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SIGNAL: SCUBA-Integrated Gear for Noiseless Audio and Lighting

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Visible light communication is a method of data transmission in which a light source is modulated to send a signal. This senior engineering design project employs an LED-based visible light communication system which facilitates underwater SCUBA-diver correspondence. This report explains the final design, the methods with which it was tested, and the results of those tests. Out of six total project objectives, three of them are fully met, two are partially met, and one fails. The design is successful in including a transmitter and receiver architecture, being battery powered with an operating life of at least one hour, and costing less than $800. It is partially successful in achieving the desired signal-to-noise ratio and demonstrating its use underwater. Unfortunately, the design is not successful in meeting the transmission distance requirement of four meters. If further work is to be completed on the project, the transmission distance and signal-to-noise ratio should be improved and the design made more suitable for commercial use.

Executive Summary

SCUBA divers, both recreational and professional, need an effective way to communicate underwater, but there are drawbacks to all of the existing methods. Hand signals can easily be misinterpreted, and devices that use ultrasonic waves can disturb the underwater environment. This project explores using visible light as the signal carrier instead of ultrasonic waves because it minimally disturbs the environment with a single beam of light instead of bouncing ultrasonic waves throughout the water. It also has virtually no harmful effects on the environment, and most divers already carry a light with them during a dive.

The prototype costs $464.46 to build, less expensive than current underwater communication systems, and consists of a transmitter unit, a receiver unit, a set of bone conduction headphones, and a microphone. These parts are all waterproof except for the microphone, which will be enclosed in the diver's full-face mask. The device uses an analog transmission scheme where the intensity of an array of four light-emitting diodes (LEDs) in the transmitter directly corresponds to the voice that the microphone captures. The photodiode in the receiver then picks up these changes in intensity, and the headphones play back the speaker's voice. The receiver is powered by a single 9 V battery, while the transmitter is powered by two 9 V batteries: one for the printed circuit board (PCB) and one for the microphone.

Since it is difficult to observe the circuit on a PCB with standard lab equipment due to its size, several signal tests are conducted with breadboard prototypes. According to the power consumption tests, if both the transmitter and receiver are powered by a single 9 V battery, the estimated battery life would be 2 hours and 43 minutes, which meets the 1 hour goal stated in the project charter. The project charter also states that the signal-to-noise ratio (SNR) of the headphone output must be at least 14 dB and operate at least 4 m apart. Depending on the lighting conditions, the SNR ratio varies considerably. The test results clearly show that the design cannot function at a distance of 4 m no matter what the lighting conditions. With respect to noise expected in an outdoor, underwater environment, the design achieves at least 14 dB up to a distance of around 0.61 m (2 ft) depending on the lighting conditions.

The frequency response shows that the circuit passes frequencies between 25 Hz and 7 kHz, which encompasses the entire range of human voice and rejects most of the other frequencies within human hearing. Since the design is only intended to transmit human voice, any frequencies outside of human speech are not necessary.

Outdoor and environmental testing with the breadboard prototype also shows that the design works in non-laboratory settings. The design works outside, provided the photodiode is not in direct sunlight. The sunlight's DC current saturates the photodiode, rendering it incapable of detecting changes in LED intensity. To ensure clarity of the system alone, soundproof rooms with clear doors are also used in tests to isolate the listener from the speaker. These qualitative tests indicate that the system transmits voice clearly on its own. As expected, water attenuates the signal more than air, and greater distances produce greater differences in attenuation.

The design described in this report can be improved in several ways. The design has not been properly tested on the PCB, and the transmitter and receiver should be condensed into a single unit powered by a single battery. More LEDs should also be used to improve SNR at a farther distance. All of the devices should also be waterproofed for common SCUBA diving depths. However, this design serves as a successful proof of concept for an underwater visible light communication system for SCUBA divers.

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1 Introduction

SIGNAL, SCUBA-Integrated Gear for Noiseless Audio and Lighting, is a senior engineering design team tasked with using visible light communication (VLC) to allow SCUBA divers to communicate underwater. VLC uses the entire visible light spectrum which includes wavelengths between 380 nm and 780 nm [1]. The use of radio waves is not feasible underwater because they attenuate too quickly [2]. According to a diving instructor at Dive World West, that is why most SCUBA divers currently use hand signals or a form of ultrasonic waves. However, hand signals are easy to forget and limit the content of what can be said. Ultrasonic waves can disrupt the wildlife and can even injure fish when used with sufficient intensity [3]. Communication systems don't use a strong enough intensity of ultrasonic waves to cause actual damage but sensitivity to sound does vary between fish species. The American Shad is able to detect ultrasonic wave frequencies up to 180 kHz and would therefore be able to detect frequencies used for underwater communication purposes [4]. Through the use of VLC, this project aims to create a system that will allow divers to communicate without the drawbacks of existing methods. Flashlights are common gear among SCUBA divers, so the use of light to communicate should not increase the disruption factor of the diver.

There are several constraints that dictate the structure of the project. The product must not endanger the safety of the user, particularly due to electric shock or impairment of equipment or diver mobility. It must conform to all standards for safety and waterproofing. The environmental impact must be considered to ensure the device is not toxic to underwater wildlife. No permanent damage may be caused to the ecosystem due to use of the product. Budgetary constraints require that the total expense of the project, including research, testing, and the final design, must not exceed $1,200. Experimental capabilities are constrained by the available testing environments. It is not possible to test the product at typical diving depths since proper diving equipment and facilities are not available. The final constraint requires that data transmission occurs through the use of an LED-type light source. This ensures that visible light communication designs are produced.

Initial assumptions state that all aspects of the project should be designed for use in clear water. It is also to be assumed that there is access to SCUBA equipment and testing areas. These are based upon the project description details initially presented to the team and were approved in the project charter. Due to the assumption that SCUBA equipment is accessible, a facemask is presumed to be available for a final design and is not included in the project cost. The final design should be integrated with SCUBA gear to ensure its functionality and prevent any possible safety issues such as movement impairment. The final design should also meet or exceed all SCUBA equipment standards.

2 Design Description

The following sections describe the main objectives that guided the design process and how the final design was achieved. An explanation is also provided of how the system is waterproofed and how parts are interfaced with one another. See Appendix A for a list of vendors whose products were purchased for the design, along with their contact information.

2.1 Design Objectives

The project is guided by several objectives which will dictate whether the project is considered successful. These are derived from comparisons to an existing commercial system [5]. First, a transmitter and receiver architecture must be included in the final design. This ensures that a voice signal can be both sent and received. A 14 dB signal-to-noise ratio must be maintained at the output to ensure intelligibility of the voice signal [6]. The final design should operate at a range of at least 4 m between the transmitter and receiver. There should be a demonstration of the transmitter and receiver operating underwater. The final design must be battery operated and have an operating life of at least one hour. Finally, the design should cost less than $800 dollars to ensure competitive rates with currently available SCUBA communication options [7], [8]. See Appendix B for a schedule and breakdown of all tasks that were completed as a part of the design process.

2.2 Digital Approach

A digital transmission archetype is first chosen because of its robustness against noise [9]. With digital transmission, the signal voice is sampled and digitized into bits, which are then transmitted via the LED that as a higher brightness ('1') or a lower brightness ('0'). The photodiode on the receiver detects these changes and then the receiver decodes the data into a reconstructed voice signal. Although the digital design archetype is possible, it is ultimately scrapped for this project because the purchased encoder/decoder combination could not reproduce a voice signal in real-time. In addition, purchasing a working encoder/decoder set is too expensive for the project (roughly $18/chip with a minimum purchase order of 760 units at Digikey, for example) and could not be received in time to pursue this architecture [10]. A more in-depth analysis of the digital alternative to this design is described in Appendix C.

2.3 *Packaging*

The final design consists of a transmitter and receiver placed on separate PCBs. See Appendix D for the layout of each PCB. Since one of the objectives of the project is to demonstrate the device functioning underwater, each PCB and battery source is encased in an OverBoard Waterproof Smart Phone Case. Not only are these cases waterproof up to 6 m, they also feature a waterproof connection between the external headphone jack input and the inside of the pouch. Figure 1 depicts the 4”x7” waterproof pouch.

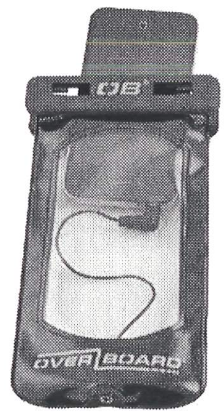

Figure 1. Waterproof case used to store PCB and battery [11].

These clear plastic cases allow the light to transmit through the water and also allow the receiver to detect the incoming light. These cases also allow for simple integration of the system into a diver’s SCUBA gear. A carabiner is included with each case, which can easily be hooked onto the diver’s buoyancy compensator vest. The small, portable cases would neither add significant weight to the existing gear nor impair the diver’s mobility.

2.4 *Transmitter*

Because a digital design could not be achieved, an analog archetype is chosen for transmission. The analog implementation is simpler in design than its digital counterpart, but does lose some of the integrity of the original signal. Figure E-1 shows the full transmitter circuit schematic. At the most basic level, the analog transmitter takes voice input from a microphone, filters out non-vocal frequencies to reduce extraneous noise, amplifies the voice signal, and then sends it to an LED driver network that sends the signal through the LEDs. The

LEDs then transmit the voice signal via visible light to the receiver end of the system. A block diagram summarizing the main stages of the final transmitter design can be seen in Figure 2.

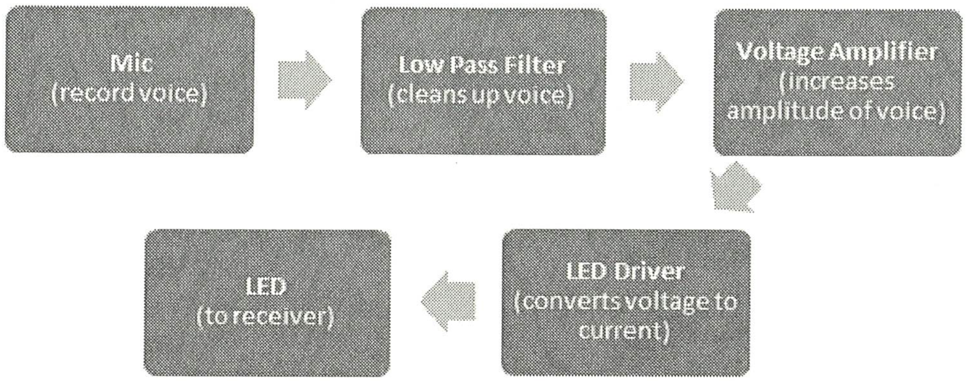

Figure 2. Simplified block diagram for analog transmission.

The microphone used in the transmitter is the RadioShack Electret Microphone Element with Leads [12]. This electret condenser microphone consists of a very light diaphragm, which acts as a moving plate, and a stationary back plate. When sound waves hit the diaphragm, the capacitance between the two plates changes synchronously and creates an AC voltage on the back plate [13]. Since this design assumes the use of a fully-enclosed facemask, the microphone is not submerged. To interface with the pouches, the microphone voltage output is fed through a male headphone jack, which can then be directly connected to the pouch. The outer surface of the pouch features a female headphone jack for input, which connects through to the inside waterproofed area, and ends in a male headphone jack output. To reconnect the voice signal to the system, a female headphone jack is placed on the transmitter that connects to the pouch's male jack component. Figure 3 shows the connections between the microphone and the submerged transmitter circuit.

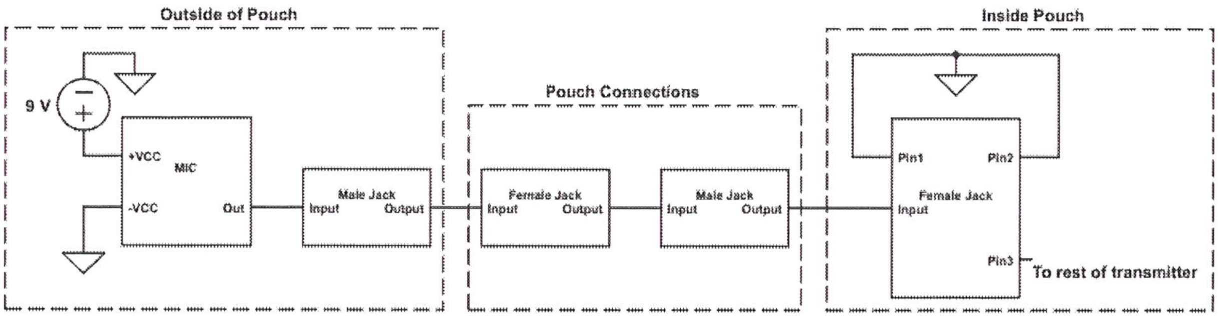

Figure 3. Interface between submerged and non-submerged components.

As seen in Figure 2, the microphone signal is sent to a lowpass filter. This filter is designed to only allow low frequencies through the circuit, while attenuating those above a certain cutoff frequency. The cutoff frequency is defined as the frequency at which the gain of the system falls 3 dB below the maximum. For the purpose of transmitting human voice, a cutoff frequency of 1.7 kHz is chosen because, while the major frequencies of human voice range from 300-3400 Hz [14], the most common frequencies for both male and female speech ranges from about 65-1280 Hz [15]. The lowpass filter consists of a resistor in series with the input and output voltage and a shunt capacitor that goes from the resistor to ground. The cutoff frequency is set by the resistor and capacitor values, as seen in Equation 1. The schematic of the lowpass filter can be seen in Figure 4.

$$f_c = \frac{1}{2\pi RC} \tag{1}$$

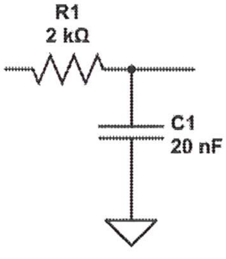

Figure 4. Lowpass filter with cutoff frequency of 1.7 kHz.

Following the lowpass filter, the signal's magnitude must be amplified before it is fed to the LED array. Since the output from the microphone is only about 125 mV peak-to-peak and the LEDs require a minimum 3 V input, the voltage amplifier circuit needs a gain of 24 V/V [16]. To accomplish this, an inverting operational amplifier (op amp) configuration is chosen for the voltage amplifier circuit, which can be seen in Figure 5 [17]. The op amp used in this circuit, as well as in the rest of the transmitter, is the Texas Instruments NE5532P dual op amp.

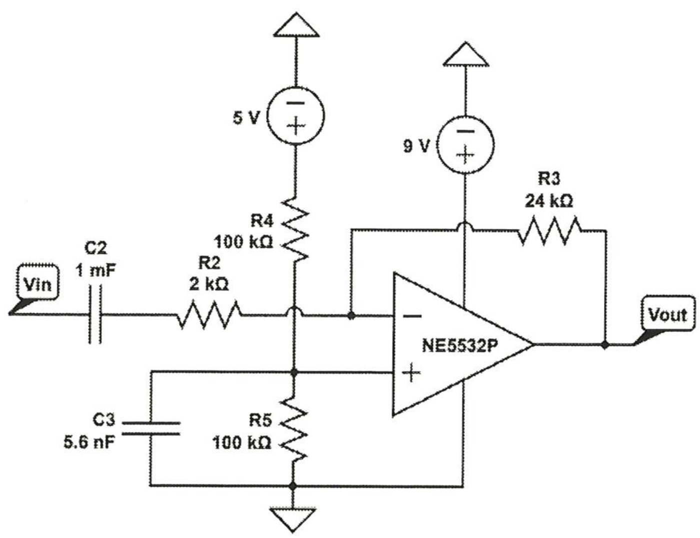

Figure 5. Transmitter voltage gain amplifier.

A coupling capacitor, C2, precedes the voltage amplifier in order to ensure that only the AC components of the signal pass through to the amplifier. This capacitor in series with R2 creates a highpass filter with a cutoff frequency of 0.08 Hz, given by Equation 1. The resistors chosen in the amplifier help to create the necessary gain. A DC offset is introduced at the positive terminal of the op amp to offset the output and avoid using a negative supply [17]. For an op amp in the inverting configuration, the gain is calculated using Equation 2, where R3 is the feedback resistor and R2 is the resistor feeding into the negative input terminal.

$$^{v_{out}}/_{v_{in}} = -\frac{R3}{R2} \qquad (2)$$

Lastly, the signal is fed through an LED driver network. The drivers convert the voltage into a proportional current flow through the array of LEDs. A coupling capacitor is placed before the drivers to ensure a zero DC offset entering the driver. A large resistance is added between the input signal and ground in order to improve clarity. A condensed LED driver circuit can be seen in Figure 6, where two of the four driver circuits are shown.

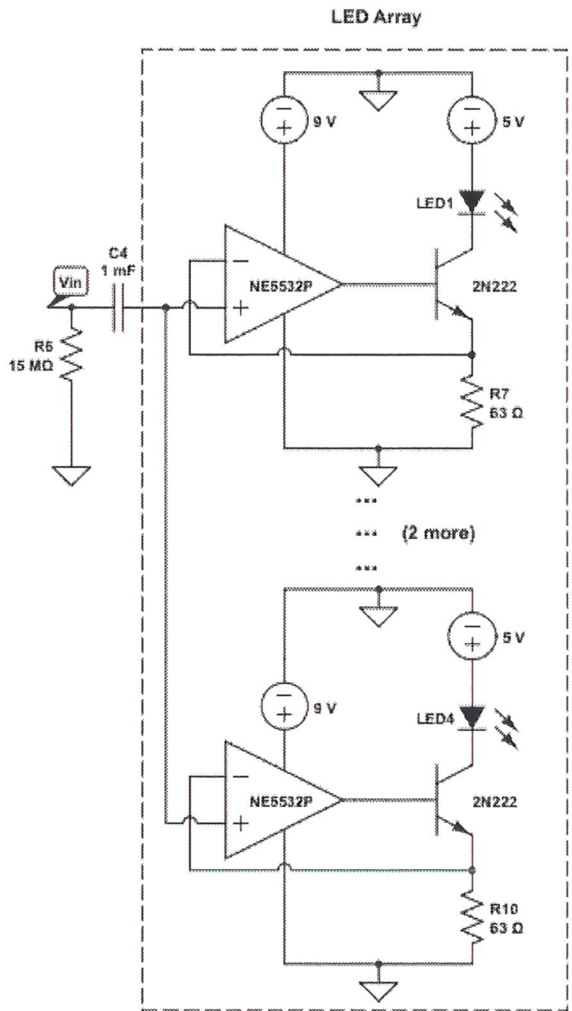

Figure 6. Driver circuit for 4-LED array.

The op amps in the circuit form a feedback loop between the input and the emitter of the bipolar junction transistor (BJT). This feedback drives the base of the BJT and ensures that the voltage at the emitter is equal to the input voltage [18]. The AC portion of the current flowing through the LED is given by Equation 3.

$$I = \frac{v_{in}}{R} \cdot \left(\frac{\beta}{\beta + 1}\right) \tag{3}$$

The light transmitting from the LEDs is directed towards the receiver, which then processes the signal back to audio. An array of 4 Cree XMLAWT-00-0000-0000T6053 white LEDs is chosen for optimal transmission. A smaller array of LEDs would not shine as brightly as 4 LEDs, resulting in a smaller transmission distance. However, too many LEDs would require more current than can be supplied, causing the brightness of each LED to decrease.

2.5 Receiver

The analog receiver works opposite the transmitter. Figure 7 shows the block diagram for the receiver. A full schematic is given in Appendix E.

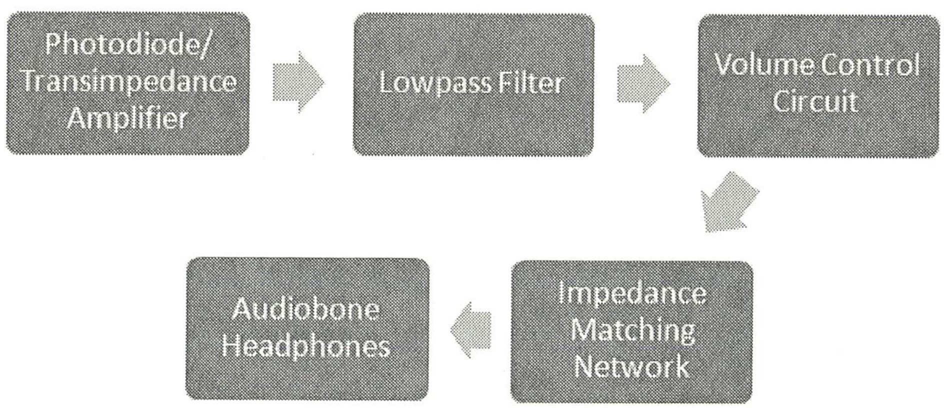

Figure 7. Block diagram for analog receiver.

The photodiode captures the light signal from the LEDs as a current signal, and the transimpedance amplifier converts that current back to a voltage signal. External noise can be introduced during transmission from ambient lighting or other environmental factors, so the signal must be filtered again. The signal is adjustably amplified to provide volume control for the user, and the impedance matching stage allows the system to play clearly through the headphones.

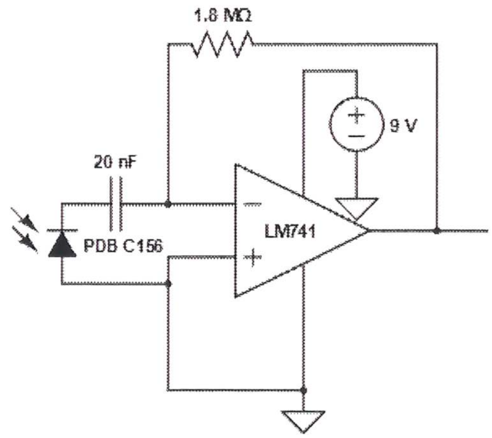

Figure 8. Photodiode and transimpedance amplifier setup for analog receiver.

The preceding figure gives the schematic for the photodiode and transimpedance amplifier circuit setup. The photodiode is a PDB C156, chosen for its sensitivity, response rate, and cost. A capacitor is placed in series with the photodiode to block the offset added to the amplifier by ambient light. The transimpedance amplifier converts the current signal from the photodiode to a voltage signal. This signal is sent through a simple RC lowpass filter to reduce the higher frequency noise added to the system (Figure 4).

Again, the resistor and capacitor values are chosen to create a cutoff frequency of 1.7 kHz for this filter. The remaining signal is amplified by the following stage, the schematic for which is given in Figure 9.

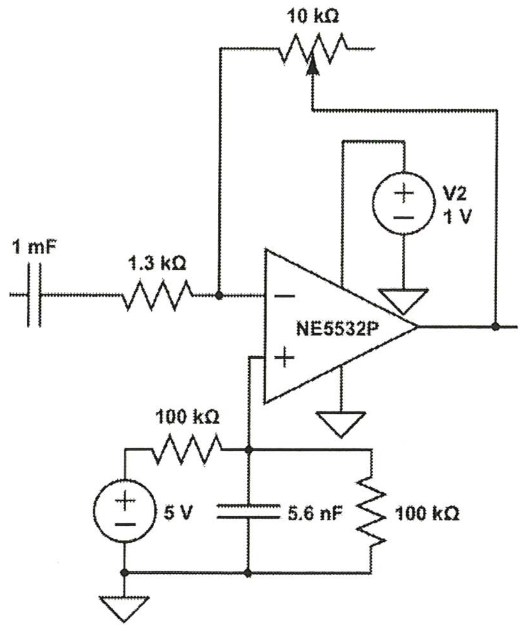

Figure 9. Volume control circuit for analog receiver.

This amplification stage features an adjustable gain, from approximately 0 V/V to 8.3 V/V. With this stage, the user can control the gain by sliding the potentiometer at the negative terminal to ensure the signal outputs at the correct volume for comfort and intelligibility. The components at the positive terminal introduce a 2.5 V DC offset to ensure the output voltage is always positive, thereby needing only one battery to supply power. In this case, the 5 V supply from the voltage regulator is used because it is a more stable voltage source than the battery itself.

The final stage before the signal can play through the headphones features a combination of a voltage-follower circuit and common-collector amplifier (Figure 10). The op amp voltage-follower helps to regulate the current sent to the common-collector stage. This impedance-matching stage creates the current required to power the headphones. Without this section, too little current would flow through the output to force sound through the headphones.

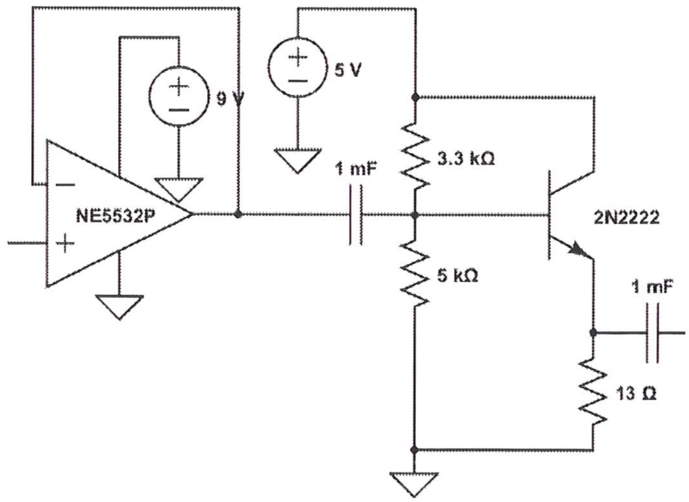

Figure 10. Impedance matching network for analog receiver.

The headphones used for the system are Audio Bone 30 mW headphones with an impedance of 8 Ω [19]. As such, they require 61 mA RMS of current to function optimally. The common collector stage allows for the design of exactly this amount of current to flow through to the headphones. These headphones are used instead of conventional headphones because the eardrum in the ear does not vibrate underwater. The Audio Bone headphones work by lightly vibrating the bones in the user's skull, near the temple, to transmit sound to the brain instead of the bones of the inner ear. These vibrations are too small to feel and cause no discomfort for the user.

3 Methods

A series of tests are conducted in order to quantitatively and qualitatively determine whether or not the final design met the design objectives. The following sections detail the methods of testing developed and executed during the testing phase of the project. Each test is performed with the transmitter and receiver set up on separate PP 272 breadboards.

3.1 Distance and Signal-to-Noise Ratio Testing

The range and clarity of the system is determined by its signal-to-noise ratio (SNR). This is the ratio of the voice signal amplitude (A_S) to the amplitude of other noise in the system (A_N), and is calculated using Equation 4 [20].

$$SNR = 20 * \log\left(\frac{A_S}{A_N}\right) \tag{4}$$

As stated previously, the system must achieve an SNR of at least 14 dB.

For this testing, the transmitter and receiver are placed up to 6 ft apart under varying lighting conditions. For these tests, the blinds are opened to allow sunlight into the room, and measurements are taken with the lights turned on and off. Then the blinds are closed, and the tests are repeated. All measurements are taken with the volume set to maximum and two transmitting LEDs.

With both the transmitter and receiver turned on, the amplitude of the noise immediately prior to the headphone jack is sampled and recorded using the oscilloscope. When the building lights are on, the amplitude of the noise due to the overhead lights is measured and recorded separately from the other noise. This is because the overhead lights create a much larger signal than other noise sources. Although the system is intended mainly for outdoor use, where fluorescent overhead lights are not present, measurements are taken with respect to these lights for the cases when the system may be used in an indoor pool, such as a SCUBA training pool. A sample measurement of this type is given in Figure F-1.

Once the noise amplitude is recorded, a constant tone is played into the microphone from an HTC Thunderbolt, and the signal amplitude is measured as in the noise measurement. Figure

F-2 is a screenshot of one of these measurements. The SNR is calculated from these amplitude measurements using Equation 4. For a more qualitative assessment, a group member listens through the headphones at each test distance while another group member speaks into the microphone.

3.2 Power Testing

A test of the power consumption is necessary in order to quantify the amount of battery life expected from the final design. Using the ammeter function on the FLUKE 45 Digital Multimeter (DMM), the current through each powered circuit component is measured and recorded. Once the total current consumption through the transmitter and receiver is determined, the battery life can be calculated. A typical 9 V Duracell battery has a capacity of 580 milliamp-hours (mAh) [21], meaning that it is able to provide 580 mA of current for one hour. To calculate the battery life of a full system equipped with both a transmitter and receiver powered by a single battery, the capacity must be divided by the total current consumption, as seen in Equation 5. This calculation verifies whether or not the design team was able to meet the one hour battery life project objective.

$$battery\ life\ [h] = \frac{capacity\ [mAh]}{current\ through\ system\ [mA]} \tag{5}$$

3.3 Overall Frequency Response Testing

Part of maximizing signal clarity is ensuring that only the relevant frequencies travel through the system. To test this behavior of the circuit, the microphone in the transmitter is temporarily disconnected on the breadboard transmitter prototype and a sinusoidal wave is fed through the system to the Audio Bone headphones on the breadboard receiver prototype. The receiver photodiode is roughly 2 ft away for this test, and the volume control gain in the receiver is set at maximum of roughly 8.3 V/V. Both the input and output peak-to-peak voltages are measured with an Agilent Technologies MSO-X 2012A oscilloscope with 5 tested frequencies per decade between 1 Hz and 50 kHz.

3.4 Environmental Testing

Several tests are conducted to evaluate the system's response to different environmental factors. The final breadboard design is first tested outside in different amounts of sunlight. The full system is taken outside to an unshaded region where one group member speaks into the microphone while the other listens through the Audio Bone headphones. Once this is completed, the test is repeated after the system is moved under a tree that provided moderate shade and in the shadow of a building that provided considerable shade.

The next test determines the effectiveness of transmission and the ability to transmit through a soundproof barrier. The final breadboard design is tested using the practice rooms in the Dicke-Smith music building. One member enters the practice room with the receiver portion and shuts the door. The lights are turned off inside the soundproof practice room and the receiver is placed on the ground approximately 6" from the glass of the practice room door. Another member sits in the lit hallway with the transmitter section. Due to the thick black border surrounding the glass in the practice room door, the receiver is approximately 6" from the door and lifted about 8" from the floor to ensure proper line of sight between the two components. Once the person inside the practice room closes their eyes and plugs their ears, necessary due to the nature of the Audio Bone headphones, the outside person asks three questions into the microphone. Each question is a yes or no question enabling the listener to shake or nod his head according to his answer. Once the three questions are asked, the listener is instructed to come out of the practice room and repeat what was heard to ensure intelligibility.

In order to test the system's ability to function through water, the transmitter and receiver breadboard systems are placed on opposite sides of a fish tank full of clear tap water. For the first stage, the tank is oriented so the breadboards are up against the glass 10" from each other, as seen in Figure 11a. The signal coming out of the microphone (input) and the signal entering the Audio Bone headphones (output) are monitored using an oscilloscope. Images of the two signals are captured with and without the overhead lights on. No sunlight is present during these tests. In order to obtain standardized results, a 440 Hz pitch is produced by an iPod and fed into the microphone. Qualitative readings are also taken by periodically listening to a voice signal through the headphones to ensure intelligibility at different distances. Once this portion is completed, the fish tank is turned long ways so the breadboards are 20" apart. Coverings are placed along the outside of the tank, leaving the ends with the breadboards and the top of the tank exposed, to ensure the light captured by the receiver indeed traveled through the water. This can be seen in Figure 11b. The same measurements are recorded for this portion. Finally, baseline measurements are taken at the two distances, with and without the lights, without the water tank present.

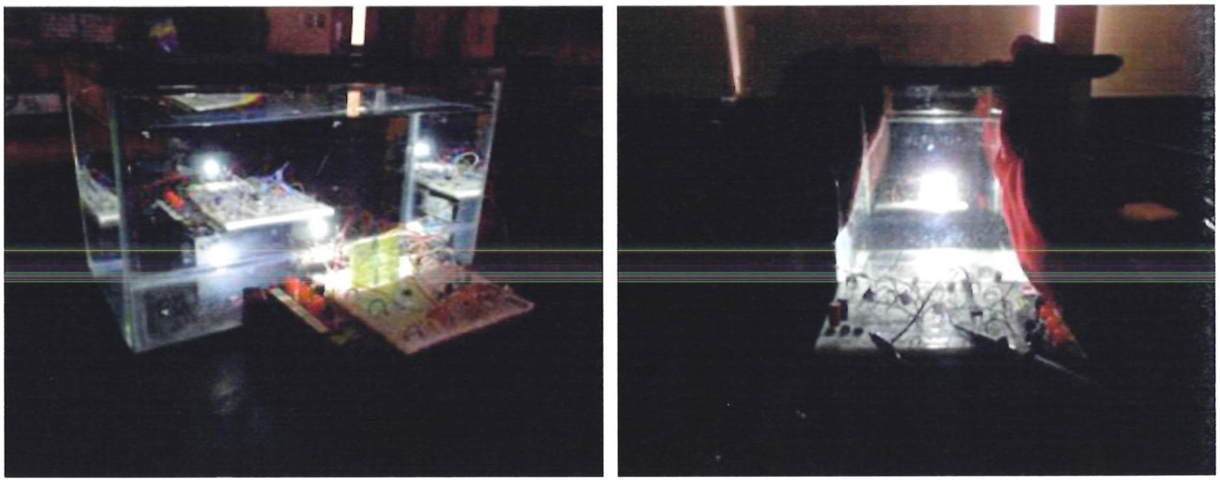

Figure 11. a) Left, underwater testing with 10" water distance. b) Right, underwater testing with 20" water distance and covering of walls.

4 Results

After all testing is concluded, the performance of the final design is evaluated. The results of the previously mentioned tests are compiled and explained in the following sections.

4.1 Distance and Signal-to-Noise Ratio Testing

Table 1 lists the calculated SNR values for all testing conditions. The SNR is expressed in decibels (dB) with respect to the overhead lights (when present) and all other extraneous noise. Blank cells appear where the noise amplitude was unobservable or where accuracy of the test could not otherwise be guaranteed.

Table 1. Results for distance and SNR testing.

		Lights On				Lights Off	
		Blinds Open		Blinds Closed		Blinds Open	Blinds Closed
Distance		SNR		SNR	SNR		
(m)	(ft)	(Lights)	SNR (Other)	(Lights)	(Other)	SNR (Other)	SNR (Other)
0.15	0.5	9.45	30.31	5.86	24.35	22.62	20.57
0.30	1.0	9.71	25.18	5.11	*	24.61	29.25
0.45	1.5	2.89	21.22	4.48	27.36	22.32	24.54
0.60	2.0	-3.40	16.78	-3.17	19.65	16.22	24.03
0.76	2.5	-4.03	11.70	-5.74	16.69	12.59	20.17
0.91	3.0	-7.62	10.50	-9.69	13.06	8.29	13.77
1.37	4.5	-12.04	1.40	-18.84	5.33	3.22	7.07
1.82	6.0						6.02

* Unobservable noise level

From the table it is clear that the overhead lights quickly overpower the voice signal and make it difficult to understand the speaker. However, the system would be used more often outdoors, where this will not be an issue.

Sunlight tends to reduce the SNR value. As the ambient light grows brighter, it is more difficult to separate the LED signal from the ambient light. For this reason, the largest SNR values tend to be achieved under the dimmest lighting conditions.

Increasing the distance between the transmitter and receiver also tends to decrease the SNR value. The further the signal must travel, the more it attenuates. This trend can be observed in Figure F-3 through Figure F-5. According to Table 1, clarity begins to be lost between 2 ft and 2.5 ft (0.6 m - 0.76 m). At this point, the SNR values start to drop below 14 dB. Qualitatively, the voice reduces in volume as the transmitter and receiver are moved further apart, becoming rather quiet at a distance of 3 ft. At 4.5 ft, the speaker can be understood, with some strain, only at the lowest lighting level, with intermittent clarity as the blinds are opened. The signal is completely unintelligible with the overhead lights on at this distance. At a distance of 6 ft (1.82 m), the speaker can no longer be understood even at the dimmest lighting level.

4.2 Power Testing

Table 2 and Table 3 show the current measured through each powered circuit component in the transmitter and receiver, respectively. The final measurement of the 9 V source from the breadboard represents the overall current flow through each system. Each measurement contains a reference to the measurement location, shown in Figures E-1 and E-2. Not shown in the figures are the 9 V supplies from the breadboard and the 5 V regulators. Additionally, since the NE5532P components are dual op amps, only one measurement is required at the positive supply terminal for each pair of op amps in the figures.

Table 2. Current drawn through transmitter.

Location of Measurement	Schematic Reference	Current (mA)
5 V source into microphone	A	0.0275
9 V source into voltage gain op amp	B	4.194
5 V source into voltage gain op amp	C	0.025
9 V source into top LED driver op amp	D	8.805
9 V source into bottom LED driver op amp	E	28.621
9 V source into 5V regulator	N/A	44
5 V source leaving 5V regulator	N/A	40
5 V source into LED1	F	9.164
5 V source into LED2	G	8.646
5 V source into LED3	H	12.4 – 20
5 V source into LED4	I	11.2 – 21
9 V source from breadboard	N/A	95

Table 3. Current drawn through receiver.

Location of Measurement	Schematic Reference	Current (mA)
9 V source into transimpedance amplifier	A	0.743
9 V source into volume control amplifier	B	8.359
5 V source into volume control amplifier	C	0.000
9 V source into 5 V regulator	N/A	108
5 V source leaving 5 V regulator	N/A	102
5 V source into common collector	D	91
9 V source from breadboard	N/A	118

This breakdown indicates which components contribute most to draining the battery power. In the transmitter, the largest current flow occurs through the op amp supplying the bottom 2 LEDs of the array, consuming 30% of the overall transmitter current. The common collector draws the most current in the receiver, accounting for over 75% of the total receiver current.

Based on the combined current flow through both the transmitter and receiver and using Equation 5, the battery life for the system is determined. If both the transmitter and receiver are powered by a single 9 V battery, it would have a minimum expected battery life of 2 hours and 43 minutes. This exceeds the 1 hour battery life project objective, and provides the typical recreational diver with more than enough time to complete a dive while having the capability to talk and listen to surrounding divers.

4.3 Overall Frequency Response Testing

The results of the frequency response testing are plotted in Figure 12. The plot shows that the system behaves as expected and rejects frequencies lower than 25 Hz and above 7 kHz (the corner frequencies are defined as the frequencies with a gain of 16 dB, 3 dB below the midband gain of around 19 dB). Since this communication system is an analog design, this means that frequencies between 25 Hz and 7 kHz will be clearly audible. Although humans can typically hear frequencies between 20 Hz and 20 kHz, the underwater communication system does not need to accept all audible frequencies [22]. The goal of the project is to facilitate human communication, so only the common frequencies of human speech need to be in the passband. The test results show that the passband encompasses the typical range of human speech—65 Hz to 1280 Hz—and thus the design can accurately transmit human speech [15].

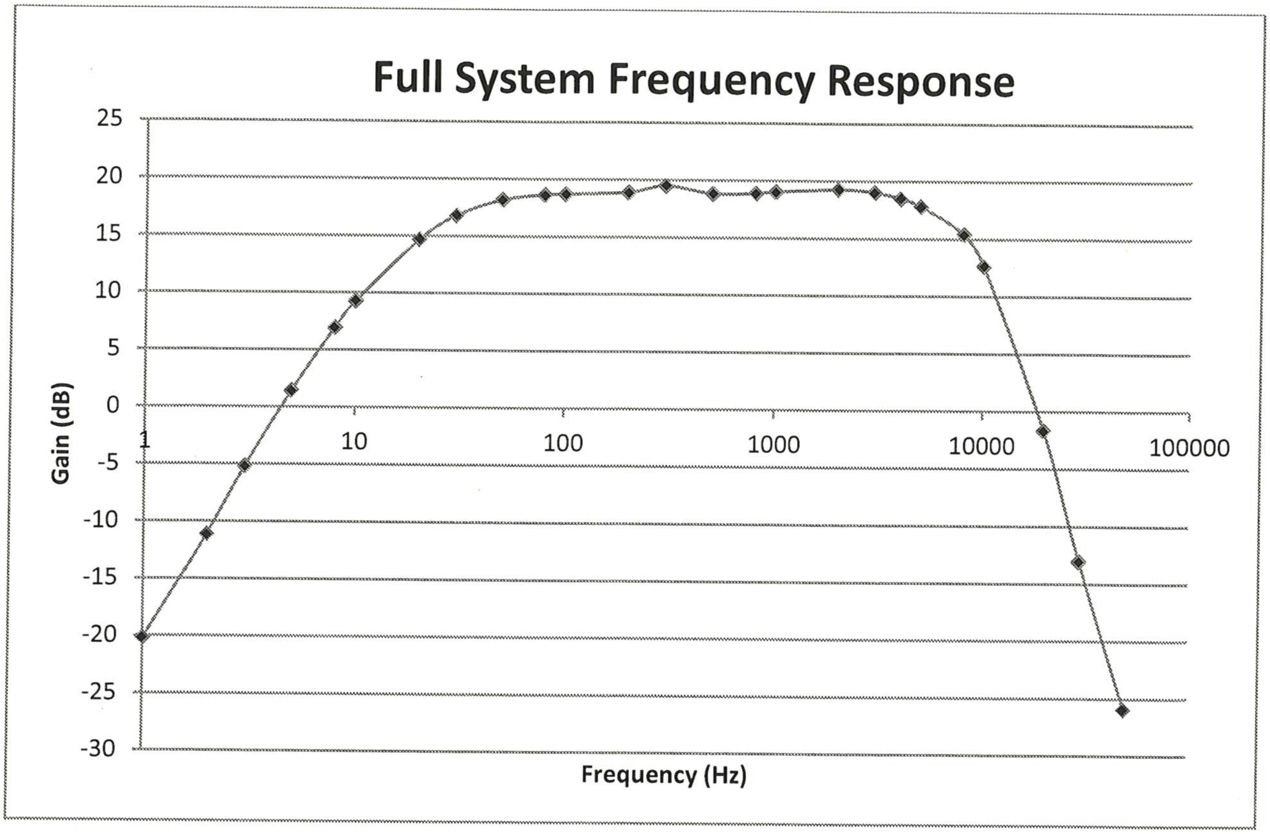

Figure 12. Full system frequency response.

4.4 Environmental Testing

The outdoor testing yields interesting but not unexpected results. While no quantitative data is collected due to the inability to br ing necessary lab equipment outside, qualitative measurements are obtained by listening through the Audio Bone headphones. Loud screeching noises occur in both the direct and mildly shaded conditions. This is most likely due to the combination of instability from the battery voltage supply and additional noise from the environment. When the breadboards are in the shadow of the building, there is still some screeching but it is manageable to an extent that words can still be understood over the disturbance. The amount of screeching is minimized by placing a 1 mF capacitor between the positive and negative battery terminals, stabilizing the voltage supply.

The practice room testing is conducted four times. On each occasion all questions were answered correctly and the listeners were able to properly relay what was said to them. This proves that glass does not significantly affect the light during transmission. It also proves that the signal is being completely transmitted and the listener is only hearing the transmitted voice, not a combination of the transmission and the original voice from the speaker.

The testing with the fish tank yields the results in Table 4. For both lights on and off, there is a larger gain without the tank of water than with in all cases except for lights off at 20”. This is most likely due to the need to re-measure this sample on a different occasion since the first measurement reading clearly had even more significant error with an output of only 77 mV and an input of 42 mV. Unfortunately, the system is extremely sensitive to light and any slight change in the environment could have caused the difference seen in the measurement ratio. However, in the other three cases, the decrease in gain while using the tank of water suggests the light doesn’t transmit as well through the water. There is only a 16 dB decrease with the tank at 10 inches, but there is a 32 dB decrease when the tank of water is used at the 20 inch distance. The effects of the glass can’t be correctly accounted for since the system is tested using a fish tank instead of being directly placed in the water. Reflection occurs at each medium change, such as the air to the glass and then to the water [23]. While this shouldn’t cause significant disturbance, the combination of all the reflections in the system may cause slight variance from true underwater conditions. However, ignoring reflections leads to the conclusion that the measured functional distance of the design above water will most likely be decreased upon a full underwater demonstration. There is also no significant difference between the ratios when looking at the situation with and without the use of coverings. This suggests that not a significant amount of the light signal was escaping from the fish tank.

Table 4. Water transmission testing.

	Peak-to-Peak Amplitude (mV)			
	Input		**Output**	
Distance	**Lights On**	**Lights Off**	**Lights On**	**Lights Off**
10” without tank	43	51	940	940
10” with tank	39	42	607	442
20” without tank	11	38	651	620
20” with tank, jacket	29	23	611	474
20” with tank, no jacket	37	27	635	482

5 Conclusions and Recommendations

The successfulness of the project is determined by the ability to fulfill the project objectives stated in the project charter. Both the PCB and breadboard design versions include an independent transmitter and receiver architecture, fulfilling the design requirement. The requirements to maintain a SNR of 14 dB and transmit over a distance of at least 4 m are interconnected. The 14 dB requirement is met up to 0.61-0.76 m when looking at the SNR which includes noise from outside sources such as the Trinity radio station, battery instability, and computer monitors. Therefore, the system only transmits clearly at a distance of less than 1 m. While the speaker can still be understood even at a distance of 1.1 m, the 14 dB standard is not maintained. However, all intelligibility is lost by 1.8 m so the distance requirement of at least 4 m is not achieved. Although the PCB system was not able to be tested underwater, the testing with the fish tank proves that the system can transmit through water. Therefore, this objective is partially met since the system can transmit through a water medium but could not be tested underwater with all the waterproofing components. The requirement to reach at least one hour of battery life is met since a single battery can operate the entire system for 2 hours and 43 minutes. The final objective to make the design cost less than $800 is fully achieved. The final cost for a combined transmitter and receiver system is $464.46, which is 42% less than the requirement. This price assumes a working PCB system and incorporates all waterproofing costs. An itemized cost breakdown of the final design can be seen in Table G-1. Table G-2 displays the estimated retail price of a mass-produced system of 100 or more units, and Tables G-3 and G-4 give a full expense report for the entire project. A mass-produced system would feature both the transmitter and receiver on a single PCB encased in a larger waterproof pouch. For this version of the product, the Audio Bone headphones would be significantly cheaper by purchasing from an international seller. This was not done originally for the sake of time. Mass-producing the design would decrease the costs by two-thirds, resulting in a retail price of approximately $158. This price makes the design less expensive than most, if not all, existing comparable products. Overall, the goal to create an underwater communication system using visible light is achieved. While the functionality of the final design does not meet all the desired specifications, the created system successfully transmits voice through water using visible light.

A functional PCB will allow for a more complete evaluation of the final design. While changes need to be made to the specifications to increase the distance and improve SNR, the inability to use the PCBs is a great hindrance for underwater testing. Further testing and de-bugging of the currently designed PCBs will allow for complete testing of the waterproofing aspects in conjunction with the project instead of on an individual basis. Additional research is necessary to determine a way to increase the distance between the transmitter and receiver. This might be achieved through the use of a larger LED array on the transmitter, but this would require significantly more current in the existing transmitter. Increasing the SNR would require additional research and might require the use of different circuit topologies.

Once all circuit issues are resolved, it will become necessary to begin adapting the system for practical use in a commercial setting. Ideally, the transmitter and receiver will be incorporated into the same board instead of each diver needing two boards to communicate with another diver. This would require different packaging to house a larger board. The waterproof packaging would also need to be rated for appropriate diving depths since the current solution is only functional up to 6 m. This is also true of the Audio Bone headphones since they are only rated for 1 meter. Water pressure considerations for greater depths will need to be accounted for since the current design is intended for testing in a swimming pool or bath tub. Final stages of the design will need to incorporate the actual SCUBA diving gear and ensure all design specifications meet or exceed all diving regulation standards.

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A Vendor Information

The following is a list of vendors from which the design components were purchased, along with their contact information.

Amazon.com
401 Terry Avenue North
Seattle, WA 98109
206-266-1000
www.amazon.com

Digikey Corporation
701 Brooks Avenue South
Thief River Falls, MN 56701
1-800-344-4539
www.digikey.com

Intertex Electronics, Inc.
1200 West Hildebrand
San Antonio, TX 78201
1-800-820-3908
www.intertexelectronics.com

RadioShack Corporation
Store #01-8202
Crossroads Mall #A-11
4522 Fredericksburg Road
San Antonio, TX 78201
210-735-9161
www.radioshack.com

Sunstone Circuits
13626 S. Freeman Road
Mulino, OR 97042
1-800-228-8198
www.sunstone.com

Wal-Mart
8500 Jones Maltsberger Road
San Antonio, TX 78216
210-377-1899
www.walmart.com

B Work Breakdown Structure and Gantt Chart

1. **Project Work**
   - ***1.1. Initiating the Project***
     - *1.1.1. Problem Statement*
       - 1.1.1.1. Library Research
       - 1.1.1.2. Brainstorming
       - 1.1.1.3. Writing/Editing
     - *1.1.2. Charter*
       - 1.1.2.1. Review DocSpec
       - 1.1.2.2. Define Scope
       - 1.1.2.3. Define Requirements
       - 1.1.2.4. Writing/Editing of Charter
     - *1.1.3. Problem Description Presentation*
   - ***1.2. Initial Design***
     - *1.2.1. Literature Review / Investigation*
     - *1.2.2. Brainstorming Approaches*
     - *1.2.3. Analyzing/Testing Potential Approaches*
     - *1.2.4. Design Development*
       - 1.2.4.1. Specifying Function
       - 1.2.4.2. Part Selection
       - 1.2.4.3. Printed Circuit Board (PCB) Design
     - *1.2.5. Documentation*
       - 1.2.5.1. Design Matrix
       - 1.2.5.2. Design Review Presentation
       - 1.2.5.3. Design Report
   - ***1.3. Prototype/Proof of Concept (PPOC)****
     - *1.3.1. Specifying Functionality*
     - *1.3.2. Ordering Parts*
     - *1.3.3. Construction*
       - 1.3.3.1. Breadboard Circuit
       - 1.3.3.2. PCB Fabrication & Preparation
       - 1.3.3.3. Packaging
     - *1.3.4. Testing/Evaluation*
       - 1.3.4.1. Circuit Simulation
       - 1.3.4.2. Component Blocks
       - 1.3.4.3. Completed Circuit
     - *1.3.5. Documentation*
       - 1.3.5.1. PPOC Demonstration
       - 1.3.5.2. PPOC Presentation
   - ***1.4. Final Design***
     - *1.4.1. Specifying Functionality*
     - *1.4.2. Ordering Parts*
       - 1.4.2.1. Electrical Components
       - 1.4.2.2. PCB
       - 1.4.2.3. Housing Components
     - *1.4.3. Construction*
       - 1.4.3.1. PCB Assembly
       - 1.4.3.2. Waterproofing & Packaging
     - *1.4.4. Testing/Evaluation*
       - 1.4.4.1. Circuit Simulation
       - 1.4.4.2. Component Blocks
       - 1.4.4.3. Open-Air
       - 1.4.4.4. Underwater
     - *1.4.5. Documentation*
       - 1.4.5.1. Bill of Materials
       - 1.4.5.2. CAD Drawings / Assemblies
       - 1.4.5.3. Final Report
       - 1.4.5.4. Final Presentation
   - ***1.5. Closeout***
     - *1.5.1. Cleanup of Area/Project*
     - *1.5.2. Clearance Form*

2. **Administrative**
   - ***2.1. Planning***
     - *2.1.1. Work Breakdown Structure*
     - *2.1.2. Schedule*
     - *2.1.3. Budget*
     - *2.1.4. Project Plan Writing/Editing*
   - ***2.2. Project Management***
     - *2.2.1. Monthly Management Reviews*
   - ***2.3. Self-Peer Evaluations***
   - ***2.4. Group Meetings***
   - ***2.5. Executive Summary***

3. **Course Content (Non-Project)**
   - ***3.1. Reading***
   - ***3.2. Studying***
   - ***3.3. Homework/Quizzes***
   - ***3.4. In-Class time***

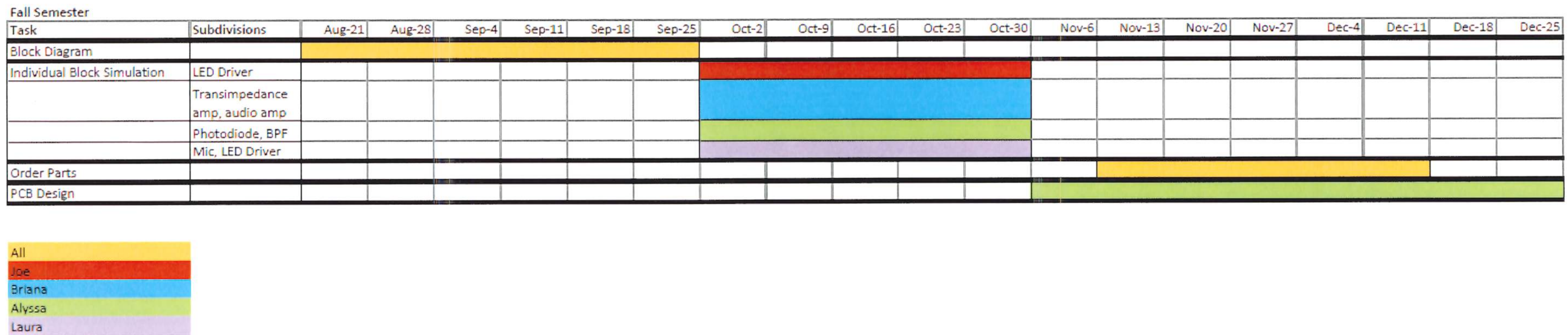

Figure B-1. Fall semester Gantt chart.

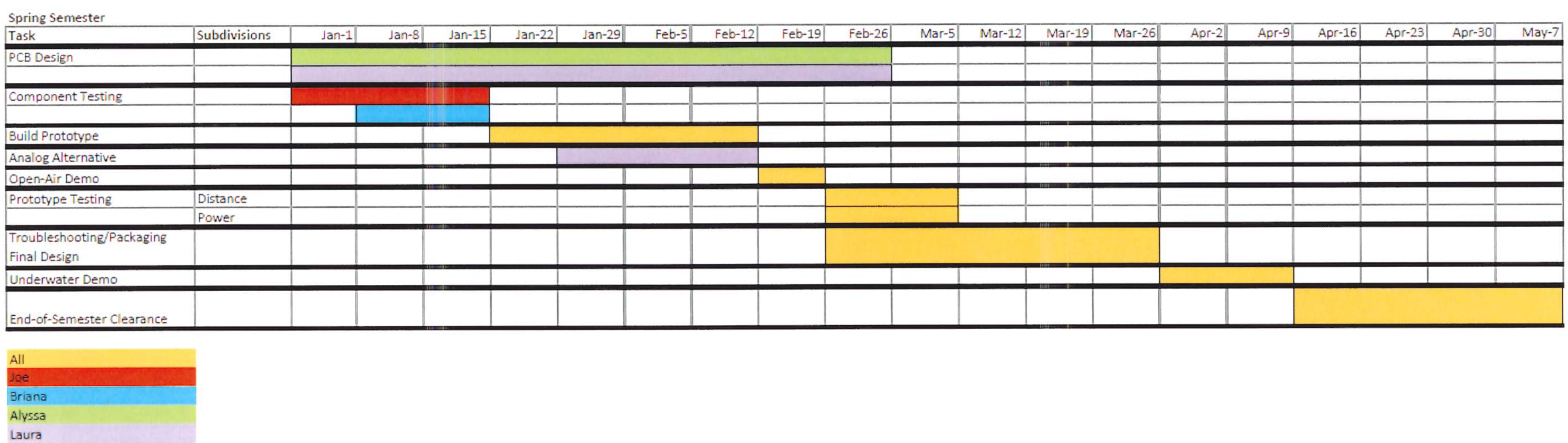

Figure B-2. Spring semester Gantt chart.

C Digital Transmission Alternative

A digital design follows the same overall progression as the analog final design but adds several steps.

C.1 Digital Transmitter

Figure C-1 summarizes the main stages in the transmitter for digital transmission.

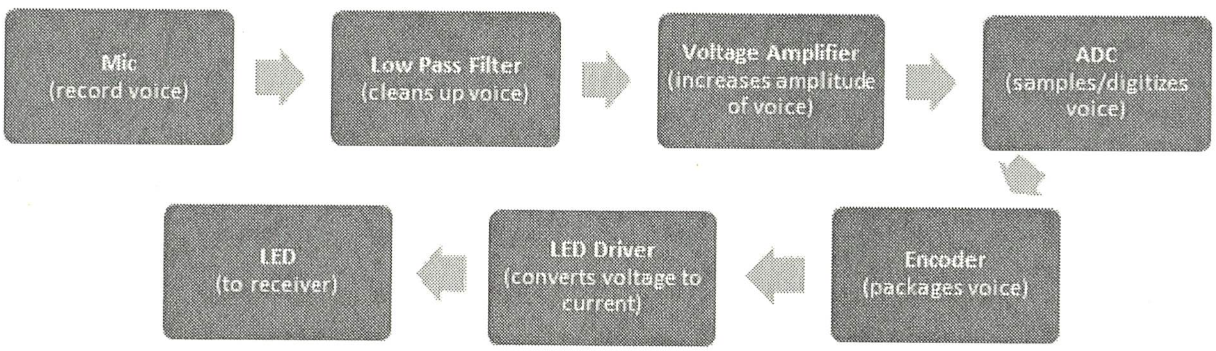

Figure C-1. Simplified transmitter block diagram for digital transmission.

The digital design uses the same microphone and low pass filter as the analog design (see section 2.4 Transmitter for more information). These effectively capture a person's voice and removes higher frequencies that are outside the normal range for human speech.

Afterwards, the voice signal is amplified with the two cascaded common emitter BJT stages depicted in Figure C-2. The overall gain of these two stages together is roughly 100 V/V, and the input of the microphone is commonly around 25 mV peak-to-peak. Since the analog-to-digital converter (ADC) in the next stage only accepts voltages between -1.28 V up to 1.27 V or a peak-to-peak maximum of 2.56 V, amplifying the microphone output up to 2.5 V peak-to-peak helps the design make full use of the 10 mV resolution of the ADC.

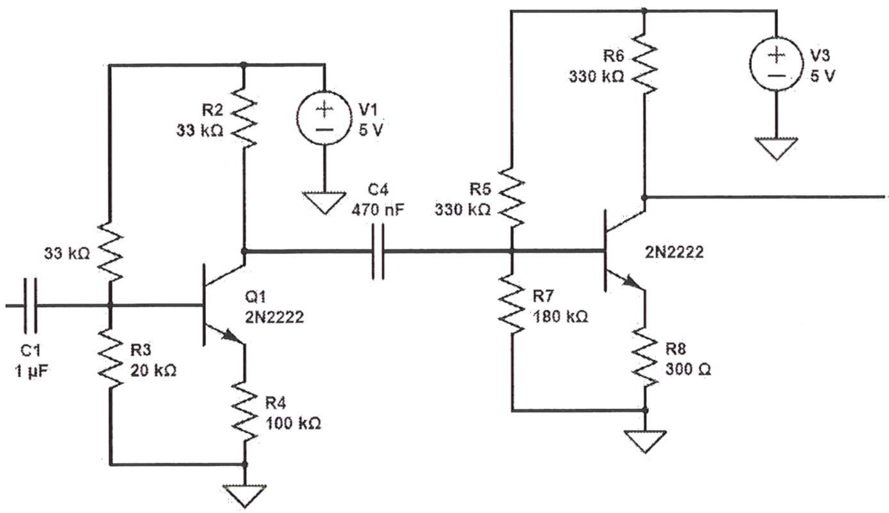

Figure C-2. Cascaded common emitter stages for voltage amplification.

Chosen because of its 8-bit resolution (10 mV/bit sequence) and its 10 µs conversion time (max operating speed of 100 kHz), the AD670 is used as the ADC. According to online sources, to preserve the frequency content of a person's voice after digitization, the chosen ADC must have at least 8 bits of resolution [24]. The circuit diagram for the ADC stage is shown in Figure C-3.

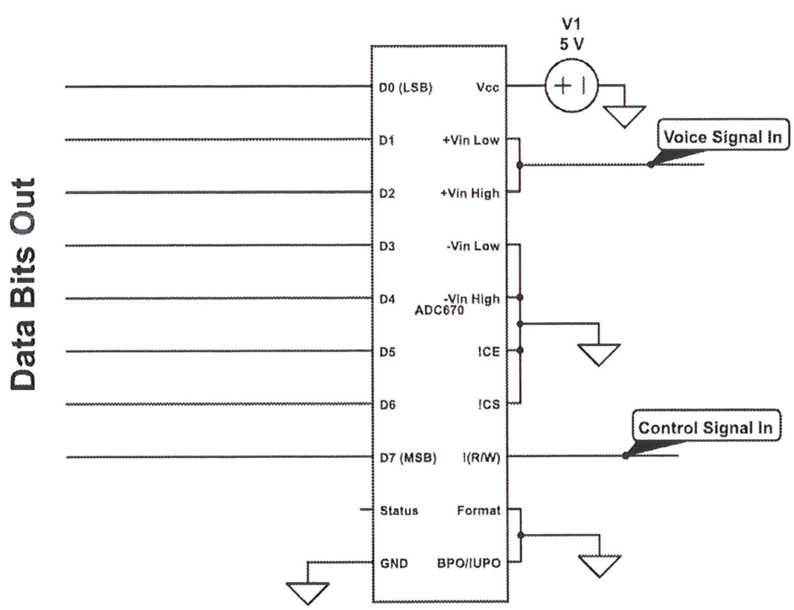

Figure C-3. Circuit diagram of the ADC stage.

Although the ADC accepts differential inputs, Figure C-3 shows how to hook it up such that the ADC will digitize only one input. Pins 11 and 12 control how the digitization process takes place. Setting pin 11 to high (5 V) configures the ADC to accept a bipolar input (centered around 0 V between -1.28 V to 1.27 V), which is required since the output from the voltage amplification stage is decoupled by a capacitor. Setting pin 12 to low (ground) configures the ADC to output its bits in offset binary as opposed to two's complement. This means that the lowest possible voltage (-1.28 V) is 0000 0000 while the highest possible voltage (1.27 V) is 1111 1111, and all the intermediate voltages count up in binary via equivalent voltage step sizes. This mode of transfer is compatible with the digital-to-analog converter (DAC) in the receiver, which will be explained later.

To coordinate with the slower sampling speed of the encoder in the next stage, the ADC needs to down-sample its output by holding each discrete set of bits at the output until the encoder is ready for the next transmission. This is accomplished by toggling pin 13 between high and low at a rate slow enough for the encoder to keep up. Since the rate of toggle depends on the needs of the encoder, its implementation will be explained after describing the encoding stage.

The Linx High Performance MS Series encoder/decoder is chosen for the design because it combines multiple stages into one. This pair of integrated circuit (IC) chips works as a shift register by taking the 8 bits in parallel coming from the ADC and transmitting them out in series, as shown in Figure C-4, which allows easy transmission for a single LED using amplitude shift keying (high brightness/voltage represents a '1' while low brightness/voltage represents a '0').

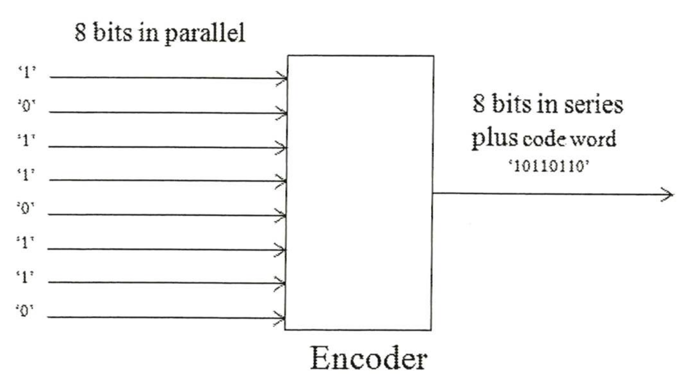

Figure C-4. Block 8 bits in; 1 line out with 8 bits in series.

They also implement asynchronous communication between the transmitter (encoder) and receiver (decoder). By adding a "code word" bit sequence or address to the output, the encoder can signal to the decoder when it is time to start accepting data. When the decoder does not see the starting "code word," it remains in a standby mode and holds the last received data at its output pins until another complete set of data is read. The "code word" must be taught to the decoder through a calibration process, which is summarized in Table C-1.

Table C-1. Encoder-Decoder calibration steps.

Step #	Procedure
1	Set the LEARN pin on the decoder to LOW for 10 seconds to clear the memory The decoder LED indicator should turn on initially and then turn itself off).
2	Set the CREATE_ADDR pin the encoder HIGH for 5 seconds and then set it to LOW. The encoder LED indicator should flash, indicating that the encoder is generating an address or code word.
3	Quickly set the CREATE_ADDR pin on the encoder to HIGH and then quickly LOW to set the address or code word. The encoder LED indicator should stop flashing and turn itself off.
4	Set the decoder LEARN pin to HIGH for around 3 seconds and the decoder LED indicator will turn on. Then bring the LEARN pin back to LOW and the decoder LED indicator will start flashing, meaning the decoder is ready to learn the encoder's newly generated address.
5	While the decoder LED is still flashing, set the encoder SEND pin to HIGH to transmit the address to toe encoder. Then toggle the decoder's LEARN pin up to HIGH and back down to LOW once, which will turn off the decoder LED indicator. At this stage, the decoder has learned the address (encoder LED indicator will still be on because it is on so long as SEND is high).

Figure C-5 is a circuit diagram of how the encoder is set up. The ADDR pin is permanently grounded to ensure that the encoder does not enter calibration mode. SEL_BAUD0 and SEL_BAUD1 are both set high to ensure that the encoder transmits at its fastest baud rate: 28.8 kbps. Keeping send high also ensures that the encoder continually transmits as quickly as possible. Since the encoder needs to transmit 8 bits for each transmission, the fastest it can transmit one discrete sample is 3.6 kHz, meaning each sample must be held by the ADC for at least $(3.6\ \text{kHz})^{-1}$ or at least 0.2778 ms.

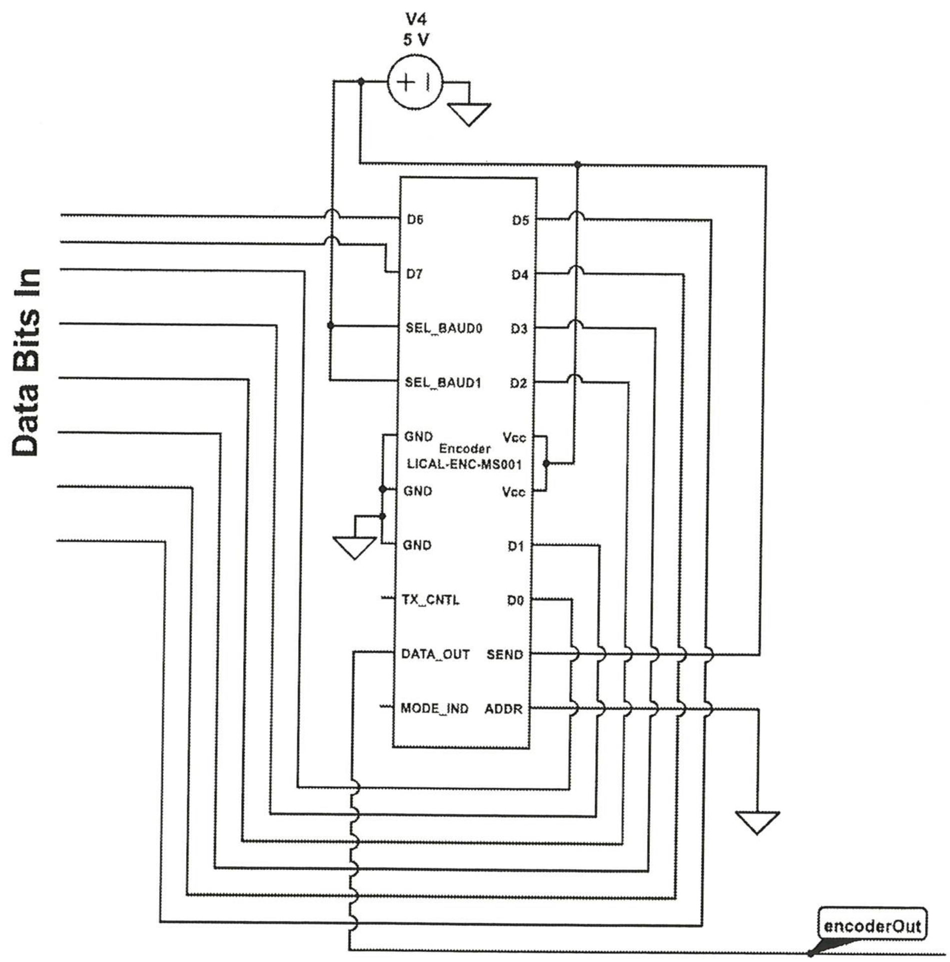

Figure C-5. Encoder circuit diagram.

In other words, the ADC needs to be synchronized with the encoder via an external clock. The circuit in Figure C-6 shows how to achieve clocking with a 555 timer in astable mode.

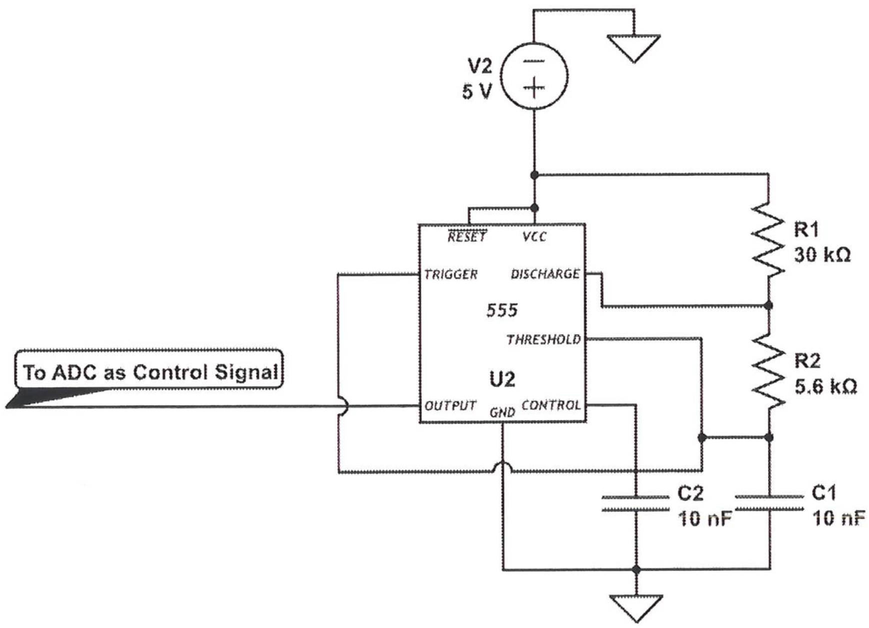

Figure C-6. Astable 555 timer circuit for transmitter clocking [25].

The frequency of oscillation, along with its high and low time, is dictated by the resistors R_1 and R_2 along with the capacitor C_1. Equation C-1 describes the frequency of oscillation while Equations C-2 and C-3 describe the high and low times respectively [25].

$$f = \frac{1}{\ln(2)\, C_1(R_1 + 2R_2)} \quad \text{(C-1)}$$

$$high\ time = \ln(2)C_1(R_1 + R_2) \quad \text{(C-2)}$$

$$low\ time = \ln(2)C_1R_2 \quad \text{(C-3)}$$

Although the overall frequency needs to be 3.6 kHz or slower, the amount of high time must be greater than the amount of low time because the ADC holds onto its value for however long the timer holds its higher value. Thus, a larger resistor is chosen for R_1 than R_2 since R_2 is the only resistor that controls the low time. With the values shown in Figure C-6, the 555 timer produces a clock with an overall frequency of 3.5 kHz with an 86% duty cycle (active time in one cycle vs. the overall period).

With the ADC and encoder synchronized, the result is then transformed from a voltage into a current with the LED driver transconductance amplifier and then pushed through the LED.

This stage is the same as the analog counterpart, so refer to the main body section 2.5 Receiver for more detail.

C.2 Digital Receiver

The receiver is intended to work independently from the transmitter and can decode the data from the transmitter without any extra communication between the two circuits. Figure C-7 is a simplified block diagram of the receiver.

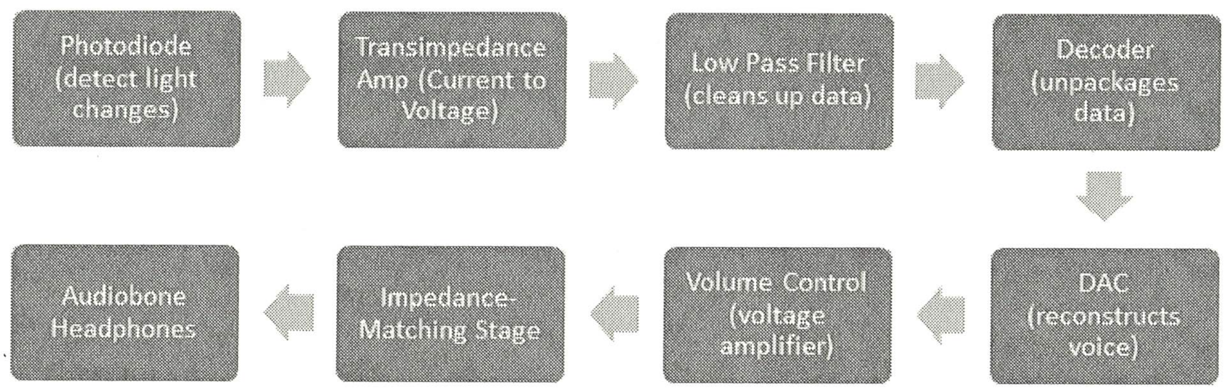

Figure C-7. Simplified receiver block diagram for digital transmission.

The receiver first reads the data using the PDB C156 photodiode-transimpedance amplifier combination. Then it is once again cleaned up using a lowpass filter. These stages are all identical to the analog design.

Following the low pass filter, the result is passed to the decoder, shown in Figure C-8. Once the decoder sees a code word, it starts collecting the subsequent data and outputs it in parallel. The LATCH pin is set to high so that the decoder outputs are held until another set of data is read. The other pins on the decoder are set complimentarily to the encoder in the transmitter.

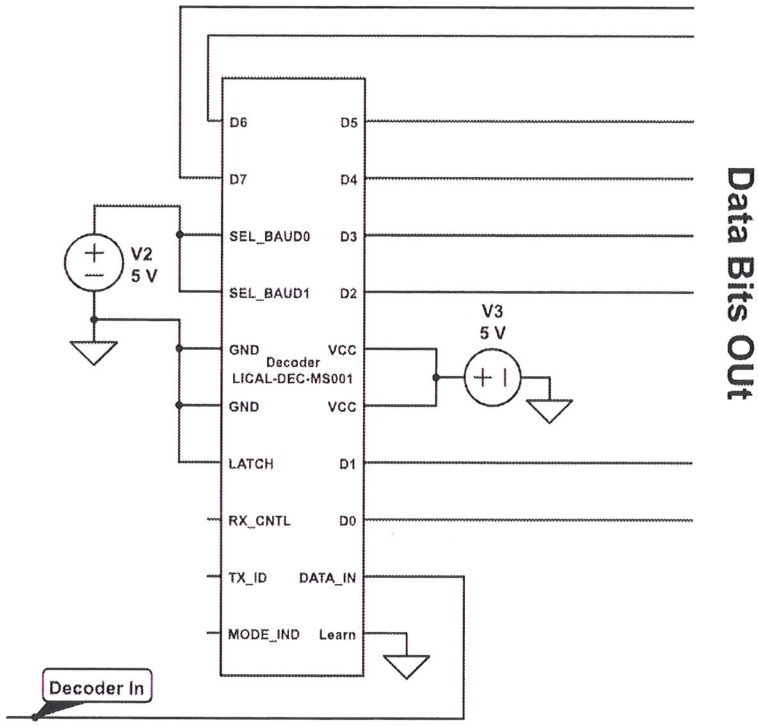

Figure C-8. Decoder circuit.

After the signal is decoded, the digital-to-analog converter (DAC) shown in Figure C-9 is used to reconstruct the voice signal for playback. Similar to the ADC, the AD557 8-bit DAC features an absolute voltage range of 0 to 2.56 V, but the configuration is unipolar (above zero only) instead of bipolar (centered around zero). Although a bipolar configuration is possible with the AD557, its recommended configuration utilizes a negative power source, which would require a second battery to operate. However, this DAC can read the values from the ADC because it accepts straight binary. Straight binary is similar to offset binary in that the lowest value is assigned 0000 0000, the highest value is assigned 1111 1111, and the intermediate voltages are distribute in order in between. However, 0000 0000 instead corresponds to 0 V while 1111 1111 corresponds to 2.56 V. However, a bipolar output can still be achieved by placing a coupling capacitor at the output of the DAC stage.

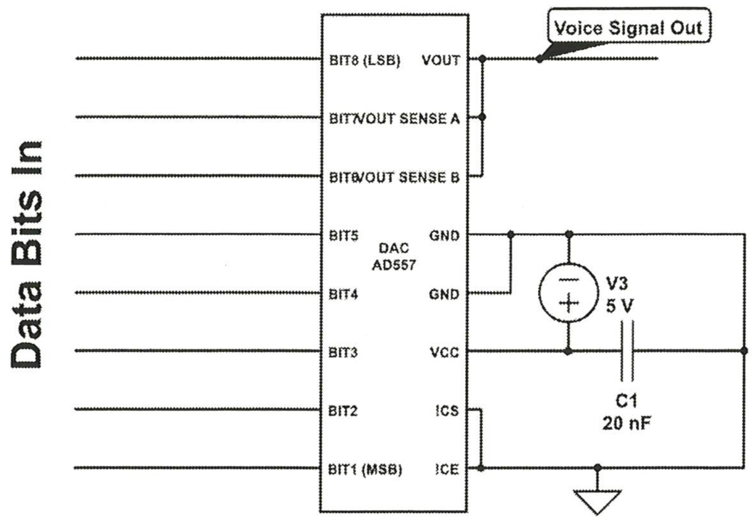

Figure C-9. DAC circuit.

The remaining stages—volume control, impedance matching, and Audio Bone headphones, are analogous to the design presented in the main body of the report.

C.3 Shortcomings of Digital Transmission Design

The main oversight in the digital design is that it underestimates how much asynchronous communication can slow down transmission. Although the baud rate of the encoder is very close to 28.8 kbps, the transfer of a single data point is much slower than the 3.6 kHz predicted. When the encoder stage is directly hooked up to the decoder stage, the highest frequency sine wave that can be preserved from input to output is measured as roughly 100-200 Hz.

After further investigation of the encoder/decoder data sheets, the address used for asynchronous communication consists of 24 bits. This large number of address bits is appropriate for applications such as keyless door access, simple security, and remote control because it minimizes the chance of encountering a device with a conflicting address. However, in a design that requires speed, such as the digital communication design outlined above, this large address size limits the design's transmission speed. Mathematically, this means that 24 address bits + 8 data bits = 32 total bits must be transferred per data point transmission. Thus, with the encoder and decoder running at top speed and no delay, the set has a top speed of 28800 bits per second / 32 bits or 900 Hz (1.111 ms). However, the encoder and decoder each have a delay of 1.64 ms before transmission according to each data sheet, so the total ideal time it takes to transfer one data point is 4.39 ms. This puts the ideal frequency on the same order of magnitude as what was observed with an oscilloscope (227.7 Hz ideal, 100-200 Hz measured).

Even though other encoder/decoder combinations exist, such as those with Manchester encoding, they must be ordered from lesser known distributors than Digikey and tend to be very expensive. Furthermore, these combinations are less often in stock, and their delivery estimates average to around six weeks for most distributors. Because of time constraints, purchasing a new encoder/decoder combination is not possible. Another possibility is designing an encoder from more basic elements, such as a shift register. Although this is technically a workable solution, the added complexity, time constraint, and lack of space on the printed circuit board made it unreasonable for this design.

Although a digital transmission scheme is common in the field of visible light communication, the scope of the project limits the design possibilities. For instance, many existing visible light communication systems interface with a computer which can digitize a person's voice, clean it up, encode the transmission, decode any incoming transmissions, and reconstruct voice all in one. Since the project is intended to be portable so that SCUBA divers can take it with them underwater, interfacing with a desktop computer and using wall power are not feasible options. Interfacing with a low-power microcontroller is a good compromise, but a microcontroller has more functionality than is needed for this design, so simpler off-the-shelf application-specific integrated circuit (ASIC) chips are the most appropriate given the design goals. However, using ASIC chips instead of computer interfacing means that this design reaches into an area of visible light communication that is less thoroughly documented. In other words, this project requires developing alternative implementations of the different stages of visible light communication instead of simply following a blueprint design. With its extra stages and thus added complexity, the digital design has more potential pitfalls than the analog design.

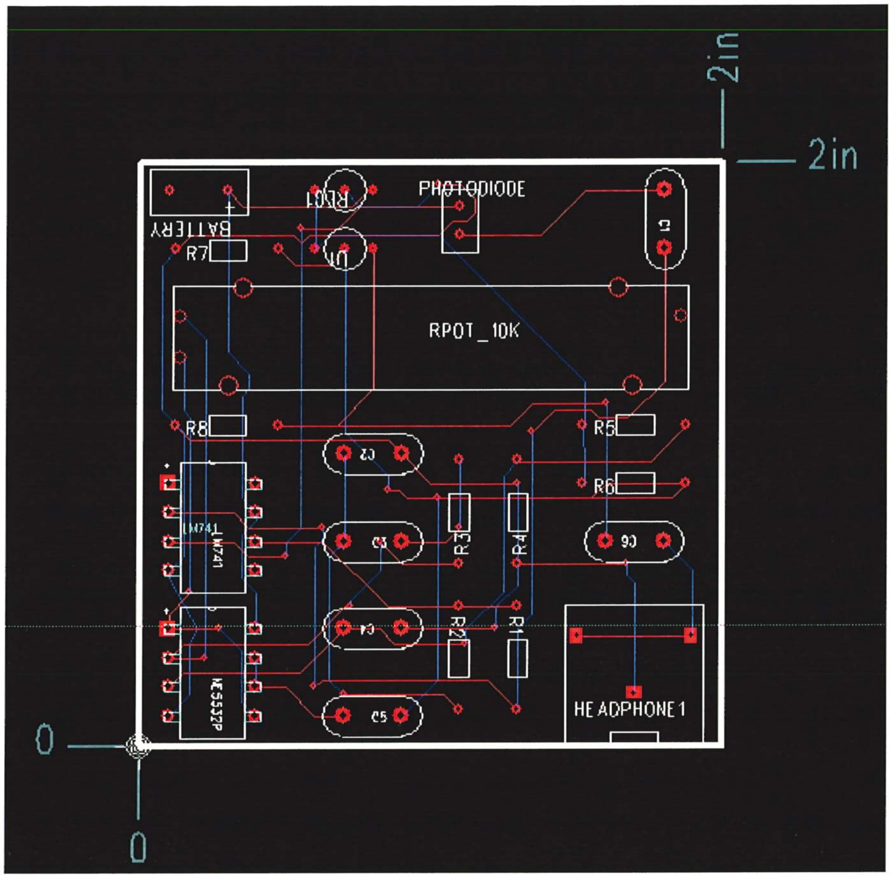

Figure D-2. Layout of receiver on 2x2" PCB.

D PCB Design

The PCBs were made using the free PCB123 Design Software, provided by Sunstone Circuits. The following pictures show the layout of the transmitter and receiver on the PCBs.

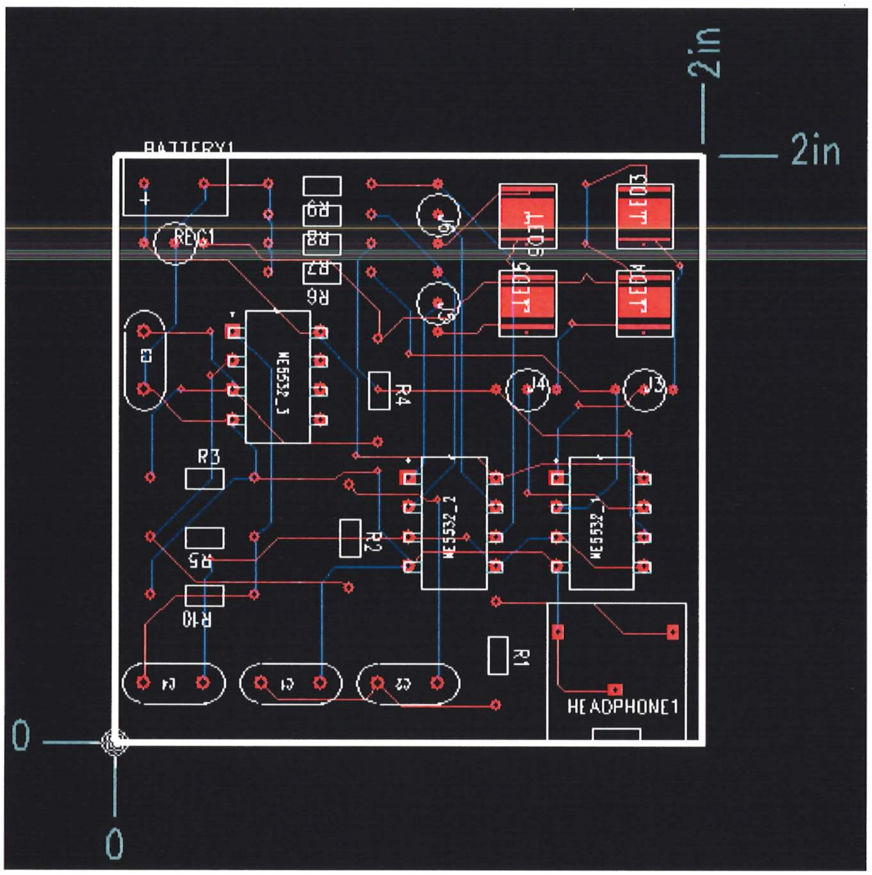

Figure D-1. Layout of transmitter on 2x2" PCB.

E Analog Design

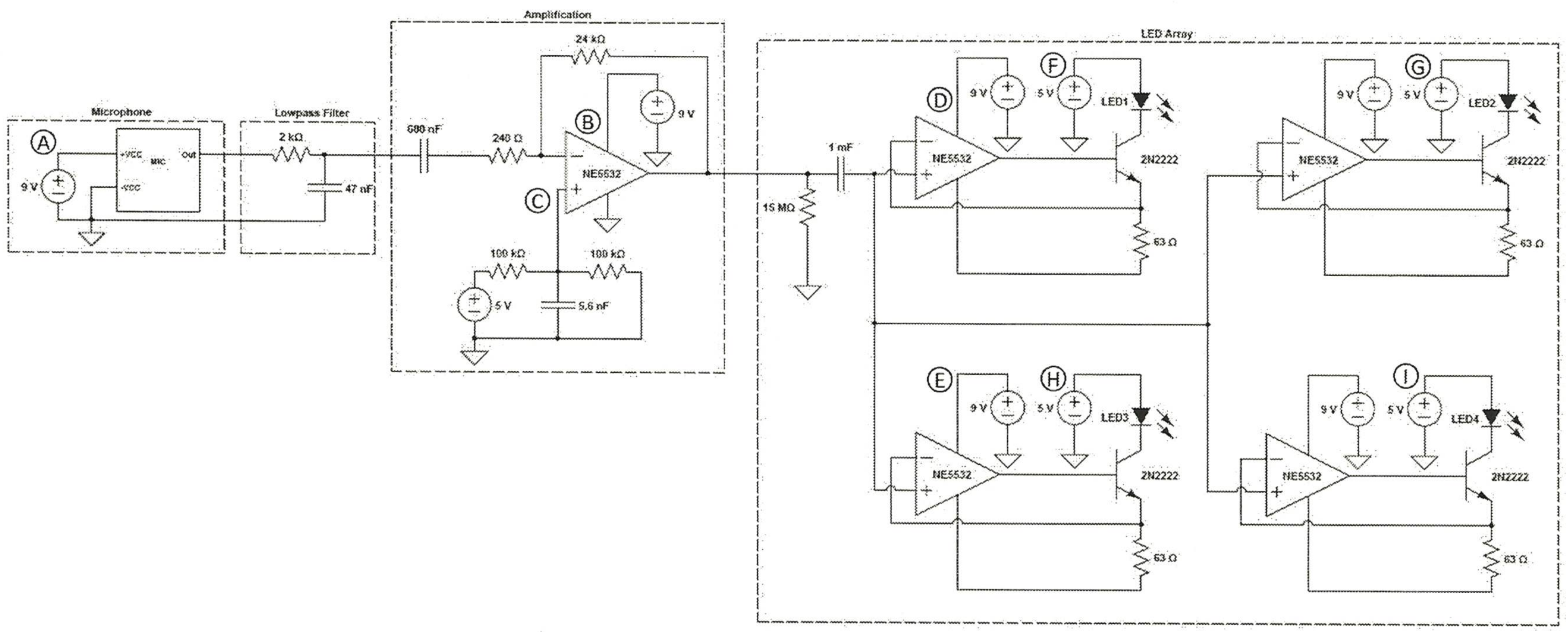

Figure E-1. Full analog transmitter schematic.

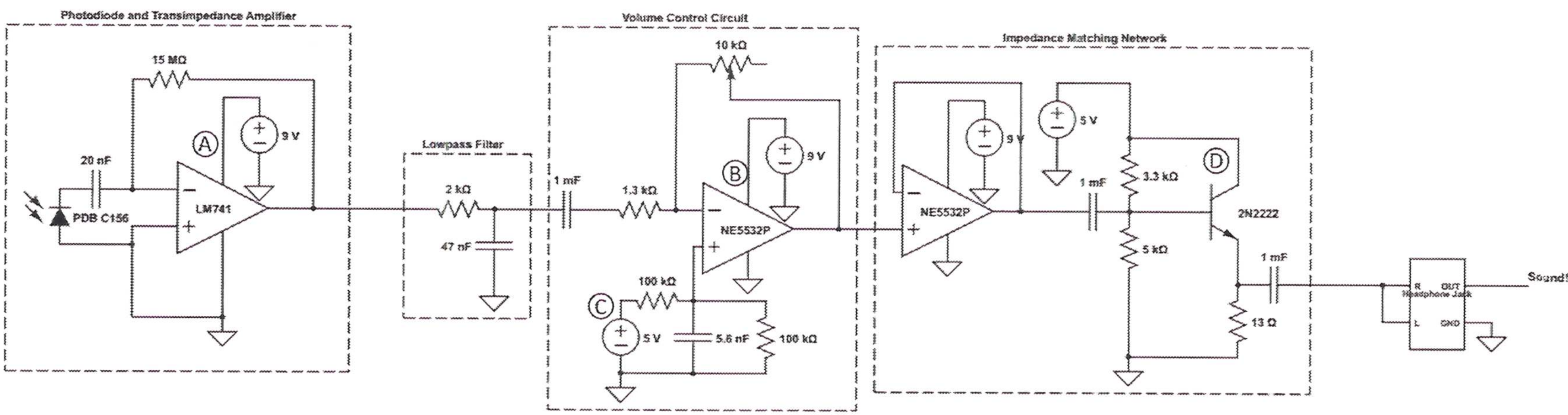

Figure E-2. Full analog receiver schematic.

F Testing Results

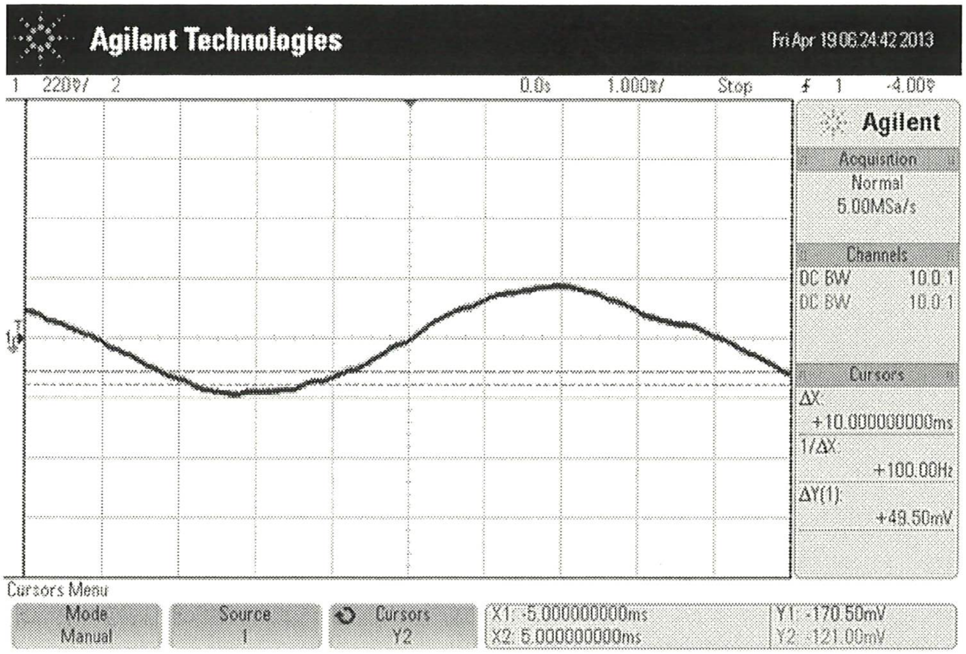

Figure F-1. Noise amplitude measurement superimposed on overhead light sinusoid.

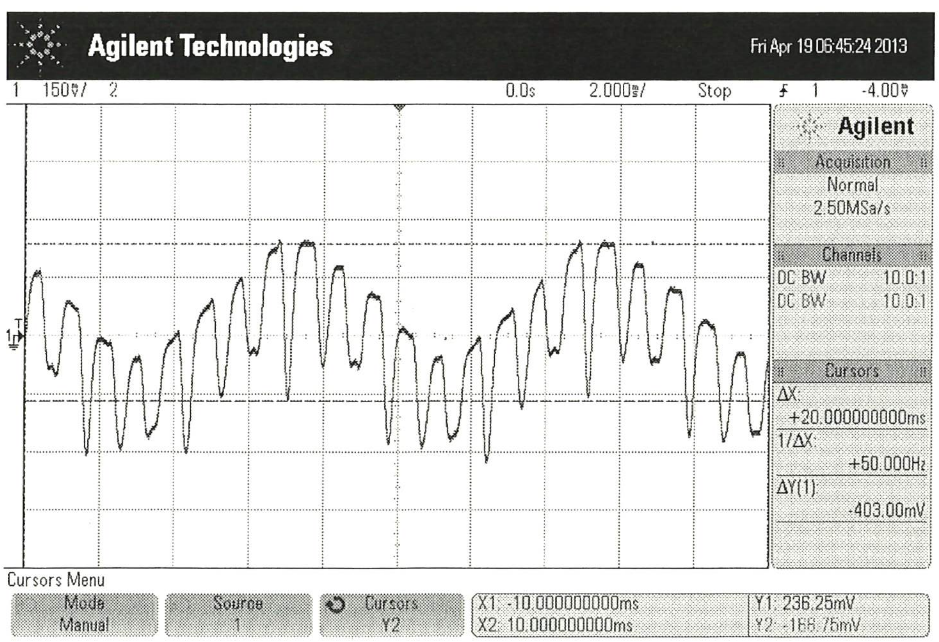

Figure F-2. Signal amplitude measurement superimposed on overhead light sinusoid.

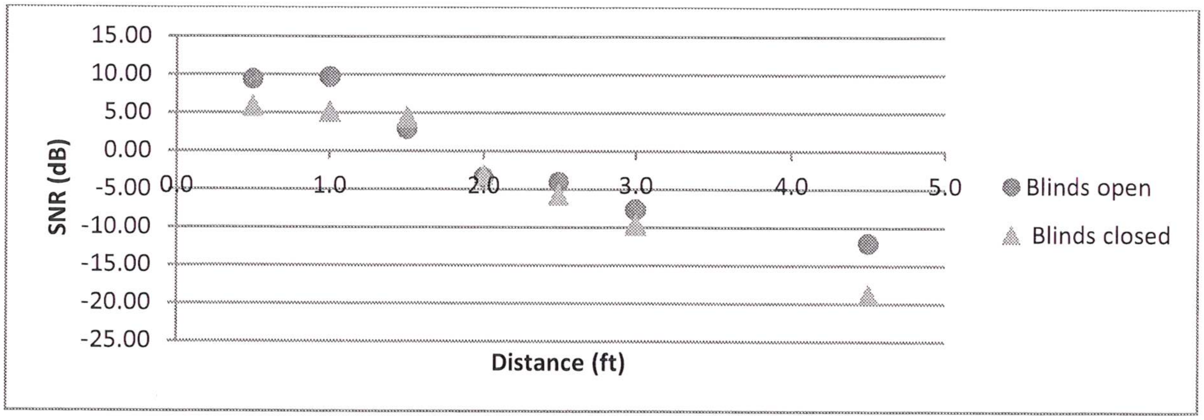

Figure F-3. SNR trends with respect to overhead lights.

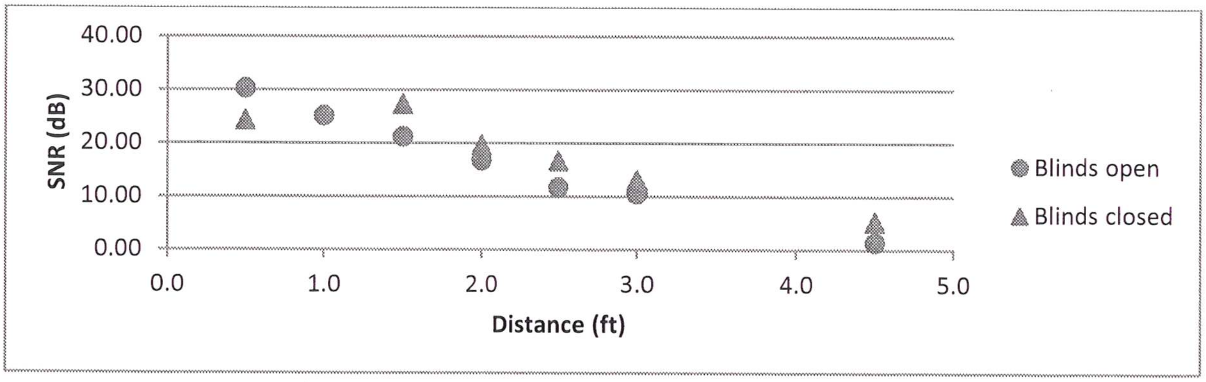

Figure F-4. SNR trends with respect to other noise with overhead lights on.

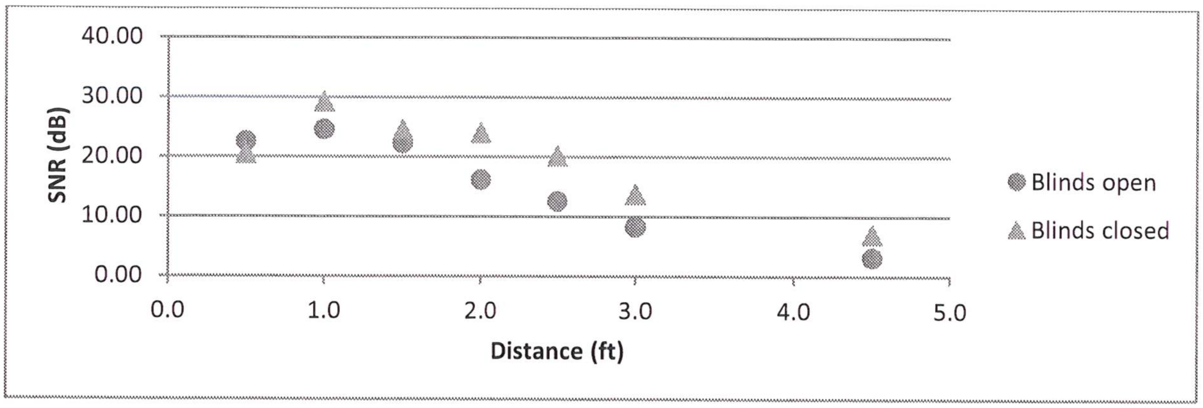

Figure F-5. SNR trends with respect to other noise with overhead lights off.

G Project Expenses

Table G-1. Itemized cost breakdown for prototype.

Item	Number in Transmitter	Number in Receiver	Unit Cost	Cost
NE5532P Op Amp	3	1	$1.16	$4.64
LM741 Op Amp	0	1	$0.70	$0.70
XMLAWT-00-0000-0000T6053 LED	4	0	$7.41	$29.64
SJ1-352XN Headphone Jack	1	1	$0.84	$1.68
PS30-10PB10BR10K Sliding Potentiometer	0	1	$6.50	$6.50
PDB-C156 Photodiode	0	1	$1.30	$1.30
Resistor	10	8	$0.09	$1.62
Capacitor	4	7	$2.00	$22.00
MC78L05ACP751 5 V Regulator	1	1	$0.45	$0.90
2N2222 BJTs	4	1	$1.26	$6.30
Duracell 9 V Battery	2	1	$7.14	$21.42
Battery Case	2	1	$2.98	$8.94
Electret Condenser Microphone with Leads	1	0	$2.99	$2.99
Headphone Jack Adapter	1	0	$2.00	$2.00
Audio Bone Headphones	0	1	$179.95	$179.95
OverBoard Waterproof Smart Phone Case	1	1	$26.95	$53.90
Transmitter Printed Circuit Board	1	0	$54.56	$54.56
Receiver Printed Circuit Board	0	1	$54.56	$54.56
Epoxy	1	0	$5.86	$5.86
Solder	0.125	0.125	$20.00	$5.00
			Total:	**$464.46**

Table G-2. Itemized breakdown of mass-produced design.

Item	Quantity	Unit Cost	Cost
NE5532P Op Amp	4	$0.2025	$0.81
LM741 Op Amp	1	$0.4725	$0.47
XMLAWT-00-0000-0000T6053 LED	4	$6.578	$26.31
SJ1-3523N Headphone Jack	2	$0.3948	$0.79
PS30-10PB10BR10K Sliding Potentiometer	1	$0.8325	$0.83
PDB-C156 Photodiode	1	$0.945	$0.95
Resistor	18	$0.0271	$0.49
Capacitor	11	$0.08607	$0.95
MC78L05ACP751 5 V Regulator	2	$0.2081	$0.42
2N2222 BJTs	5	$0.1708	$0.85
Battery Case	2	$2.98	$5.96
Electret Condenser Microphone with Leads	1	$2.99	$2.99
Headphone Jack Adapter	1	$2.058	$2.06
Audio Bone Headphones	1	$55.99	$55.99
OverBoard Waterproof eBook Reader Case	1	$39.95	$39.95
Transmitter/Receiver Printed Circuit Board	1	$9.84	$9.84
Epoxy	1	$5.86	$5.86
Solder	0.125	$20.00	$2.50
		Total:	**$158.01**

Table G-3. Total project income.

Date	Sponsor	Description	Status	Budgeted Amount	Actual Amount
9/2/2012	Engr Dept	Senior Design Project Allotment		$1,200.00	$1,200.00
3/7/2013	Donation	9 V Battery Case with On/Off Switch (4)		$0.00	$11.94
	Donation	9 V Battery (8)		$20.00	$57.12
	Shop	Breadboard Loaned from Dept (4)		$599.80	$599.80
	Shop	Oscilloscope Loaned from Dept (1)		$2,400.00	$2,400.00
	Shop	DMM Loaned from Dept		$400.00	$400.00
	Shop	Probes Loaned from Dept (2)		$200.00	$200.00
	Shop	Resistors Loaned from Dept (15)		$4.50	$4.50
	Shop	Capacitors Loaned from Dept (10)		$20.00	$20.00
	Shop	Potentiometer Loaned from Dept		$0.50	$0.50
	Shop	LEDs Loaned from Dept (2)		$1.00	$1.00
	Shop	DIP Switch Loaned from Dept (2)		$2.36	$2.36
	Shop	5 V Regulator		$0.90	$0.90
	Shop	DIP Switch Loaned from Dept (2)		$0.70	$0.70
	Shop	Soldering Iron		$29.49	$29.49
	Shop	Solder		$5.00	$5.00
	Shop	Epoxy	Expected	$5.00	$5.00
Total Income				**$4,889**	**$4,938**

Table G-4. Total project expenses.

Date	Vendor	Item Description	PO # (Invoice #)	Status (Planned/ Pending/ Cleared)	Budgeted Amount	Actual Amount	Status: Internal	Status: Dept Purchase Order	Status: Reim-burse-ment
10/20/2012	Home Depot	Rayovac Flashlight	1	Cleared	$20.00	$16.21			x
12/12/2012	SparkFun	SSOP to 20-DIP Adapter (10)	2 (657078)	Cleared	$0.00	$35.60		x	
12/12/2012	SparkFun	Shipping	2 (657078)	Cleared	$0.00	$3.64		x	
12/18/2012	Digikey	ADC	3 (40401164)	Cleared	$5.00	$3.22		x	
12/18/2012	Digikey	ADC	3 (40401164)	Cleared	$5.00	$23.29		x	
12/18/2012	Digikey	DAC	3 (40401164)	Cleared	$15.00	$11.09		x	
12/18/2012	Digikey	Decoder (5)	3 (40401164)	Cleared	$5.00	$19.90		x	
12/18/2012	Digikey	Encoder (5)	3 (40401164)	Cleared	$5.00	$19.90		x	
12/18/2012	Digikey	Microphone	3 (40401164)	Cleared	$2.50	$2.62		x	
12/18/2012	Digikey	Microphone	3 (40401164)	Cleared	$2.50	$4.58		x	
12/18/2012	Digikey	Photodiode	3 (40401164)	Cleared	$5.00	$1.30		x	
12/18/2012	Digikey	Photodiode	3 (40401164)	Cleared	$5.00	$1.06		x	
12/18/2012	Digikey	Transimpedance Amplifier (3)	3 (40401164)	Cleared	$5.00	$22.95		x	
12/18/2012	Digikey	Shipping	3 (40401164)	Cleared	$0.00	$7.75		x	
2/1/2013	Digikey	Op Amp (10)	4 (40819761)	Cleared	$1.00	$11.63		x	
2/1/2013	Digikey	Female Headphone Jack	4 (40819761)	Cleared	$1.00	$0.84		x	
2/1/2013	Digikey	9 V Battery Connector (4)	4 (40819761)	Cleared	$1.00	$0.61		x	
2/1/2013	Digikey	LEDs (2)	4 (40819761)	Cleared	$10.00	$14.88		x	
2/1/2013	Digikey	DAC (3)	4 (40819761)	Cleared	$45.00	$33.27		x	
2/1/2013	Digikey	ADC (3)	4 (40819761)	Cleared	$15.00	$9.66		x	
2/1/2013	Amazon	Audio Bone Headphones	5	Cleared	$150.00	$179.95		x	
2/25/2013	RadioShack	Electret Mic Element with Leads (4)	6	Cleared	$15.00	$11.97			x
2/25/2013	RadioShack	PC-Mount Condenser	6	Cleared	$5.00	$2.99			x

Date	Vendor	Item Description	PO # (Invoice #)	Status (Planned/ Pending/ Cleared)	Budgeted Amount	Actual Amount	Status: Internal	Status: Dept Purchase Order	Status: Reim-burse-ment
		Mic Element							
2/25/2013	RadioShack	Tax	6	Cleared	$0.00	$1.23			x
3/7/2013	Intertex	9 V Battery Case with On/Off Switch (4)	7	Cleared	$0.00	$11.94	x		
3/8/2013	Digikey	10k Potentiometer	8 (41193004)	Cleared	$10.00	$6.50		x	
3/8/2013	Digikey	LEDs (2)	8 (41193004)	Cleared	$15.00	$14.88		x	
3/8/2013	Digikey	Shipping	8 (41193004)	Cleared	$0.00	$7.49		x	
3/11/2013	Amazon	Waterproof Smart Phone Case	9	Cleared	$200.00	$53.90		x	
3/11/2013	Amazon	Shipping	9	Cleared	$0.00	$6.17		x	
4/3/2013	Digikey	LEDs (8)	10 (41457918)	Cleared	$40.00	$66.52		x	
4/3/2013	Digikey	Photodiode (2)	10 (41457918)	Cleared	$10.00	$2.60		x	
4/3/2013	Digikey	Female Headphone Jack (4)	10 (41457918)	Cleared	$0.00	$3.36		x	
4/4/2013	PCB Express	Transmitter Printed Circuit Board (2)	11 (P10309891)	Cleared	$200.00	$109.12		x	
4/4/2013	PCB Express	Receiver Printed Circuit Board (2)	11 (P10309891)	Cleared	$200.00	$109.12		x	
4/18/2013	Walmart	9 V Battery (4)	12	Pending	$0.00	$15.09			x
4/20/2013	Walmart	Fish Tank	13	Pending	$0.00	$14.74			x
	POD	9 V Battery (8)			$20.00	$57.12	x		
	Shop	Breadboard Loaned from Dept (4)			$599.80	$599.80	x		
	Shop	Oscilloscope Loaned from Dept			$2,400.00	$2,400.0 0	x		
	Shop	DMM Loaned from Dept			$400.00	$400.00	x		
	Shop	Probes Loaned from Dept (2)			$200.00	$200.00	x		
	Shop	Resistors Loaned from Dept (15)			$4.50	$4.50	x		
	Shop	Capacitors Loaned from			$20.00	$20.00	x		

							Status		
Date	Vendor	Item Description	PO # (Invoice #)	Status (Planned/ Pending/ Cleared)	Budgeted Amount	Actual Amount	Internal	Dept Purchase Order	Reim-burse-ment
		Dept (10)							
	Shop	Potentiometer Loaned from Dept			$0.50	$0.50	x		
	Shop	LEDs Loaned from Dept (2)			$1.00	$1.00	x		
	Shop	DIP Switch Loaned from Dept (2)			$2.36	$2.36	x		
	Shop	5 V Regulators			$0.90	$0.90	x		
	Shop	LM 741 Op Amp			$0.70	$0.70	x		
	Shop	Soldering Iron			$29.49	$29.49	x		
	Shop	Solder			$5.00	$5.00	x		
	Shop	Epoxy		Expected	$5.00	$5.00	x		
Total Expenses				**$4,682.25**	**$4,587.94**				