzer Test

The procedure for the Revision 2 buzzer test was slightly different than in Revision 1. The receiver board was turned on normally, but the transmitter boards needed to either be supplied power and ground from the whistle or wired to a battery or power supply. Once the transmitters were given power, the white wire connected to PAD 2 on the PCB was then given 3 volts from a whistle press or another power source to send the transmission to the receiver. The new buzzers encountered the same issue that was seen in the Revision 1 buzzer test (Section 4.4.3). Although the buzzers required less voltage (1.5V) than the originals (3V), the tone was still not as loud as it was desired to be because the voltage was still dropping to under 1.5V. While testing with various arrangements of the buzzers, it was concluded that they were not receiving enough current. The buzzers being current limited was causing a decrease in their supply voltage. Each pin on the decoder can only output a maximum current of 25 mA, and both sets of the buzzers require 20 mA per buzzer. Therefore, the current was only outputting half of what was needed to power the buzzers. A fix for this issue is discussed later in future recommendations (Section 10.2).

7.6.4. Range Test

The same range test procedure from Revision 1 (Section 4.4.4) was performed on the Revision 2 devices, aiming for a minimum range requirement of 394 ft. Transmitter 2.1 was able to send the 433 MHz signal across the minimum range, and therefore passed the test. The transmitter module chosen for design 2.1 operated with better overall functionality; it was more consistent throughout all the tests performed on Revision 2, as it was not selective to how the board was held or positioned when trying to activate the device.

7.6.5. Multi-receiver Communication with One Transmitter Test

The same multiple receiver communication test procedure from Revision 1 (Section 4.4.6) was performed on the Revision 2 transmitter and receiver modules. The receiver from Revision 2 and receiver from Digi Key Evaluation Kit were used to perform this test. Again, the Revision 2 transmitter was activated, and the Revision 2 receiver emitted a tone from the buzzers and the Digi Key receiver "DOUT" pin LED turned on. This indicated that the Revision 2 board design passed the multiple receiver communication test.

7.6.6. Battery Life Test

A battery life test was performed in Revision 2 to calculate how long each device would last and to ensure it would be long enough to remain in use for an entire NFL game. First, the idle currents and active currents of the electronic whistle, the receiver, and both transmitters were measured using a DMM. The idle current refers to the current when the device is in the "on" position but is neither receiving nor transmitting a signal. The active current refers to the current the device draws when it is on and is actively receiving or transmitting a signal. The current draw of all three devices was measured and will not create an issue with power consumption to create too much heat as mentioned in Section 2.1. Using the battery capacities for a zinc carbon AAA battery, 500-600mAh, and a CR2032 lithium coin cell battery, 220mAh, the battery life was calculated by also factoring in the average NFL game time of 3.2 hours, and the average number of whistle blows per game. Figure 29 below shows part of the procedure performed during the battery life test. Here, Receiver 2.0 was connected to the power supply and its currents were measured. The same was done for Transmitter 2.0 and 2.1.

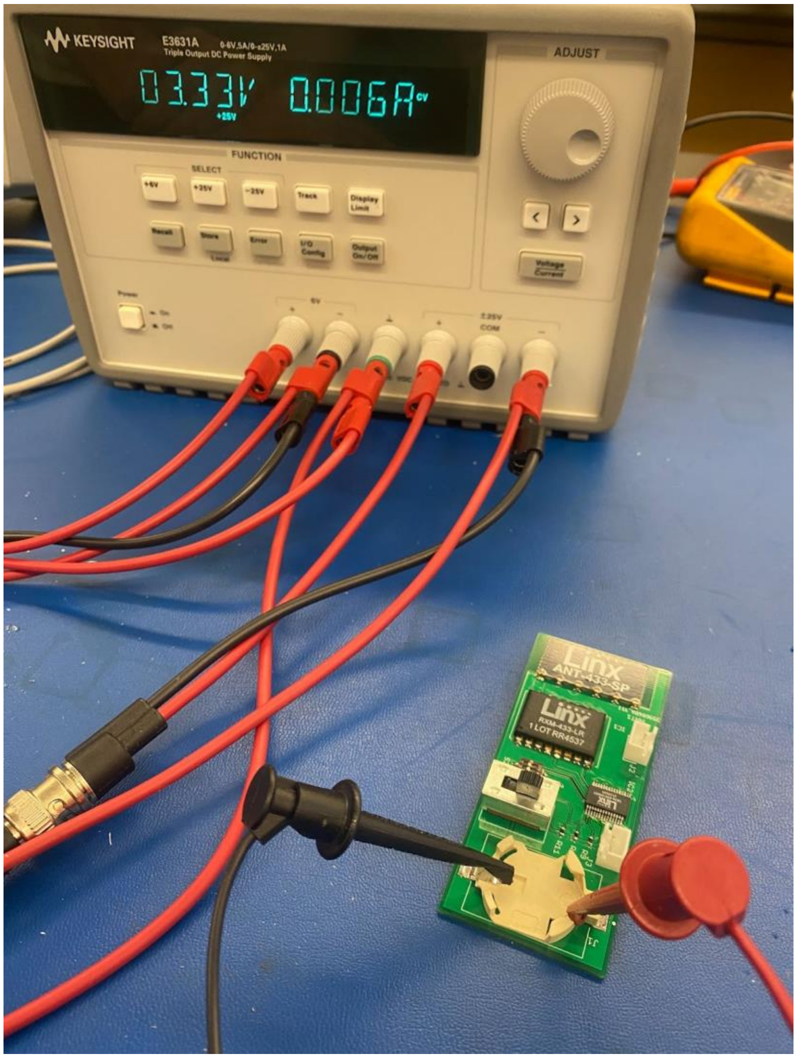

Figure 29: Power Supply Used for Battery Life Testing

Table 3 displays the results for the battery life test, showing that the receiver will last the least amount of time. However, all the devices should theoretically make it through an entire NFL game without needing to change out the batteries.

Table 3: Battery Life Test Results

Device	Battery Life (hours)	Approximate Number of Games
Receiver 2.0	24.24	7
Transmitter 2.0	189.63	59
Transmitter 2.1	143.64	45

7.6.7. Helmet Fit Test

A helmet fit test was performed to fit the Revision 2 receiver module with buzzers inside of a football helmet. The football helmet that was donated had an accelerometer already placed in the back anatomical left side of the helmet. Knowing that the existing accelerometer had fit inside of the helmet, it was possible to fit the Revision 2 receiver module in the back right side of the helmet. A glimpse of the green receiver PCB (circled) can be seen in Figure 30 below.

Figure 30: Inside Helmet View

The power switch of the receiver PCB (circled) can be seen on the right in the backside view of the helmet shown in Figure 31 below.

Figure 31: Back of Helmet View

To prove that the receiver and buzzers would fit in the football helmet, the receiver and buzzers were temporarily mounted using tape. The receiver module fits into the back left side of the helmet with buzzers placed on each side of the ears. Figure 32 below shows the buzzer from the Revision 1 design mounted on the inside right ear of the helmet (circled).

Figure 32: Right Ear Buzzer Inside Helmet

Figure 33 shows the buzzer from Revision 2 of the design mounted in a pre-cut hole on the left ear of the helmet (circled).

Figure 33: Left Ear Buzzer Inside Helmet

The method of mounting the receiver inside the helmet could be improved by adding a form of padding or protection around the receiver. This could be done during the production process of a new NFL helmet to ensure it is properly mounted before the existing head padding is placed. Additionally, the electrical components have a possibility of being exposed to minimal moisture during use. To protect the board from moisture and dust, a conformal coating can be added onto the boards to achieve an IP rating of IPX4 [7].

7.6.8. Electronic Whistle Fit Test

An electronic whistle fit test was performed to fit the Revision 2 transmitter module inside of the electronic whistle. Since the electronic whistle was designed to be a small, handheld, user-friendly device, the transmitter module was too large to be mounted inside of the electronic whistle. Instead, the transmitter module was mounted on the outside of the electronic whistle. This was accomplished by drilling a hole through the back covering of the electronic whistle to thread the source and ground wires of the transmitter into the source and ground lines of the electronic whistle.

Figure 34: Transmitter Wired to Whistle Side View

Figure 35: Transmitter Wired to Whistle Front View

After the mounting of the transmitter module, it was verified that when the electronic whistle was activated the transmitter was activated. When pressing the button on the whistle, the receiver responded with the buzzers emitting a tone. This indicated that the mounting of the transmitter onto the electronic whistle was successful.

7.6.9. *Summary of Test Results*

Table 4 below displays the previously discussed Revision 2 tests along with their pass or fail results.

Table 4: Revision 2 Test Results

Test	**Results**
Short Test	Pass
Communication Test	Pass
Buzzer Test	Pass
Range Test	Pass
Multi-Receiver Communication with One Transmitter	Pass
Battery Life Test	Pass
Helmet Fit	Pass
Electronic Whistle Fit	Fail

8. JUSTIFICATION OF COMPONENTS

This section discusses important design considerate components that were chosen for a specific usage. It discusses what each component does, their capabilities, and what they are used for in this project. It was important to note the reasoning behind choosing a specific component.

8.1. Electronic Whistle

An electronic whistle is a device used in American Football to alert players that a play has ended [19]. In this project, the effectiveness of the tone from the electronic whistle will be increased by implementing a secondary alert. The secondary alert will be a tone that sounds from a receiver inside a player's helmet. This secondary alert will be connected via radio frequency (RF) to the electronic whistle. The secondary alert tone will be closer to the player's ears and decrease the amount of injury after a play has ended. The electronic whistle is needed for this project to increase player safety and communication in American Football.

Figure 36: Electronic Whistle [19]

8.2. *Linx DS Series Encoder/Decoder Module*

The encoder/decoder module utilizes 10 address lines, 8 data lines, 2.2-5.5 operating voltage, low standby current (3uA), small package, and no programmer is required [16]. This encoder/decoder module was chosen because it is a small surface mount device with the capability of using multiple addresses to encode and decode signals. More on the functionality of the device is discussed in section 5.1. This device will be used in the transmitter and receiver modules. Figure BLANK is an image of the encoder/decoder module from its datasheet.

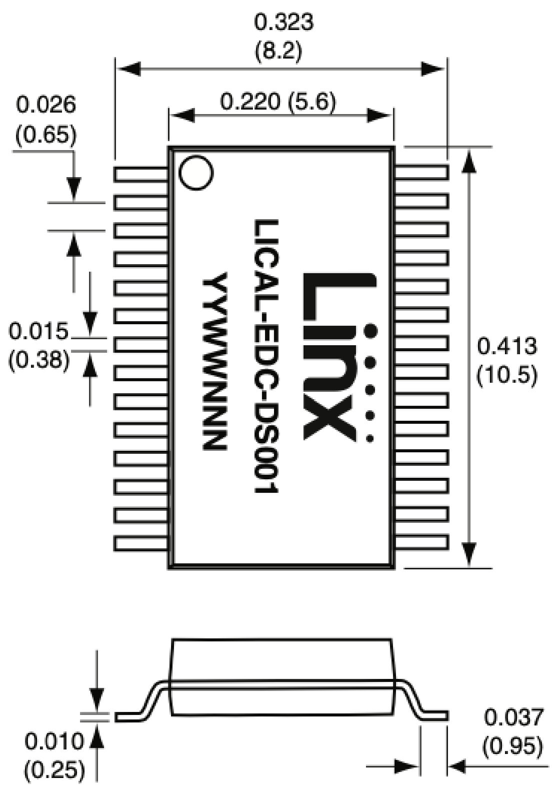

Figure 37: Encoder/Decoder Module [16]

8.3. *LR Series Receiver Module*

This device is used to wirelessly receive serial data, control, or command information. It has the capability to work in the 250-460MHz range [18]. The receiver can carry 10,000 bps at distances up to 1.5 miles [18]. This distance capability is greater than what is needed (150 yds). The receiver device will be used to communicate with the electronic whistle (transmitter). When the transmitter is activated, a signal at a certain frequency will be received and turn-on/activate the tone in the helmet to alert players. Additionally, this receiver module was chosen because it has a larger efficiency when paired with an LR Series transmitter module. The DigiKey Evaluation Kit uses this receiver module [15].

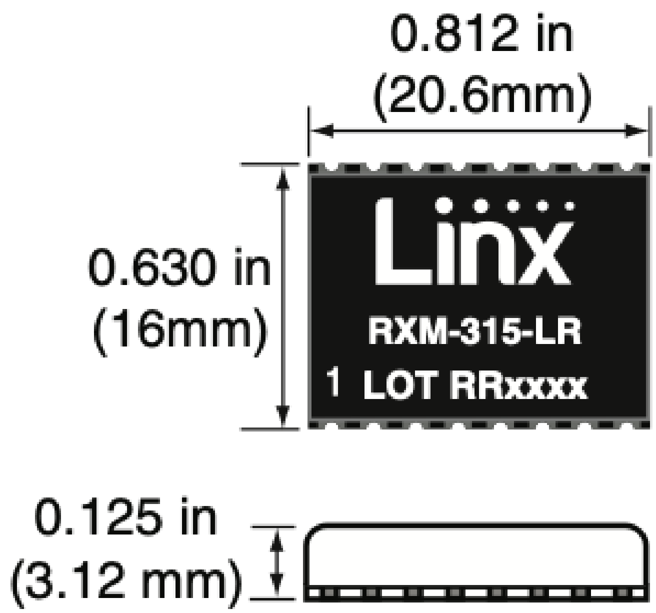

Figure 38: LR Series Receiver Module [18]

8.4. *LC Series Transmitter Module*

This device is used to wirelessly transfer data, control, commands, etc. over a specific radio frequency [20]. When paired with a matching LC Series receiver, a reliable wireless link is formed, capable of transferring serial data at distances of up to 3,000 feet [20]. Additionally, no external RF components are required (except an antenna). This device will be used in the electronic whistle to send a signal to the receiver unit when the button/whistle is activated. Additionally, this transmitter module was chosen because it has a larger efficiency when paired with a Linx receiver module. The DigiKey Evaluation Kit uses this transmitter module [15].

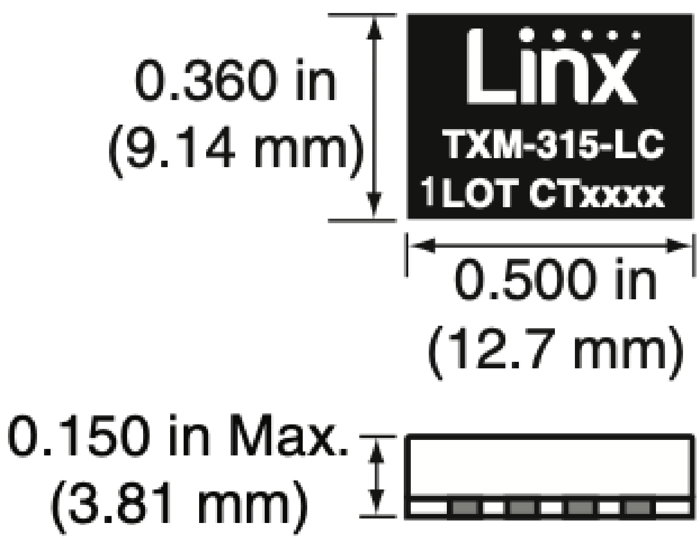

Figure 39: LC Series Transmitter Module [20]

8.5. LR Series Transmitter Module

This device is used to wirelessly transfer data, control, commands, etc. over a specific radio frequency [21]. When paired with a matching LR Series receiver, a reliable wireless link is formed, capable of transferring serial data at distances of up to 3,000 feet [21]. Additionally, no external RF components are required (except an antenna) [21]. This device will be used in the electronic whistle to send a signal to the receiver unit when the button/whistle is activated. Additionally, this transmitter module was chosen for usage in Revision 2.1 because it has a higher data rate and lower supply voltage than the LC series transmitter.

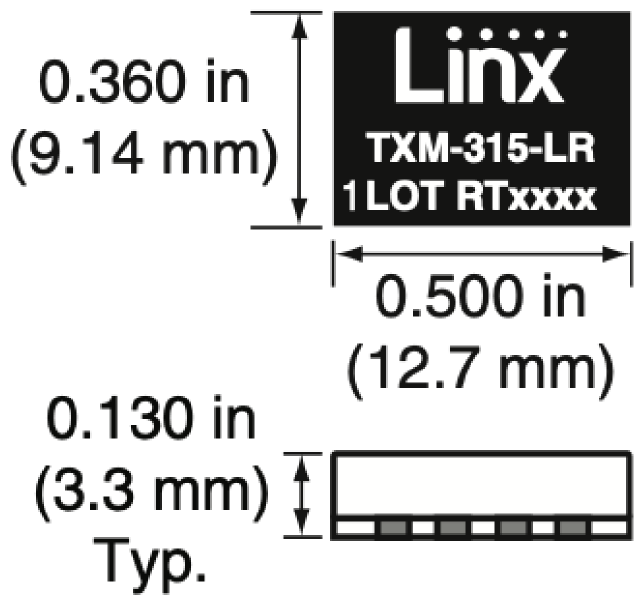

Figure 40: LC Series Transmitter Module [21]

8.6. Splatch Antenna Module

The antenna is used on both receiver and transmitter modules. It has a frequency range of 429-437MHz [22]. This specification matches the receiver and transmitter frequency specification. It emits and receives electromagnetic waves just like a standard antenna, except they are much smaller in size, and it is a surface mounted component [22]. This is a benefit when considering size constraints. This antenna matches frequency and size considerations for the custom design.

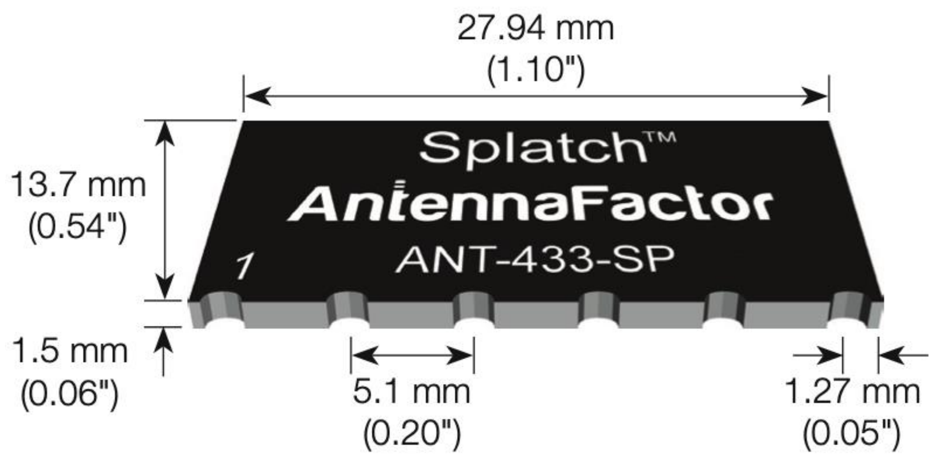

Figure 41: Splatch Antenna [22]

8.7. Buzzers

The buzzers were placed in the receiver module [23]. The buzzer itself is the secondary alert for football players. It was important to note the decibel (dB) level of the tone it emits because the receiver will be placed in the helmet, close to the player's ears. This buzzer emits a 70dB tone at 10cm. Decibel levels can reach up to 80 to 90dB in a football stadium which is considered "loud or "extremely loud" [24]. To put this in perspective, an ambulance siren is approximately 110dB. Placing the buzzer directly next to the players' ears will eliminate the players' inability to hear the electronic whistle blow from a far distance. Two internally driven buzzers were tested throughout the design. The first buzzer had a voltage rating of 3V and the second had a voltage rating of 1.5V. Either buzzer would work for the design if the changes implemented in Section 10.2 were made.

9. COST ESTIMATE

To summarize the cost of the project Table 5 contains the cost for each revision along with additional components in the electronic whistle transmitter and receiver system.

Table 5: Project Cost Breakdown

Item	Rev. 1	Rev. 2	Rev. 2.1
Transmitter	$33.45	$27.82	$23.65
Receiver	$36.04	$33.86	$33.86
Buzzers	$9.66	$9.66	$3.92
Electronic Whistle	$14.99	$14.99	$14.99
Cr2032 Batteries	$1.20	$0.60	$0.60
Wire Jumpers	$2.85	$1.90	$1.90
Total Cost	**$98.19**	**$88.83**	**$78.92**

As denoted in Table 5, the cost of the electronic whistle transmitter and receiver system decreased as each revision was made. The custom transmitter and receiver modules made up most of the cost for each revision. There was a cost reduction from Revision 1 to Revision 2 of $9.36. This cost reduction is due to the reduction in size (Section 7.2). Resistors and LEDs used to test the Revision 1 board design were removed in the Revision 2 boards. Additionally, Revision 2 transmitter board design did not need a Cr2032 lithium battery power supply because the transmitter was connected to the electronic whistles power supply. There was also a cost reduction from Revision 1 to Revision 2.1 of $19.27. This cost reduction is more significant due to the transmitter component and buzzers being cheaper than those in Revision 2 (Section 7.2). The cost of the final design, Revision 2.1, totals $78.92 including the cost of fabrication of the boards from JLCPCB. The formal Bill of Materials (BOM) of each revision is contained in Figures 48 and 49 of the Appendix.

To put in perspective the cost of this device, a professional customized football helmet costs approximately $1750 [25]. Implementing an approximately $80 device into football helmets to improve player safety is not a substantial cost increase.

10. FUTURE RECOMMENDATIONS

Ideas were generated for future implementation into the electronic whistle transmitter and receiver system to improve its operation and allow for the possibility of additional features. The flowchart shown below in Figure 42 provides a visual of some of the ideas that could be beneficial. The blocks in green represent the current design, the blocks in red represent fail state feedback, and the blocks in yellow represent future recommendations to be added to the design.

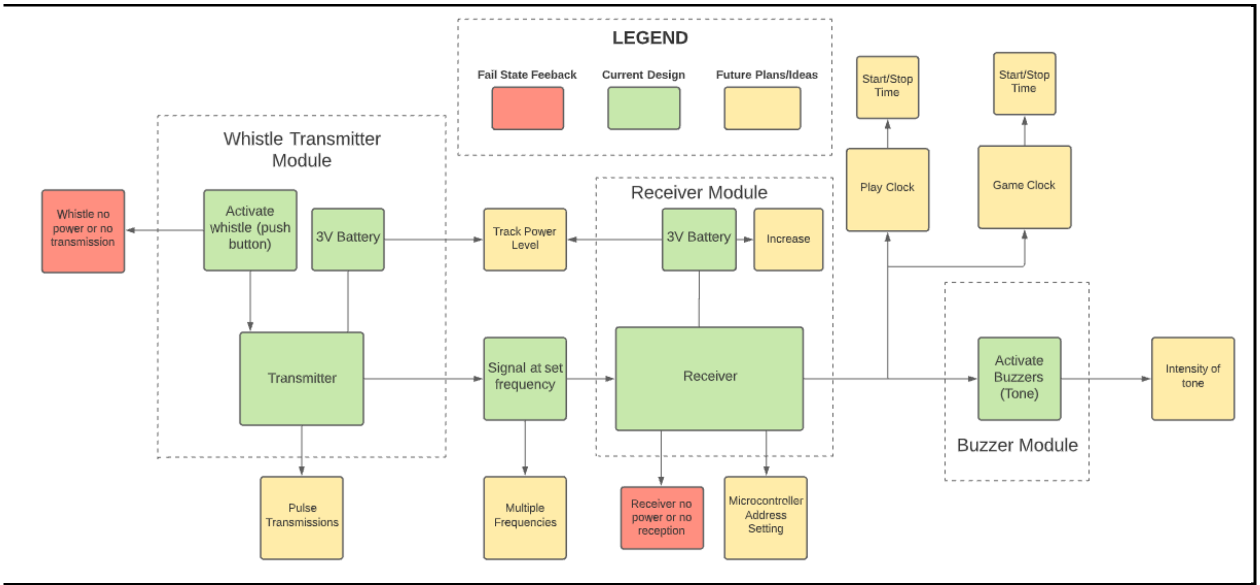

Figure 42: Future Recommendations Flowchart

The following corrective action ideas are available for future improvements:

10.1. Multi-Transmitter Communication Failure Options

This section discusses several ways to fix the multiple transmitter communication simultaneously issue discussed in section 6.4.6. The options discussed are pulse transmissions, multiple frequencies, and microcontroller address setting.

10.1.1. Pulse Transmissions

One of the three ideas generated to fix the issue with the multiple transmitters communicating with a receiver at the same time was to send out pulse transmissions. In this case, the transmitters would all be set on different clock signals so that they would not transmit signals at the same time. The receiver would be able to decode a transmission from one whistle before the next pulse from a different whistle arrived. However, with any time signals there will eventually be overlap, meaning the original issue can still occur.

10.1.2. Multiple Frequencies

Another suggested fix was for the transmitters and receivers to operate at multiple frequencies. Otherwise known as frequency hopping, the transmitter would be sending their signals at sub frequencies of 433MHz so that they were not on the same frequency bands. The receiver would not receive corrupted data packets because there would be no interference in the transmitted signals. Frequency hopping is a viable option to fix the current issue but requires more research.

10.1.3. Microcontroller Address Setting

The last idea for fixing the multiple transmitter communication issue involves programming a microcontroller. Each transmitter/whistle would be set to a different address from the dip switch. The receivers in the helmets would have a microcontroller in place of a dip switch to set the address. The microcontroller would be programmed to shuffle the receiver's address between the known addresses of the transmitters. Once a transmitter sends a signal, the microcontroller would lock the receiver into that address until the transmission ended so that the receiver could not be interrupted by another transmission from a different address. The implementation of this idea would be the next step to take before putting the design into the field.

10.2. Increase Buzzer Volume

To increase the buzzer volume there needs to be more current supplied to the buzzers. In the current design the buzzers are tied in parallel to one out pin of the decoder. The decoder output pins can only supply 25mA and the buzzers each need 20mA. In the current design the buzzers can only get a maximum of 12.5mA which is causing the voltage to drop and the buzzers to not fully operate. A simple fix for this would be to attach each buzzer to its own output pin. If the receiver board had two output pins for two buzzers, the transmitter boards would need to have two of their input pins shorted together so that a single input (whistle press) would activate two outputs.

Another way to increase the buzzer tone would be to increase the supply voltage of the receiver board. The voltage could not exceed the maximum voltage of the electronics on the board but could be more than the 3V that is on the current design. To implement this, larger batteries and potentially a linear regulator as seen on the Revision 1 transmitter could be used to increase the board's voltage. Increasing the voltage should only be done if needed after the first idea is implemented.

10.3. Track Power Level

Lastly, the whistle transmitter and receiver could use a battery tracking system. To continue to promote safety, a battery tracking system is necessary to know if a player's helmet receiver is on or if the whistle will activate mid game. Unsafe situations could arise if the devices were near the end of their battery life in the middle of a game. Coaches should be able to monitor the player's helmet receiver's battery life so that they can ensure the charge will be enough to last an entire game. Also, the referees should have the same equipment to monitor their own whistle's battery life to ensure their whistle will operate and keep play safe during the game.

11. CONCLUSIONS

Through the research and preliminary design stages of the electronic whistle transmitter and receiver project, there were several considerations to be made for how the devices should be designed. Not only did the type of alert and wireless communication need to be chosen, but also where on the player the device should be to be most effective. These considerations turned into the major decisions to use a tonal alert delivered at a low radio frequency of 433MHz to a receiver mounted inside a player's helmet, which would then output through buzzers located near the ears.

Once these design decisions were made, the first and second level architectures of the system were created, and a design solution was generated.

The formal design of the electronic whistle transmitter and receiver was completed in two separate revisions, each with their own set of specific aims. Revision 1 was similar to a trial run or proof of concept; the boards were designed to be larger and to include extra components that aided in testing procedures, such as LEDs that lit up to confirm transmission and receiving of the signal. As tests were completed, notes were made for possible changes and improvements that would be implemented into Revision 2. Some major changes included smaller PCBs, less components, electronic whistle and transmitter connection, and a more functional transmitter module. New testing was done to ensure the specific aims of Revisions 2, the overall project goals, and the applied engineering design considerations were met.

During the testing stages of Revision 1 and 2, a couple operation issues of the devices were observed that could be improved upon in a future design of the system. These include the failure of the multi-transmitter communication test and the buzzer volume. Ideas for improvement on both topics are recommended. In addition to correcting those two issues, a few ideas were generated on additions to the system that could make it more functional, such as tracking the power level and syncing the whistle blow to the game clock. Overall, the electronic whistle transmitter and receiver system was successful in prototyping an alert system for football players.

REFERENCES

[1] “Concussion care should top every youth sports playbook,” *National Safety Council*. [Online]. Available:https://www.nsc.org/home-safety/safety-topics/child-safety/concussions. [Accessed: 27-Apr-2022].

[2] “What is a concussion?,” *What is a Concussion? | Brain Injury Research Institute*. [Online]. Available: http://www.protectthebrain.org/Brain-Injury-Research/What-is-a-Concussion-.aspx. [Accessed: 27-Apr-2022].

[3] C. H. Tator, “Concussions and their consequences: Current diagnosis, management and prevention,” *CMAJ : Canadian Medical Association journal = journal de l'Association medicale canadienne*, 06-Aug-2013. [Online]. Available: https://www.ncbi.nlm.nih.gov/pmc/articles/PMC3735746/. [Accessed: 27-Apr-2022].

[4] Nfl, “Watch: NFL explained: Innovation in Player Health and Safety,” *NFL.com*, 27-Jan-2022. [Online]. Available: https://www.nfl.com/playerhealthandsafety/equipment-and-innovation/engineering-technology/nflexplainedinnovation?campaign=sp-tu-lp-bm-gg-2000058. [Accessed: 27-Apr-2022].

[5] “Health & Safety Rules Changes,” *NFL Football Operations*. [Online]. Available: https://operations.nfl.com/the-rules/rules-changes/health-safety-rules-changes/. [Accessed: 27-Apr-2022].

[6] Nfl, “Injury data since 2015,” *NFL.com*, 07-Feb-2022. [Online]. Available: https://www.nfl.com/playerhealthandsafety/health-and-wellness/injury-data/injury-data. [Accessed: 27-Apr-2022].

[7] “IP ratings explained: IP Rating Chart,” *Rainford Solutions*, 02-Nov-2021. [Online]. Available: https://rainfordsolutions.com/products/ingress-protection-ip-rated-enclosures/ip-

enclosure-ratings-standards-explained/. [Accessed: 27-Apr-2022].

[8] "ECFR :: 47 CFR part 15 -- Radio Frequency Devices." [Online]. Available: https://www.ecfr.gov/current/title-47/chapter-I/subchapter-A/part-15. [Accessed: 28-Apr-2022].

[9] "UPMC Sports Medicine Concussion Program: Pittsburgh & Cranberry, PA," *UPMC Sports Medicine*. [Online]. Available: https://www.upmc.com/services/sports-medicine/services/concussion. [Accessed: 27-Apr-2022].

[10] "History," *American Whistle Co*. [Online]. Available: https://www.americanwhistle.com/history. [Accessed: 27-Apr-2022].

[11] "Oticon hearing experts sound off about how cold, helmets, stadium design and more can impact hearing on Game Day," *AudiologyOnline*, 27-Jan-2014. [Online]. Available: https://www.audiologyonline.com/releases/oticon-hearing-experts-sound-off-12448. [Accessed: 27-Apr-2022].

[12] Jeff Blair | @SNJeffBlair January 22, J. Blair, |, and Jeff Blair @SNJeffBlair January 22, "Insider knowledge: NFL coach-to-player communication," *Sportsnet.ca*, 22-Jan-2016. [Online]. Available: https://www.sportsnet.ca/football/nfl/insider-knowledge-nfl-coach-to-player-communication/. [Accessed: 27-Apr-2022].

[13] C. McFadden, "Wi-Fi: How It Works and its pros and cons," *Interesting Engineering*, 24-Jun-2021. [Online]. Available: https://interestingengineering.com/how-exactly-does-wi-fi-work. [Accessed: 27-Apr-2022].

[14] B. Mitchell, "What is the range of a typical wi-fi network?," *Lifewire*, 06-Nov-2020. [Online]. Available: https://www.lifewire.com/range-of-typical-wifi-network-816564. [Accessed: 27-Apr-2022].

[15] "DS keyfob transmitter evaluation kit user's guide." [Online]. Available:

https://linxtechnologies.com/wp/wp-content/uploads/eval-fff-hh-kf-ds.pdf. [Accessed: 28-Apr-2022].

[16] "DS series encoder/decoder module data guide." [Online]. Available: https://www.linxtechnologies.com/wp/wp-content/uploads/lical-edc-ds001.pdf. [Accessed: 28-Apr-2022].

[17] "Sports," *Ducksters*. [Online]. Available: https://www.ducksters.com/sports/football/field_dimensions.php. [Accessed: 27-Apr-2022].

[18] "LR series receiver module data guide - linxtechnologies.com." [Online]. Available: http://www.linxtechnologies.com/wp/wp-content/uploads/rxm-fff-lr.pdf. [Accessed: 28-Apr-2022].

[19] "1430 Windsor Electronic Whistle," *Official Sports International*. [Online]. Available: https://officialsports.com/1430-windsor-electronic-whistle/. [Accessed: 27-Apr-2022].

[20] "LC Series Transmitter Module Data Guide - LINX Technologies." [Online]. Available: https://www.linxtechnologies.com/wp/wp-content/uploads/txm-fff-lc.pdf. [Accessed: 28-Apr-2022].

[21] "LR series Transmitter module data guide - linx technologies." [Online]. Available: https://www.linxtechnologies.com/wp/wp-content/uploads/txm-fff-lr.pdf. [Accessed: 28-Apr-2022].

[22] "Ant-433-HESM Data sheet by - LINX technologies." [Online]. Available: https://linxtechnologies.com/wp/wp-content/uploads/ant-433-hesm.pdf. [Accessed: 28-Apr-2022].

[23] "Drawn IE330403-1 - dbunlimitedco.com." [Online]. Available: https://www.dbunlimitedco.com/images/product_images/2D-Drawings/IE330403-1.pdf.

[Accessed: 28-Apr-2022].

[24] L. Banks, Au.D, and M. Lockington, “Are your ears ready for some football?,” *Clear Living*, 02-Nov-2020. [Online]. Available: https://www.clearliving.com/hearing/hearing-loss/playingfootball/#:text=Football%20stadiums%20can%20average%20between,very%20dangerous%20for%20your%20hearing. [Accessed: 27-Apr-2022].

[25] D. W. Lora Kolodny, “Super Bowl Players' custom helmets start with a 3D scan,” *CNBC*, 04-Feb-2018. [Online]. Available: https://www.cnbc.com/2018/02/04/super-bowl-players-custom-helmets-start-with-a-3d-scan.html#:~:text=The%20idea%20of%20custom%2Dfit,each%20for%20back%2Dup%20helmet. [Accessed: 27-Apr-2022].

APPENDIX

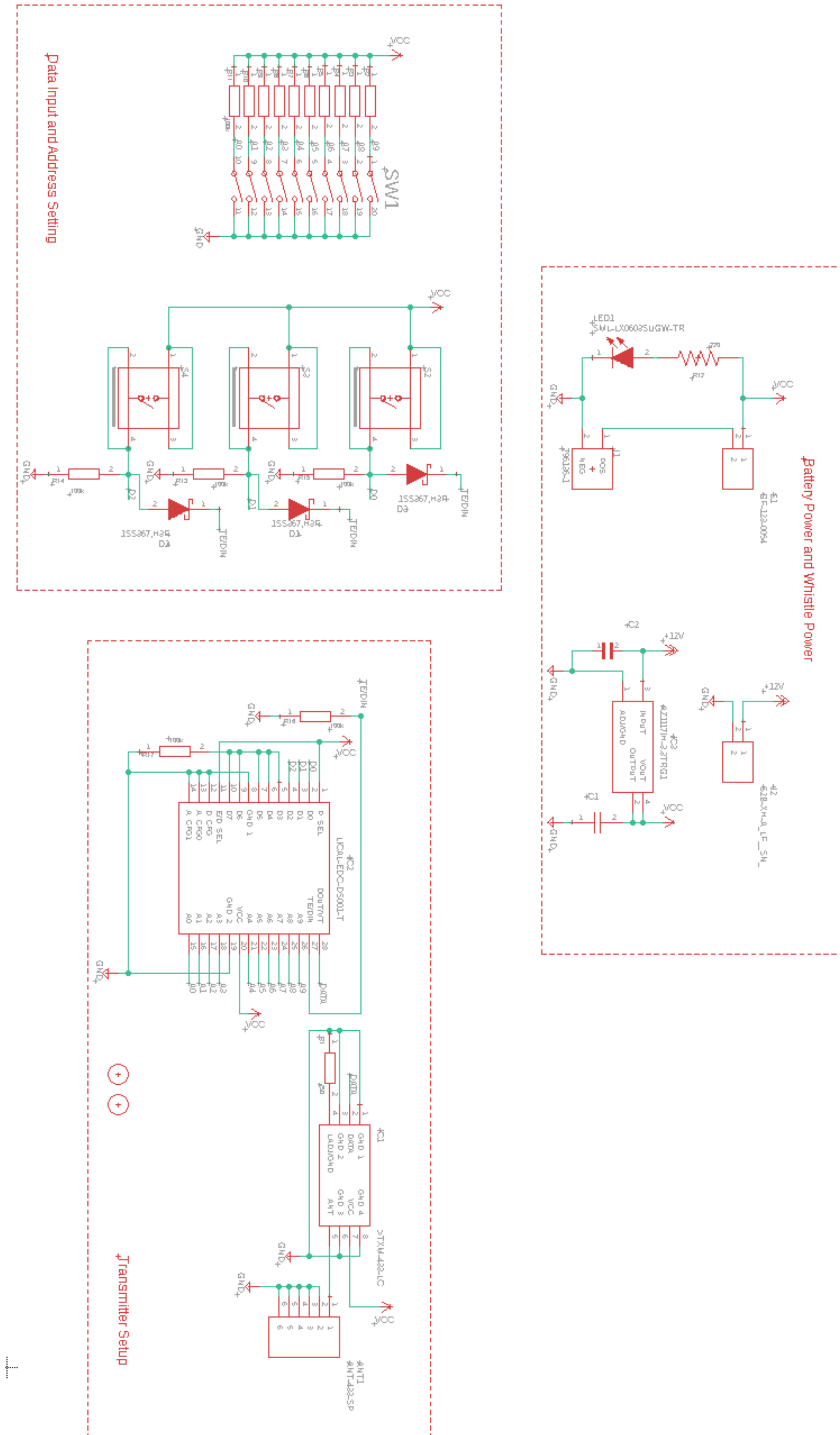

Figure 43: Transmitter 1.0 Schematic

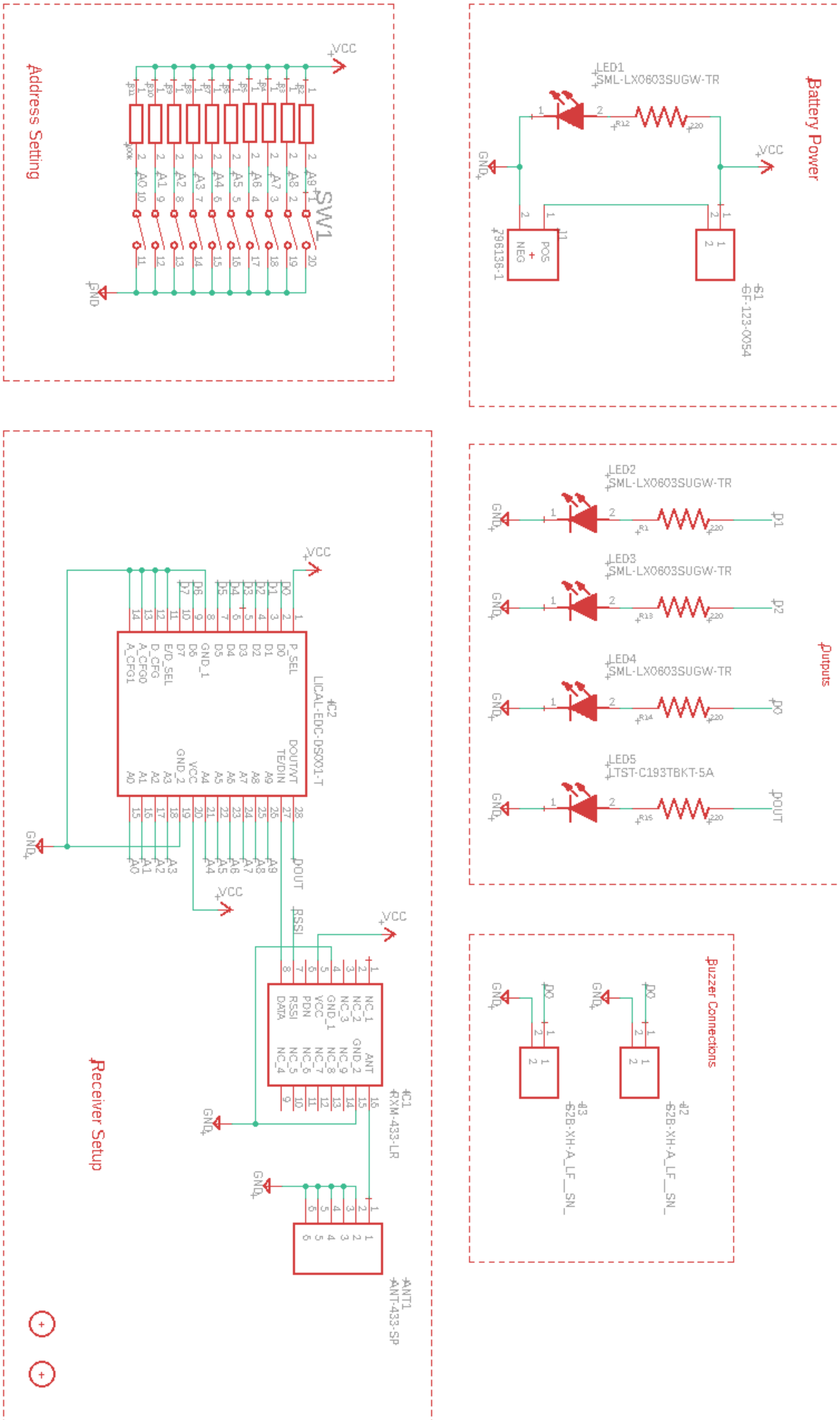

Figure 44: Receiver 1.0 Schematic

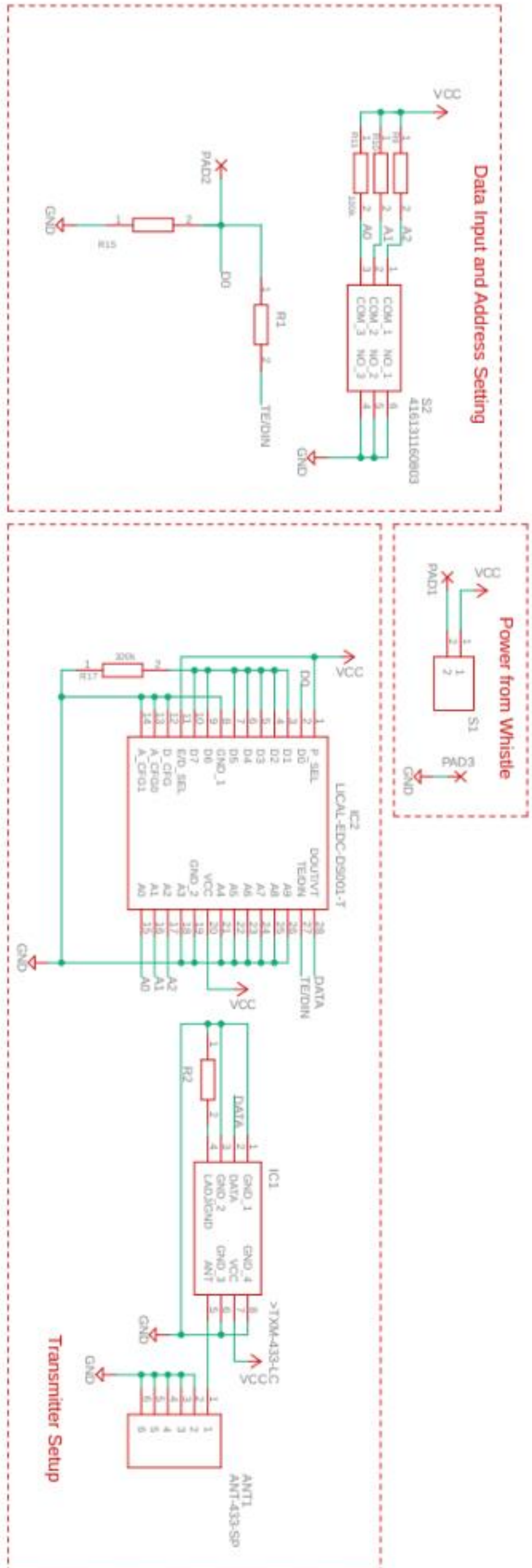

Figure 45: Transmitter 2.0 Schematic

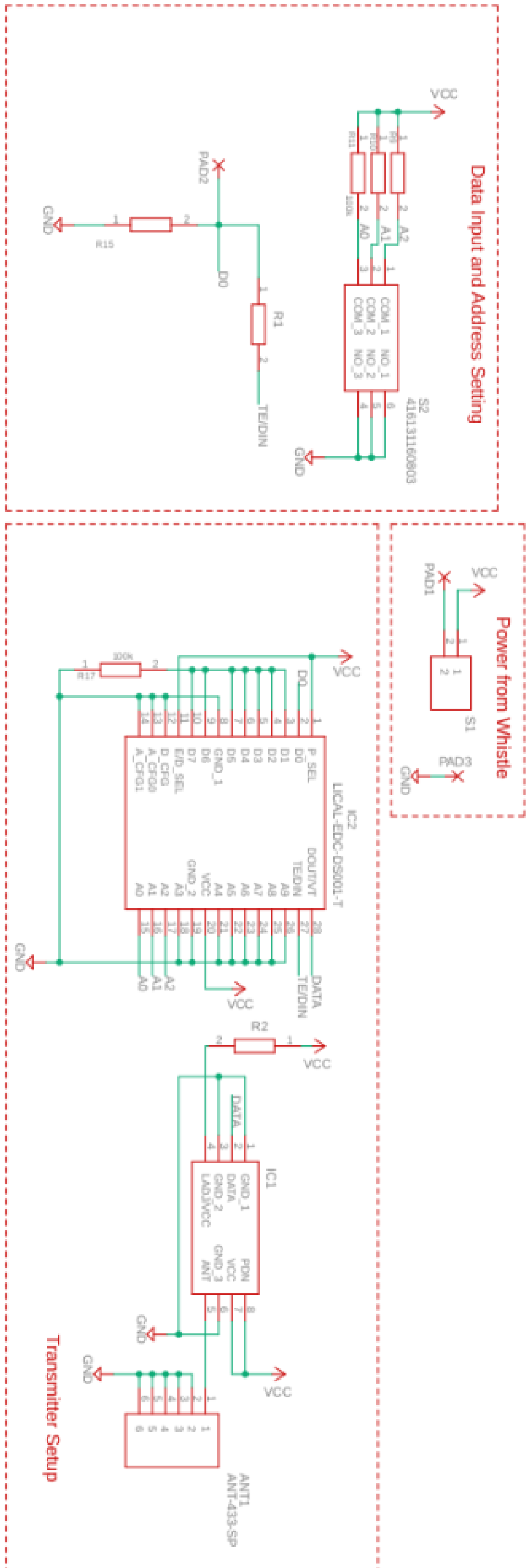

Figure 46: Transmitter 2.1 Schematic

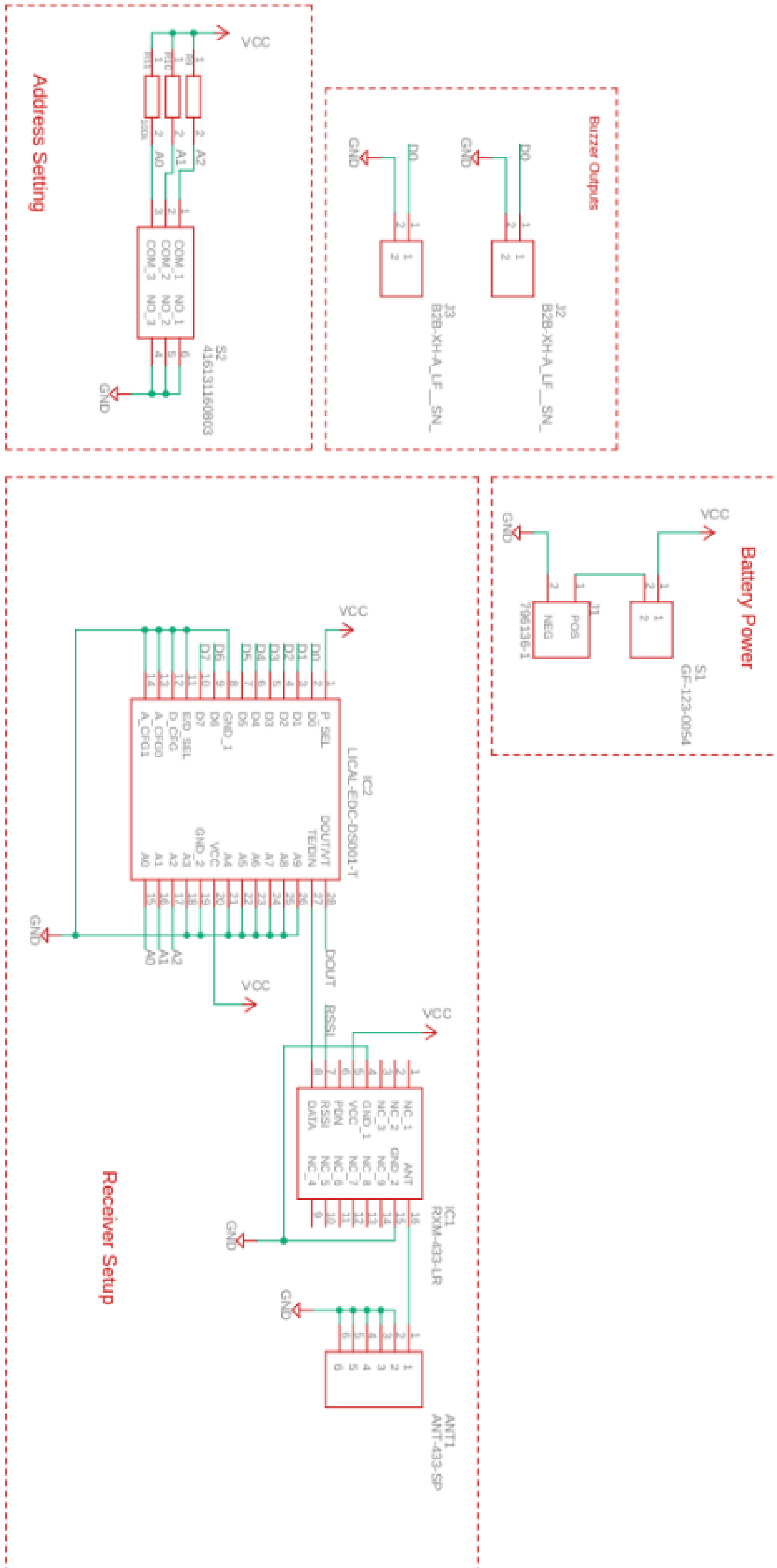

Figure 47: Receiver 2.0 Schematic

Electronic Whistle Transmitter and Receiver REV 1

Designator	QTY	Place	Description	Value	Tolerence	Footprint	Mfr.	Mfr.	Unit Price / 100	Unit Price /	Price	URL	Sub	Comment
Transmitter 1.0														
Resistors														
R2, R3, R4, R5, R6, R7, R8, R9, R10, R11, R13, R14, R15, R16,	15		RES SMD 100K OHM 1% 1/4W 0603	100k, 1/4W	1%	0603 (1608 Metric)	ERJ-PA3F1003V	Panasonic Electronic Components	$0.16	$0.14	$2.40	https://www.digikey.com/en/products/detail/panasonic-electronic-co	com/cdbs/www-data/pdf/RI	
R12	1		RES SMD 220 OHM 5% 0.3W 0603	220	5%	0603 (1608 Metric)	SDR03EZPJ221	Rohm Semiconductor	$0.08	$0.08	$0.08	/products/detail/rohm-semiconduct	ts/databook/datasheet/passi	
R1	1		RES SMD 750 OHM 1% 1/4W 0603	750 1/4W	1%		ERJ-PA3F7500V	Panasonic Electronic Components	$0.14	$0.14	$0.14	https://www.digikey.com/en/produ	com/cdbs/www-data/pdf/RI	
Capacitors														
C1	1		CAP CER 22UF 6.3V X5R 0603	22uF	10%		CL10A226KQ8NRNE	Samsung Electro-Mechanics	$0.35	$0.35	$0.35	cts/detail/samsung-electro-mechani	Sheets/Samsung%20PDFs/	
C2	1		CAP CER 10UF 25V X5R 0603	10uF	10%		GRM188R61E106KA73D	Murata Electronics	$0.23	$0.22	$0.23	https://www.digikey.com/en/produ	image/img/A01X/G101/EN	
Diodes														
D1, D2, D3	3		DIODE SCHOTTKY 10V 100MA SC76				1SS367,H3F	Toshiba Semiconductor and Storage	$0.17	$0.17	$0.51	https://www.digikey.com/en/produ	n/Downloads/1SS367_data	
LED1	1		LED GREEN DIFFUSED SMD	2V		0603 (1608 Metric)	SML-LX0603SUGW-TR	Lumex Opto/Components Inc.	$0.58	$0.38	$0.58	https://www.digikey.com/en/produ	heets/Lumex%20PDFs/SML	
ICs														
IC3	1		IC REG LINEAR 3.3V 1A SOT223				AZ1117IH-3.3TRG1	Diodes Incorporated	$0.32	$0.32	$0.32	products/detail/diodes-incorporated/	diodes.com/assets/Datasheet	
IC1	1		RF TX IC ASK/OOK 433MHZ 8SMD MOD			16-SMD Module	TXM-433-LC	Linx Technologies Inc.	$13.22	$12.21	$13.22	https://www.digikey.com/en/produ	gies.com/wp/wp-content/up	
IC2	1		IC REMOTE ENCODE/DECODE 28SSOP			28-SSOP (0.209", 5.30mm Width)	LICAL-ENC-MS001ENC/DEC	Linx Technologies Inc.	$4.98	$4.60	$4.98	https://www.digikey.com/en/produ	s.com/wp/wp-content/uploa	
Connectors														
J1	1		BATT HOLDER COIN 20MM 1 CELL SMD				796136-1	TE Connectivity AMP Connectors	$2.81	$2.37	$2.81	-connectivity-amp-connectors/79613	ECController?Action=srchrt	
J2	1		CONN HEADER R/A 2POS 2.5MM				S2B-XH-A_LF__SN_	JST Sales America Inc.	$0.18	$0.16	$0.18	https://www.digikey.com/en/produ	.jst-mfg.com/product/pdf/e	
Others														
ANT1	1		RF ANT 433MHZ CHIP SOLDER SMD				ANT-433-SP	Linx Technologies Inc.	$3.04	$2.85	$3.04	en/products/detail/linx-technologies-	gies.com/wp/wp-content/up	
S1	1		SWITCH SLIDE SPST 8.5A 125V	8.5A, 125V			GF-123-0054	CW Industries	$1.29	$1.23	$1.29	https://www.digikey.com/en/produ	https://media.digikey.com	
S2, S3, S4	3		Tactile Switch SPST-NO Top Actuated Surface Mount				TS07-667-37-BK-260-SMT-TR	CUI Devices	$0.23	$0.23	$0.69	https://www.digikey.com/en/produ	https://www.cuidevices.c	
SW1	1		SWITCH SLIDE DIP SPST 100MA 24V	100mA, 24V			1825057-9	TE Connectivity ALCOSWITCH Switches	$1.83	$1.77	$1.83	https://www.digikey.com/en/produ	https://www.te.com/com	
Receiver 1.0														
Resistors														
R2, R3, R4, R5, R6, R7, R8, R9,	10	P	RES SMD 100K OHM 1% 1/4W 0603	100k, 1/4W	1%	0603 (1608 Metric)	ERJ-PA3F1003V	Panasonic Electronic Components	$0.16	$0.14	$1.41	ponents/ERJ-PA3F1003V/5035850?	com/cdbs/www-data/pdf/RI	
R1, R12, R13, R14, R15	5	P	RES SMD 220 OHM 5% 0.3W 0603	220, 0.3W	5%	0603 (1608 Metric)	SDR03EZPJ221	Rohm Semiconductor	$0.10	$0.08	$0.50	r/SDR03EZPJ221/9675002?s=N4I	ts/databook/datasheet/passi	
Diodes														
LED5	1	P	LED BLUE CLEAR CHIP SMD	2.8V		0603 (1608 Metric)	LTST-C193TBKT-5A	Lite-On Inc.	$0.30	$0.23	$0.30	C193TBKT-5A/2053656?s=N4IgTC	ata%20Sheets/Lite-On%20	
LED1, LED2, LED3, LED4	4	P	LED GREEN DIFFUSED SMD	2V		0603 (1608 Metric)	SML-LX0603SUGW-TR	Lumex Opto/Components Inc.	$0.58	$0.38	$2.32	SML-LX0603SUGW-TR/467541?s=	heets/Lumex%20PDFs/SML	
ICs														
IC2	1	P	IC REMOTE ENCODE/DECODE 28SSOP			28-SSOP (0.209", 5.30mm Width)	LICAL-EDC-DS001-T	Linx Technologies Inc.	$4.98	$4.60	$4.98	CAL-EDC-DS001-T/4425833?s=N4I	s.com/wp/wp-content/uploa	
IC1	1	P	RF RECEIVER ASK/OOK 433MHZ			16-SMD Module	RXM-433-LR	Linx Technologies Inc.	$16.85	$15.55	$16.85	nologies-inc/RXM-433-LR/613947?	gies.com/wp/wp-content/up	
Connectors														
J1	1		BATT HOLDER COIN 20MM 1 CELL SMD				796136-1	TE Connectivity AMP Connectors	$2.81	$2.37	$2.81	tivity-amp-connectors/796136-1/22	ECController?Action=srchrt	Possible DNP
J2, J3	2		CONN HEADER R/A 2POS 2.5MM				S2B-XH-A-1(LF)(SN)	JST Sales America Inc.	$0.18	$0.16	$0.36	S2B-XH-A-1-LF-SN/9961922?s=N4	.jst-mfg.com/product/pdf/e	
Others														
ANT1	1	P	RF ANT 433MHZ CHIP SOLDER SMD				ANT-433-SP	Linx Technologies Inc.	$3.04	$2.85	$3.04	en/products/detail/linx-technologies-	gies.com/wp/wp-content/up	
S1	1	P	SWITCH SLIDE SPST 8.5A 125V	8.5A, 125V			GF-123-0054	CW Industries	$1.29	$1.24	$1.29	es/GF-123-0054/4089770?s=N4IgT	%20Sheets/CW%20Industri	
SW1	1	P	SWITCH SLIDE DIP SPST 100MA 24V	100mA, 24V			1825057-9	TE Connectivity ALCOSWITCH Switches	1.83	$1.77	$1.83	-alcoswitch-switches/1825057-9/10	trv&DocNm=1308111-1_S	
PCB Artwork														
PART COUNT	62								$61.73	**TOTAL COST:**	$68.34			

Figure 48: Revision 1.0 BOM

Electronic Whistle Transmitter and Receiver REV 2

Designator	QTY	Place	Description	Value	Tolerence	Footprint	Mfr.	Mfr.	Unit Price	Unit Price / 100	Price	URL	Sub	Comment
Receiver 2.0														
Resistors														
R9, R10, R11	3		RES SMD 100K OHM 1% 1/4W 0603	100k, 1/4W	1%	0603 (1608 Metric)	ERJ-PA3F1003V	Panasonic Electronic Components	$0.16	$0.14	$0.48	https://www.digikey.com/e	nic.com/cdbs/www-data/pdf/RDO0	
ICs														
IC1	1	P	RF RECEIVER ASK/OOK 433MHZ			16-SMD Module	RXM-433-LR	Linx Technologies Inc.	$16.85	$15.55	$16.85	ogies-inc/RXM-433-LR/6139	nologies.com/wp/wp-content/upload	
IC2	1	P	IC REMOTE ENCODE/DECODE 28SSOP			28-SSOP (0.209", 5.30mm Width)	LICAL-EDC-DS001-T	Linx Technologies Inc.	$4.98	$4.60	$4.98	-EDC-DS001-T/4425833?s=	ogies.com/wp/wp-content/uploads/l	
Connectors														
J1	1		BATT HOLDER COIN 20MM 1 CELL SMD				796136-1	TE Connectivity AMP Connectors	$2.81	$2.37	$2.81	nectivity-amp-connectors/79	/DDEController?Action=srchrtrv&	
J2, J3	2		CONN HEADER VERT 2POS 2.5MM				B2B-XH-A(LF)(SN)	JST Sales America Inc.	$0.15	$0.09	$0.30	https://www.digikey.com/e	www.jst-mfg.com/product/pdf/eng/e	
Others														
ANT1	1		RF ANT 433MHZ CHIP SOLDER SMD				ANT-433-SP	Linx Technologies Inc.	$3.04	$2.85	$3.04	roducts/detail/linx-technolog	ologies.com/wp/wp-content/upload	
S1	1		SWITCH SLIDE SPST 8.5A 125V	8.5A, 125V			GF-123-0054	CW Industries	$1.29	$1.23	$1.29	https://www.digikey.com/e	https://media.digikey.com/pdf/Dat	
S2	1		SWITCH SLIDE DIP SPST 25MA 24V	25 mA, 24V			416131160803	Würth Elektronik	$3.31	$2.48	$3.31	https://www.digikey.com/e	https://www.we-online.com/katalo	
Transmitter 2.0														
Resistors														
R9, R10, R11, R15, R16, R17	6		RES SMD 100K OHM 1% 1/4W 0603	100k, 1/4W	1%	0603 (1608 Metric)	ERJ-PA3F1003V	Panasonic Electronic Components	$0.16	$0.14	$0.96	https://www.digikey.com/e	nic.com/cdbs/www-data/pdf/RDO0	
R1,R2	2		RCS0603 0R0 ET6 E3				RCS0603 0R0 ET6 E3	Vishay Dale	$0.11	$0.04	$0.22	roducts/detail/vishay-dale/R	://www.vishay.com/docs/20065/rcse	
ICs														
IC1	1		RF TX IC ASK/OOK 433MHZ 8SMD MOD			16-SMD Module	TXM-433-LC	Linx Technologies Inc.	$13.22	$12.21	$13.22	https://www.digikey.com/e	nologies.com/wp/wp-content/upload	
IC2	1		IC REMOTE ENCODE/DECODE 28SSOP			28-SSOP (0.209", 5.30mm Width)	LICAL-ENC-MS001ENC/DEC	Linx Technologies Inc.	$4.98	$4.60	$4.98	https://www.digikey.com/e	ogies.com/wp/wp-content/uploads/l	
Others														
ANT1	1		RF ANT 433MHZ CHIP SOLDER SMD				ANT-433-SP	Linx Technologies Inc.	$3.04	$2.85	$3.04	roducts/detail/linx-technolog	ologies.com/wp/wp-content/upload	
S1	1		SWITCH SLIDE SPST 8.5A 125V	8.5A, 125V			GF-123-0054	CW Industries	$1.29	$1.23	$1.29	https://www.digikey.com/e	https://media.digikey.com/pdf/Dat	
S2	1		SWITCH SLIDE DIP SPST 25MA 24V	25 mA, 24V			416131160803	Würth Elektronik	$3.31	$2.48	$3.31	https://www.digikey.com/e	https://www.we-online.com/katalo	
Transmitter 2.1														
Resistors														
R9, R10, R11, R15, R16, R17	6		RES SMD 100K OHM 1% 1/4W 0603	100k, 1/4W	1%	0603 (1608 Metric)	ERJ-PA3F1003V	Panasonic Electronic Components	$0.16	$0.14	$0.96	https://www.digikey.com/e	nic.com/cdbs/www-data/pdf/RDO0	
R1,R2	2		RCS0603 0R0 ET6 E3				RCS0603 0R0 ET6 E3	Vishay Dale	$0.11	$0.04	$0.22	roducts/detail/vishay-dale/R	://www.vishay.com/docs/20065/rcse	
ICs														
IC1	1		RF TX IC ASK/OOK 433MHZ 8SMD MOD			16-SMD Module	TXM-433-LR	Linx Technologies Inc.	$9.45	$8.72	$9.45	gies-inc/TXM-433-LR/6139	nologies.com/wp/wp-content/upload	
IC2	1		IC REMOTE ENCODE/DECODE 28SSOP			28-SSOP (0.209", 5.30mm Width)	LICAL-EDC-DS001-T	Linx Technologies Inc.	$4.98	$4.60	$4.98	https://www.digikey.com/e	ogies.com/wp/wp-content/uploads/l	
Others														
ANT1	1		RF ANT 433MHZ CHIP SOLDER SMD				ANT-433-SP	Linx Technologies Inc.	$3.04	$2.85	$3.04	roducts/detail/linx-technolog	ologies.com/wp/wp-content/upload	
S1	1		SWITCH SLIDE SPST 8.5A 125V	8.5A, 125V			GF-123-0054	CW Industries	$1.29	$1.23	$1.29	https://www.digikey.com/e	https://media.digikey.com/pdf/Dat	
S2	1		SWITCH SLIDE DIP SPST 25MA 24V	25 mA, 24V			416131160803	Würth Elektronik	$3.31	$2.48	$3.31	https://www.digikey.com/e	https://www.we-online.com/katalo	
PCB Artwork														
PART COUNT	37								$81.04	**TOTAL COST:**	$83.33			

Figure 49: Revision 2.0 BOM

Table 6: Engineering Design Considerations

Design Factor	Page number, or reason not applicable
Public health, safety, and welfare	16, 56
Global	N/A
Cultural/Social	16, 17, 71
Environmental	61
Economic	71
Professional Standards	51