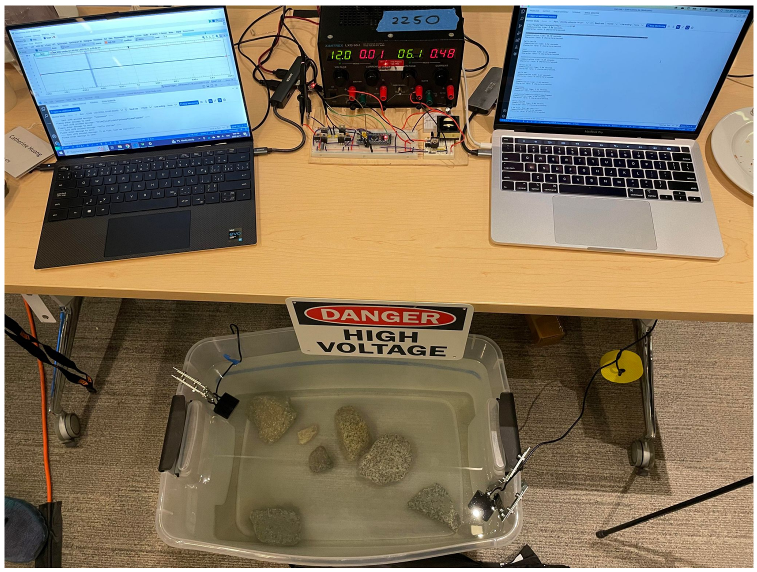
The design of an acoustic underwater communication system



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Project Number: 2250

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Executive Summary

The purpose of this project is to develop an underwater wireless communication system which facilitates flooded cave rescue efforts. Our sponsor is Dr. Carl Michal, Associate Professor at the University of British Columbia. Traditional radio communications used for rescue are unable to operate in flooded caves, where radio waves are severely attenuated in the flooded portions due to the conductivity of water. Our solution must be able to communicate within these flooded cave conditions over long ranges. A mesh network of repeater nodes placed within various points in the cave would allow for longer ranged communication while nodes consisting of both an underwater and above water communication method would allow for these devices to communicate. Initially the task was to develop a system that integrates both systems but our team has narrowed the scope to the underwater portion to prioritize solving a more unknown problem.

Our team has developed an initial prototype of the underwater communication portion of the device that prioritizes reliable communication over bit rate. Each underwater module consists of a transducer to interface and propagate through the water, a transmitting circuit, a receiver circuit, and an embedded microcontroller. Our prototype is able to successfully communicate between two devices.

1 Introduction

1.1 Background

In 2018, a group of youth soccer players and their coach were trapped in the Tham Luang Cave in Thailand. The rescue operation involved a large global effort of over 10000 people over the course of 18 days to rescue the team. The cave rescue was particularly challenging due to the complex geometry of the cave and the flooded cave conditions that made radio communication particularly difficult. Rescuers had difficulties communicating back to the rest of their team even when the group had been found. Our sponsor, Dr. Carl Michal, Associate Professor at the University of British Columbia was fascinated by this challenging problem and wanted to explore potential solutions.

1.2 Problem

This event has brought attention to how unreliable radio communication can be for flooded cave conditions whereas acoustic communication has shown to be far more reliable to propagate through water. Cave divers need a reliable way to communicate their location and status to other rescuers.

1.3 High level

Our initial high level solution consists of a bimodal mesh network of repeater nodes which would be placed in various sections within the cave. Each device would float in the water with an underwater and above water communication module. This would allow for a message to propagate even with changing water levels

Due to the complexity of the problem and proposed solution, our team has decided to narrow the scope of the project. Since underwater communication is more of an unsolved problem, we have decided to focus on an initial prototype for the underwater communication portion of this system.

The goals of this project are to develop a reliable way to send text messages between two devices underwater. Thus the project requires:

1. Sourcing a transducer to interface with water
2. Designing electronic circuits to allow transmitting and receiving within water
3. Developing firmware and a communication protocol to decode and encode text messages

While this prototype is being designed for the underwater module of the project, the core electronics and theory can still be transferable to the above water module.

2 Discussion

2.1 Theory

2.1.1 Wave theory

Electromagnetic waves are not suitable for long distance underwater communication as they are severely attenuated due to the conductivity of water found in nature. Pure water is an insulator but water often has dissolved particles which make it conductive. Acoustic waves or sound waves are longitudinal pressure waves that travel with much less attenuation in water. While sound waves travel very slow in air, at 343 m/s, due to water being a denser medium acoustic waves travel at 1500 m/s in water. An important parameter to consider is acoustic impedance, which describes the opposition of a medium to the longitudinal wave motion. The physical devices which transmit acoustic waves must be impedance matched to water.

2.1.2 Sources of Attenuation and Loss

Since we are building an acoustic communications device, it is important to consider attenuation sources that cause a reduction in amplitude as acoustic waves propagate through water. The main sources of attenuation include spreading losses, absorption, multipath propagation, and scattering and diffraction.

Table 1 outlines phenomenons that cause acoustic attenuation in water, the physics behind each attenuation source and the effects it causes on communications design.

2.2 Design

The overall design goal is to create rapid prototypes which would allow us to investigate the problem as thoroughly as possible. Many design decisions were guided by the need for flexibility for future improvements of hardware and digital design. The system consists of power electronics, transmit electronics to drive the signal, a piezoelectric acoustic transducer to act as a speaker and microphone, and receiver electronics to complete the communication system.

2.2.1 Transducer Selection

Piezoelectric materials are crystals which physically deform under an electric field, and also create an electric field under mechanical stress. Piezoelectric transducers use this effect to create acoustic waves with an applied voltage, and conversely induce voltage when an acoustic wave is detected. It is this principle which allows it to work as both a transmitter and receiver. The selection of a transducer proved to be a challenge due to our unique requirements. We needed a transducer we could source

Table 1: Acoustic Attenuation and Loss sources in water

Source	**Description**	**Effects**
Spreading losses	Sound waves spread out over a larger area approximated by a cylinder, leading to a decrease in intensity as it travels within water.	Limited range for detection.
Absorption	Sound waves lose energy as they interact with the medium depending on the frequency of the wave and the properties of the medium. In the case of water, higher frequency generally leads to higher absorption.	Limited bandwidth and operating frequency for transmitted signals
Multipath propagation	Sound waves reflect off boundary surfaces, creating multiple paths between the source and receiver.	Unpredictable noise from repeated signals, interference, and signal distortions.
Scattering and Diffraction	The presence of obstacles such as stalagmite protrusions or floating rocks in the propagation path can cause scattering and diffraction, where the waves split or bend as they encounter the obstacle.	Unpredictable noise, wave patterns, or decreased intensity observed on the receiver.

quickly and in reasonably small quantities. We also needed a transducer which worked at low resonant frequencies to mitigate attenuation, and one that was omni-directional as it will act as a transmitter and receiver. Many specialized acoustic transducer makers sell them in large quantities with custom requirements so this option was not suitable. Another solution was making our own transducer out of a piezoelectric material cylinder, however this is a complex process requiring time and professional guidance, which would take away from the project goals. We also considered waterproofing transducers made for in-air use but the process of acoustically impedance matching the transducer to water is not trivial and would require significant trial and error. Finally, we decided to adapt the transducers from commercially available fish finders. These are relatively inexpensive, easy to source, completely waterproof and impedance matched to water. Despite the downsides of a high resonant frequency at 200 kHz and directional beam, this was the most reasonable option.

The fish finder's transducer connects to a small device which sends and receives the acoustic waves, and displays the location of the fish on its screen. Since the transducer is a black box, we first needed to characterize it. The specifications state it has a resonant frequency of 200kHz and beam angle of 45°. We first opened up the module and identified components on the PCB, as shown in Figure 3. The most important components to investigate were the microcontroller and transmitter circuit. This would shed light on the actual frequency and voltage used to drive the transducer. Using an oscilloscope, we found that the microcontroller would send a 5V square wave pulse at 200 kHz, and the signal was stepped up to $200V_{pp}$ to drive the transducer. A large capacitor and transformers were also found on the PCB, suggesting that it likely used a LC resonant circuit much like the one in Figure 2 to produce the high voltage.

In addition to the frequency and voltage requirements, we also investigated the transducers' range in water. The maximum range specified by the manufacturer was 100m. To test the range, we placed 2 fish finders in a pool at various separation distances with one acting as the transmitter and the other as the receiver. We recorded the peak received voltages and plotted them against separation distance. The results are shown in Figure 4 and we found that peak receive voltage decreases non-linearly. This indicates the receiver must be able to pick up voltages on the order of millivolts.

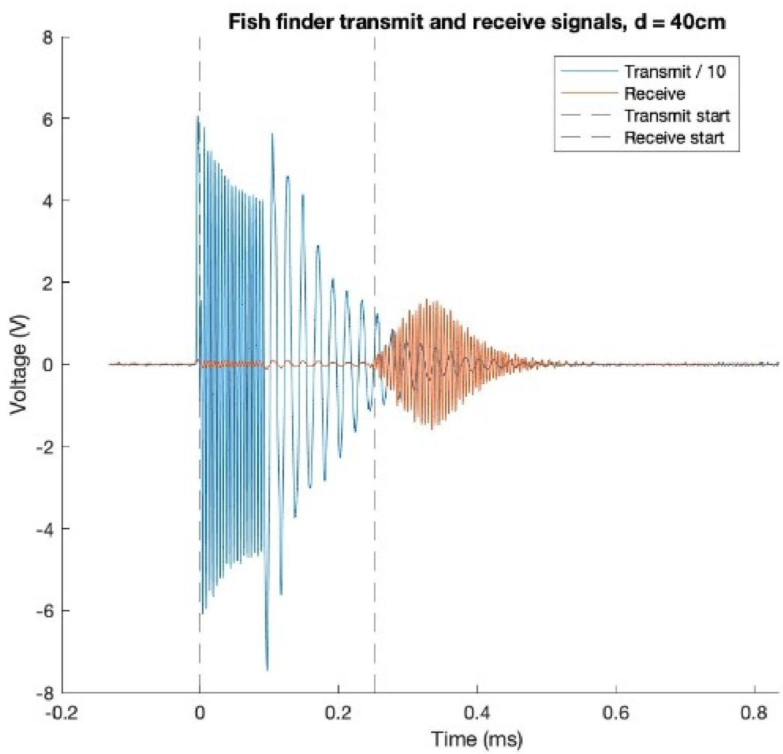


Figure 1: Transmit and receive pulse from the fish finder module, with transducers placed 40 cm apart.

2.2.2 Transmitter Electronics

To drive the transducer, we decided to use an H-bridge as shown in Figure 7. An H-bridge allows the voltage across the load to swing from the positive to negative source voltage, at any frequency. We also explored using an LC resonant circuit like the one in the actual fish finder (TODO Ref appendix if I write one); however, the circuit is designed to work at a single frequency only. In the future, a more suitable transducer may be used instead with a different resonant frequency therefore, the H-bridge solution provides the flexibility desired.

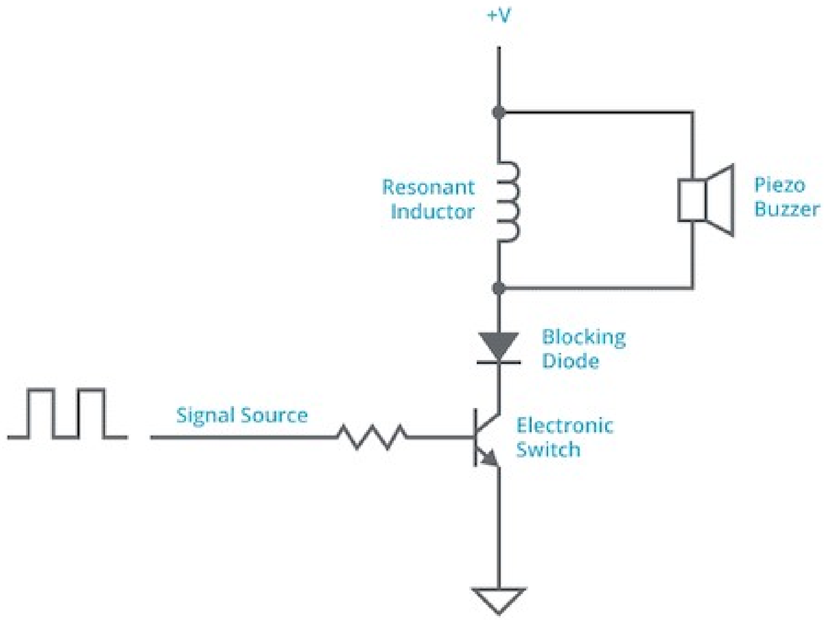


Figure 2: One possible circuit to drive a piezoelectric transducer is the LC resonant driver circuit.

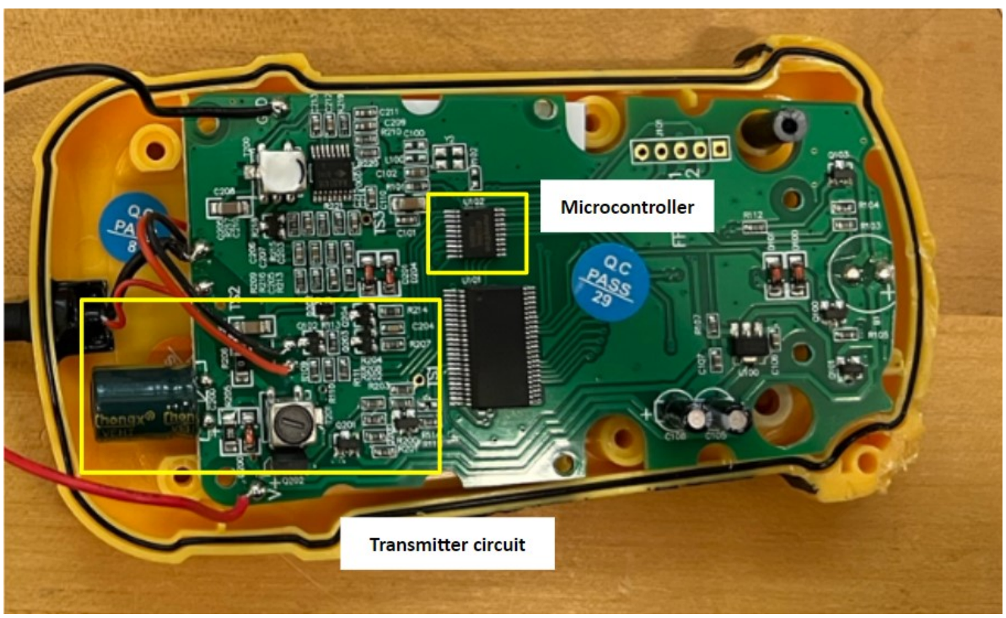


Figure 3: The PCB inside the fish finder and the identified microcontroller and transmitter electronics.

Flyback Converter - High Voltage DC Power Supply

To achieve the max range of the transducer, it must be driven at $200V_{pp}$. Portable high voltage power supplies are not readily available or affordable so it was necessary to design our own DC to DC converter to boost a low voltage 10V that can be supplied by a portable phone charger up to 200V. The topology we implemented to successfully provide this voltage boost is called a Flyback Converter.

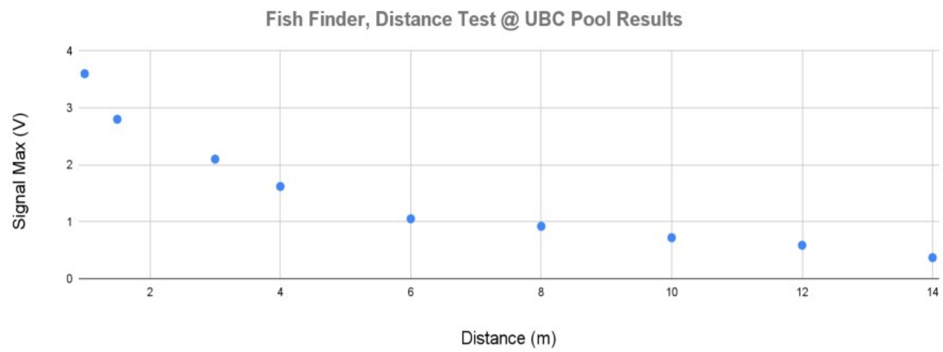


Figure 4: The max voltage seen at the receiver versus the distance between 2 fish finders.

Transformers are the key element of the Flyback Converter which allows us to achieve the desired voltage boost. They are essentially two inductors and energy is transferred between the primary (input) and output (secondary) side of the transformer by the coupling of their magnetic fields. We recommend the Transformer Wikipedia page for a more detailed description of how they work.

The Flyback can be in one of two states depicted in Figure 5:

1. **On State:** The switch is closed allowing current to flow from the primary supply and store energy in the transformer. The secondary side of the transformer is reverse polarized so no current flows through the diode. The capacitor acts as the DC voltage source on the load and discharges.
2. **Off State:** The switch is opened. Energy in the transformer induces a current on the secondary side of the transformer. This positively biases the diode and simultaneously supplies the load with power and recharges the capacitor for the next cycle.

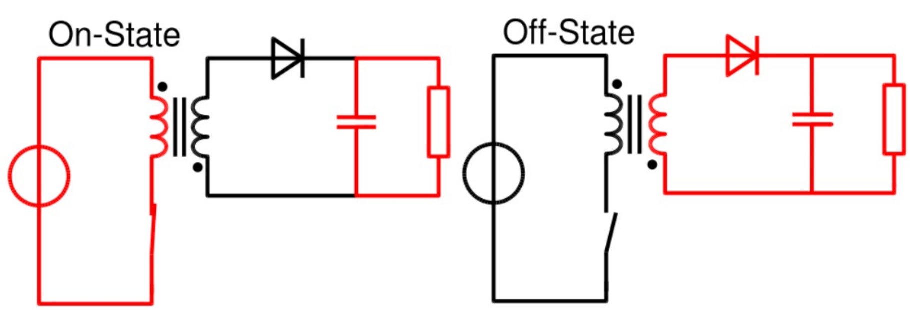


Figure 5: **Left:** Flyback converter in On-state. The transformer supplies the load and recharges the capacitor. **Right:** Flyback converter in Off-State. The capacitor supplies the load.

The parts we selected to build our Flyback Converter are summarized in table 2. Using our Flyback Converter we were able to supply a 90V DC output using a 6V DC input which was 86% efficient compared to our expected output based on the transformer's turns ratio.

Table 2: Summary of Flyback Converter elements and selection criteria.

Component	**Key Parameters and Details**
Transformer	1:17 voltage turns ratio. 400V max output voltage. A high turns ratio is ideal because it requires a lower input voltage.
Diode	400V reverse voltage. Needed so that the diode doesn't break down when a secondary voltage of -100V is applied in the off state.
Capacitor	$C = 100\mu F$. A larger capacitor was chosen so that if can store more charge. If the capacitance value is too large the recharge time will be too slow.
MOSFET + Gate Driver	$V_{DS,max} > 100V$ is ideal to protect the MOSFET from unexpected voltage spikes. A gate driver is used to switch the MOSFET so that a PWM signal from a microcontroller can drive the switch. 690 kHz switching frequency resulted in the most efficient power conversion.

Transmit Electronics Summary

To summarize our transmitter electronics, we are able to successfully drive our fish finder transducers

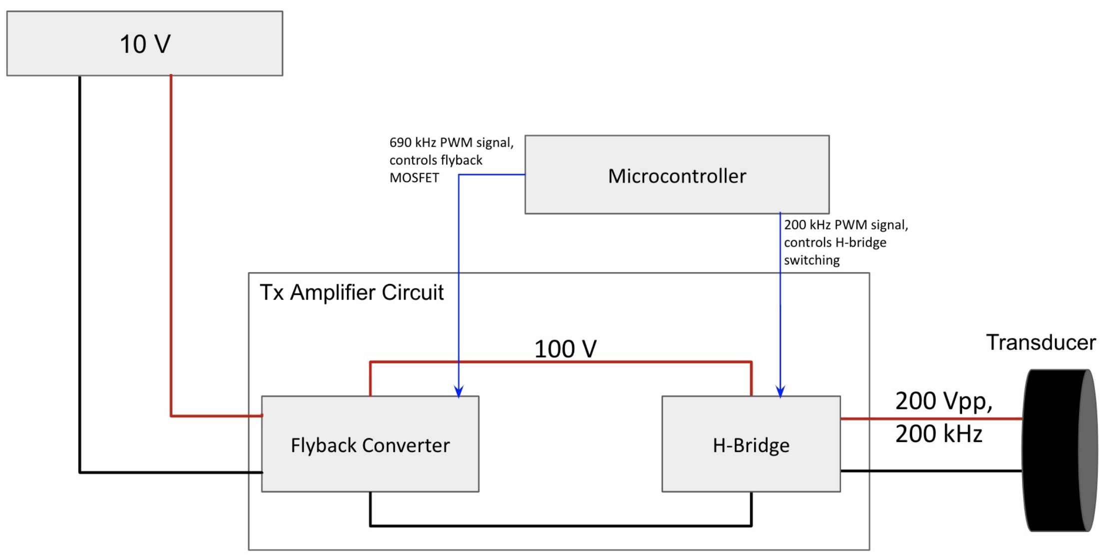


Figure 6: Transmit electronics block diagram. A 10V power supply is boosted up to 100V using a Flyback Converter which in turn powers the H-bridge that drives the transmit transducer.

using a Flyback Converter to act as a $200V_{pp}$ source and an H-Bridge which switches at the transducer's mechanical resonance frequency of $200kHz$. The block diagram in Figure 6 shows how these elements drive the transducer load, how they are driven using low voltage microcontroller PWM signals and the required external power supplies.

The complete schematic of the transmit electronics is shown in Figure 7

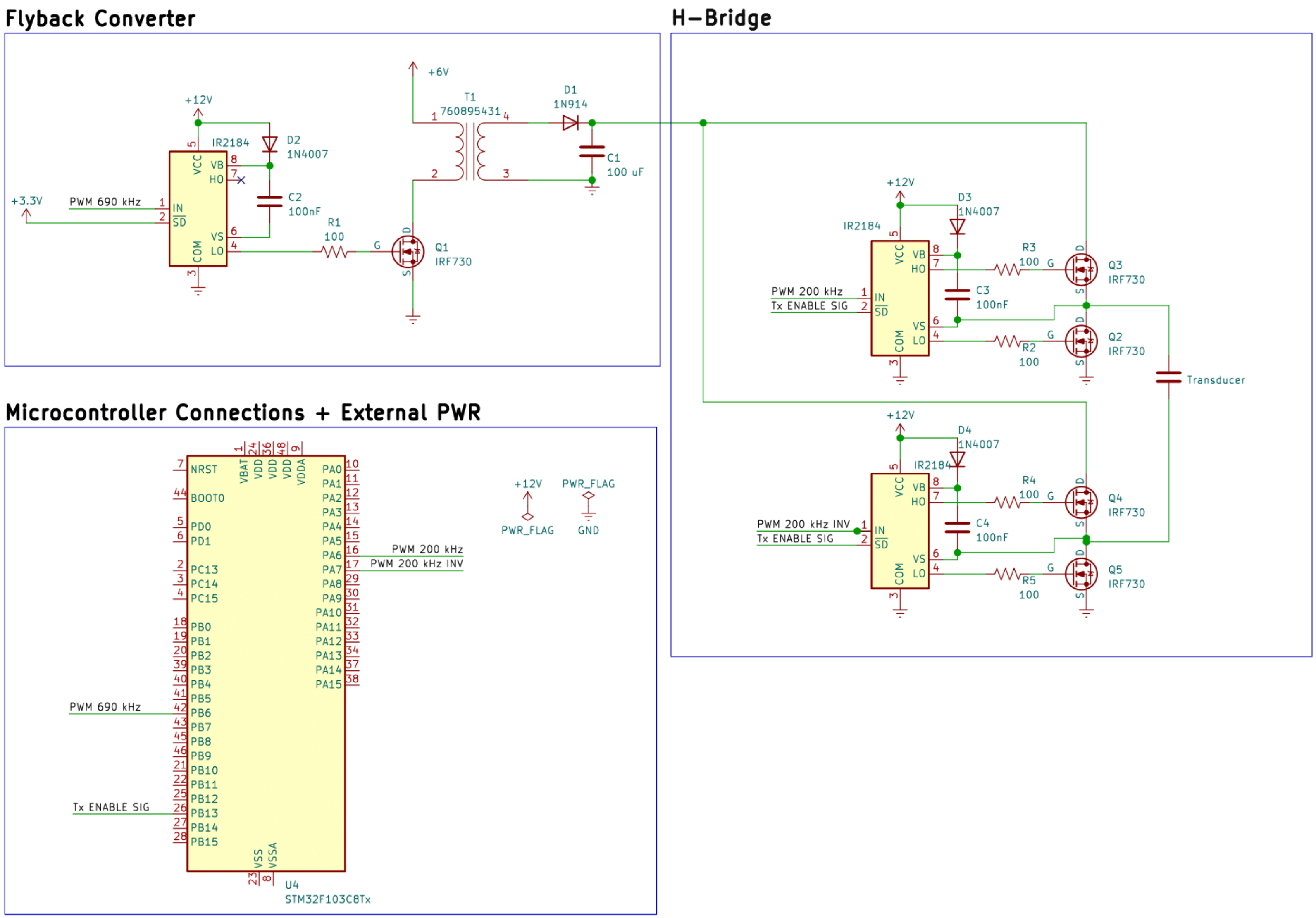


Figure 7: Complete schematic of the transmit electronics. Includes connections for the Flyback Converter and H-Bridge as well as their connections to the SMT32 Microcontroller. Note that nF scale capacitors were also placed between V and GND for all the power rails for filtering.

2.2.3 Communications

The ultimate goal of our communication system is to send text messages between nodes. We have figured out how to drive the transducers and make them vibrate. The next step is encoding text messages into a series of vibrations that can be generated on a transmit transducer and picked up and decoded back into text on a receive transducer.

Background

Our communication system is implemented by a combination of our transmitting circuit, receiving circuit, and an embedded microcontroller. The major basic elements are shown in Figure 8 below.

A user inputted message (ie. "hello") is fed into the microcontroller through a serial link, which encodes the string message into a binary sequence (ie. "0100. . . "). The microcontroller then acts as the modulator and controls the H-bridge transmitting circuit to transmit a waveform uniquely defined by the sequence through the water from the transducer. The receiving transducer obtains a channel-corrupted version of the waveform, which is returned to defined binary sequences by the demodulator implemented by the receiving circuit. The binary sequences are read on the microcontroller then decoded using the same mapping to recover the original message.

This choice of implementation introduces unique challenges. The microcontroller's limited computing reduces the encoding and decoding techniques available for use. The transmitting/receiving circuits have timing and bandwidth limitations that restrict our bit rate and modulation schemes. The presence of multipath propagation means that the channel has sources of noise that are hard to model. These affected the design decisions behind the communication system, which includes choice of bit rate, modulation scheme, and encoding protocol.

We implemented a low bit rate (50 bits per second) system using basic modulation schemes and encoding techniques detailed below. This provides as a proof-of-concept to showcase the possibility of future work to optimize this system further. The specific design decisions are discussed in the sections below.

Modulation Technique - On-Off Keying

The modulation technique chosen was On-Off Keying (OOK) amplitude modulation. OOK amplitude modulation is a widely used technique in digital communication that involves switching a signal on and off to create binary data for transmission. In amplitude modulation, a *carrier signal* is modulated based on a *message signal* signal, which forms an envelope that describes the digital message. In the case of OOK, the carrier signal is modulated such that a max amplitude pulse represents bit 1, and a zero amplitude pulse represents bit 0. This technique was chosen to reduce implementation complexity.

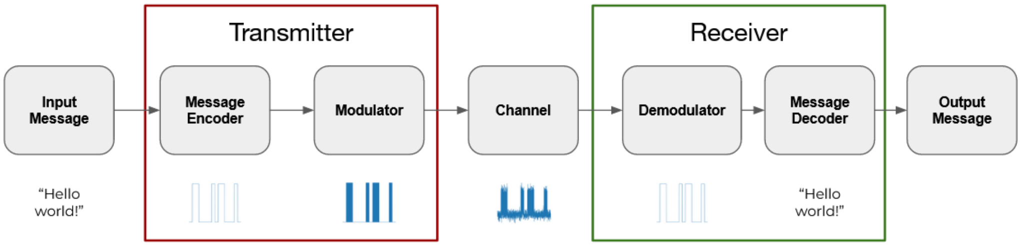


Figure 8: Block diagram of the components of a digital communications system. An example of how a simple sentence of "hello world" is transmitted through our implementation is shown below each block. The process goes from input string to binary to analog back to binary to output string.

The OOK modulator is implemented using a microcontroller to generate pulse-width modulated (PWM) carrier signals that are then digitally modulated in the transmitting circuit to form the message signals. Two PWM pins are used on the microcontroller to generate the out of phase PWM signals to act as carrier waves, which control the MOSFET gates of the H-Bridge circuit. A digital pin is used to enable/disable the H-bridge drivers with the message signal through controlling the IR2184 gate drivers logic function. A visual representation is shown in Figure 9

Transmit Firmware Implementation

ASCII is a character encoding standard where each character is represented by a unique byte (set of 8 bits (1s and 0s)). ASCII is also well defined for all alpha-numeric characters as well as symbols and punctuation making it the ideal encoding scheme for us to send text messages.

Any message a user inputs into our system (on a phone or small laptop) is represented as a string of characters which can then be encoded into a series of bits that are sent sequentially to drive the transducer. A digital 1 corresponds to an ON state where the transducer is vibrating and a digital 0 corresponds to an OFF state where the transducer does not vibrate. Specifically, we will use a digital output pin on the microcontroller to control the H-bridge gate driver enable pins.

We considered using standard communication protocols such as SPI and UART which both have well defined error handling, start/stop indicators and libraries in C++. Ultimately we had to implement our own communication protocol to get around some of the power limitations of our system.

A protocol such as UART sends all the data bits sequentially. For example, if a character was represented as 11111111 then our transducer would need to vibrate continuously. Since our transducer acts as a capacitive load it has an impedance $|Z| = |\frac{1}{\omega C}|$ which draws power any time it is vibrating. From our testing we found that it drains the power supply faster than the Flyback Converter can recharge thus transmitting a continuous series of bits is not feasible. Thus each bit had to have a transmit time as

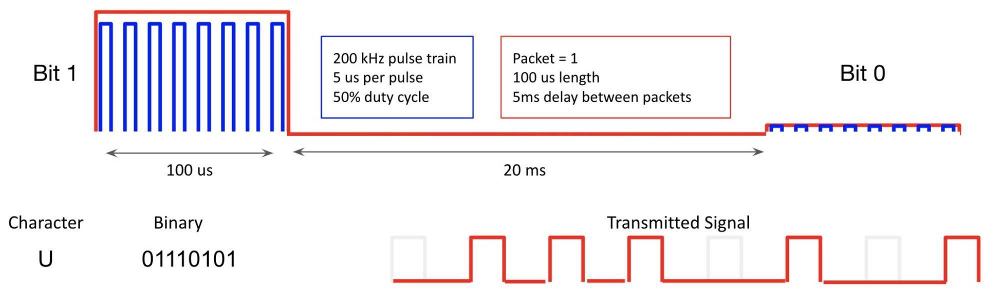


Figure 9: Visual representation of communication protocol. Characters are encoded into bits using ASCII. Each bit is a packet of pulses (100 μs duration) followed by an OFF period (20 ms duration) to allow the power supply to recharge.

well as a delay time where the H-bridge was off so that the power supply could recharge.

We had to optimize between a transmit time that was long enough to detect and a delay time that was long enough to maintain a constant supply voltage without sacrificing baud rate. After testing we settled on a transmit time of $100\mu s$ and delay time of $20ms$. With these parameters our system transmission speed is around 6 characters per second.

Receive Firmware Implementation

On the receive side we also had to implement our own communication protocol to detect the message and decode the bits back into characters that can be displayed to the user on a computer. Having already defined the communication protocol on the transmit end, implementing the receive firmware was straightforward.

We reconstructed the message as a series of bits by using rising edge detection. Each rising edge corresponds to a bit 1 and since the delay time between bits is a known and constant parameter of our system we could determine how many bit 0s were transmitted in between each 1. Then we simply segmented the bits and decoded the bytes back into characters. Additionally, at the start of each message, there is a start bit 1 that the receive firmware searches for so it knows when to start decoding. All of the receive and transmit firmware can be reviewed in our team's github repo: Cave Comms.

Table 3: The components of our communications system is summarized in this table

Component	**Key Parameters and Details**
Bit rate	Approximately 50 bits per second
Communications protocol	Custom protocol consisting of serial bits sent sequentially with a 5% duty cycle. Detailed in Figure 9.
Modulation Scheme	Digital Amplitude Modulation via On-Off Keying (OOK)
Encoding	ASCII encoding. Each character is 1 byte = 8 bits, giving us character rate of 6 characters per second

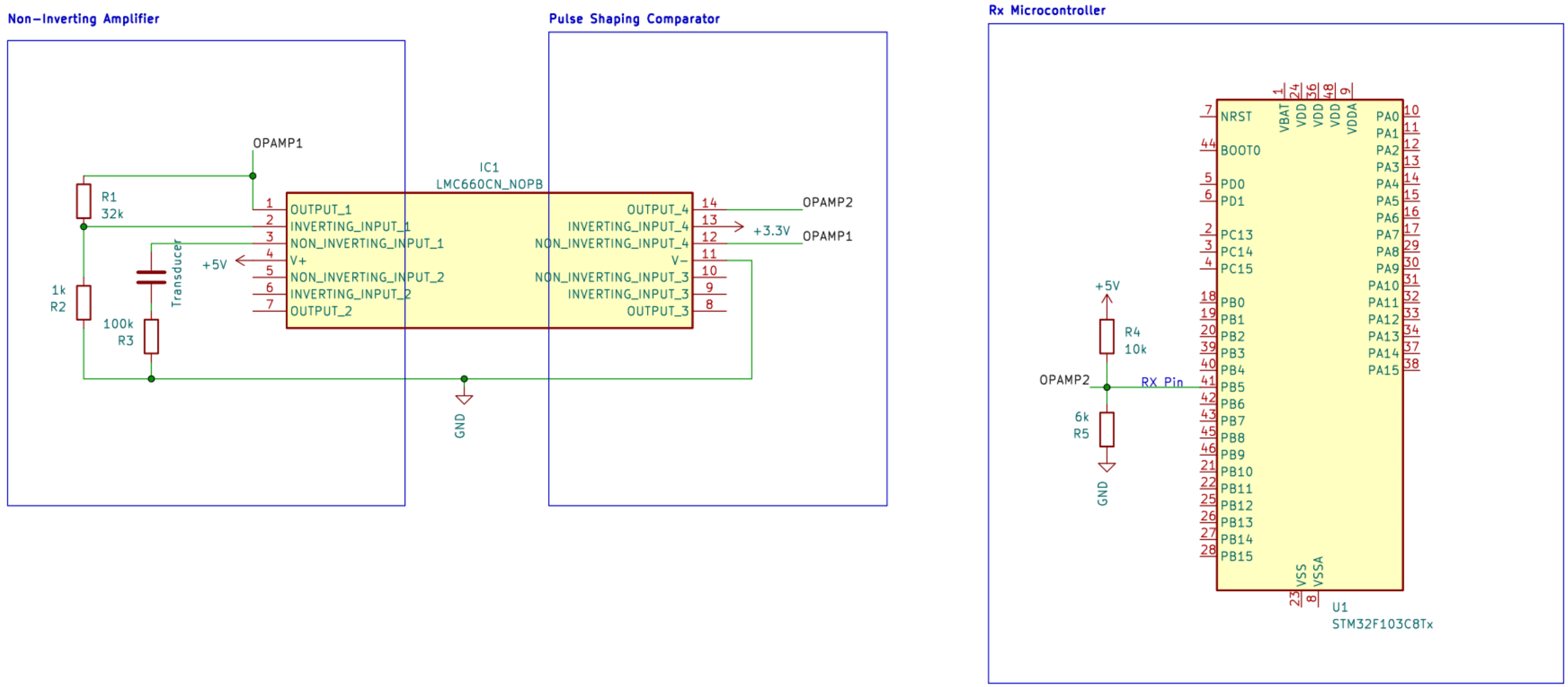


Figure 10: Schematic of receive electronics circuit.

2.2.4 Receiver Electronics

The receive electronics needs to transform the analog signal received on a transducer into a digital signal to be processed by our microcontroller. The receive electronics consists of a non-inverting amplifier, a comparator, and a resistor voltage divider. The schematic can be found in Figure 10.

From empirical testing, we determined that the receiver obtains an analog signal around $10V_{pp}$ when the transducers are nearly touching. In order to process it on the microcontroller, it needs to be converted into a digital signal from 0-3.3 V. The signal first passes through a non-inverting amplifier powered by 0-5V, which both amplifies the signal by a gain ratio of about 30 and clips it at 5V. This output is fed into the comparator, performs the demodulation by cutting off the signal at the point it reaches $V_{ref} = 3.3V$. This produces a $5V$ digital signal, which is then stepped down by a resistor voltage divider into a pin on the microcontroller to be processed. The output waveform is shown in Figure 11.

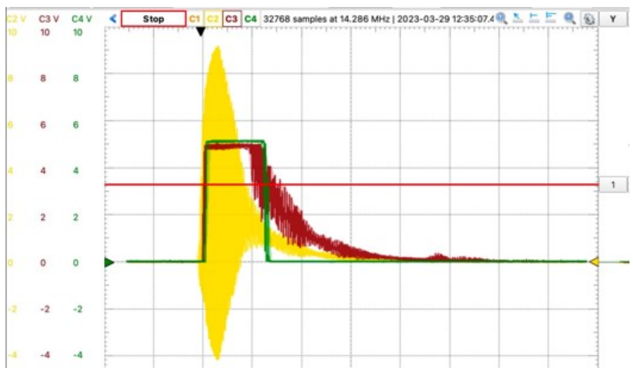
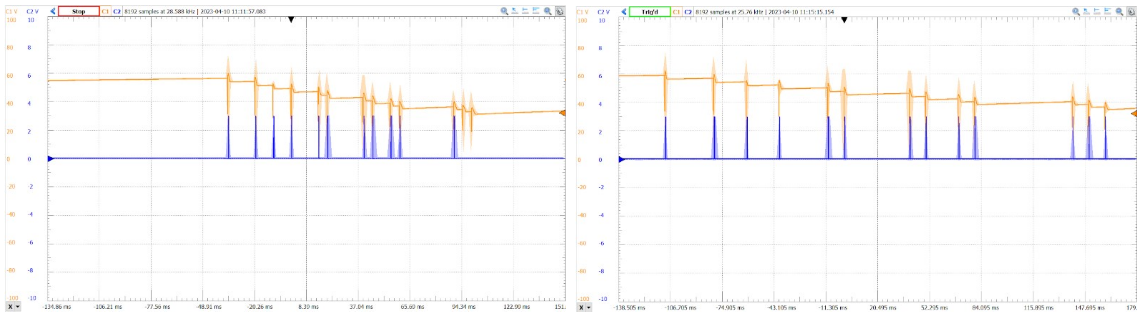


Figure 11: Waveform output of the Rx circuit. The yellow signal is the raw transducer output, the red signal is the clipped output from the non-inverting amplifier, and the green signal is the pulse generated by the comparator.

2.3 Tests

To send a bit, we used a $100\mu s$ pulse followed by a delay time. The delay time parameter allows for the Flyback converter to recharge and the pulse to fully dampen. Initially a delay time of 5 ms was chosen. Figure 12 shows the received pulses in blue and transmitted pulses in orange for a 4 character message, or $(4 \times 8) + 1 = 33$ bits including a start bit for the message. The message fails to fully send as the power becomes too low at the end. The receive is unable to receive signals which are sent below 40 V. Using a 10 ms delay time, the full message was successfully sent. We increased the delay time further to 20 ms and found that this allowed the Flyback converter to maintain a voltage of 60 V $(120V_{pp})$ for arbitrarily long messages. Using this delay time, we were able to achieve a bit rate of 50 bits/s or 5 ± 1 characters per second at a distance of 40 cm apart.



(a) (b)

Figure 12: A 4 character (36 bit) message sent using On-Off keying. Pulses are 100μs with (a) Delay time of 5ms, (b) Delay time of 10 ms. The message using 5ms delay time draws power too quickly and the final bits are too weak to be detected.

3 Conclusion

The purpose of this project was to develop a wireless underwater communication system to aid rescuers in a flooded cave environment. Our sponsor Dr. Carl Michal proposed floating communication modules that would be placed periodically along the cave. The modules would have an above water portion using radio, and an underwater portion using acoustic waves which would form a network of repeaters that focused on robustness and long distance communication over speed. Our final design focused on the underwater module and we developed a communication system which is able to send and receive text messages. We achieved a baud rate of 5 ± 1 characters per second using ASCII encoding with no errors in a test environment with two transducers placed 40 cm apart. The pulses used to send the messages were 200 kHz pulses at $120V_{pp}$. The main bottleneck of the baud rate was the power drop on the Flyback converter when pulses are sent, meaning a time delay had to be set between pulses to maintain sufficient power especially in longer messages. To increase speed, a more efficient power design should be pursued. The larger power requirement can also be offset with a transducer that has a lower resonant frequency, as it will suffer less attenuation. Additionally, while the current receiver worked for an ideal test environment, it is not an optimal solution in a real cave due to the use of an amplifier with a fixed gain. To accommodate the large range of potential voltages going into the receiver, a design with feedback and flexibility is needed.

4 Recommendations

Our team has successfully implemented a first proof of concept for a cave communications system. Specifically we have built a working underwater wireless communication system using acoustic transducers. In our work of building this first prototype we have identified and will discuss several improvements to the system that can be implemented by future teams for better performance.

4.1 Transmitter

4.1.1 Improving Transducer Performance

An omni-directional transducer with a lower resonant frequency should be selected to reduce attenuation in water and allow messages to travel in all directions. This improves the chance that it will be received by an adjacent module, thus improving robustness.

4.1.2 Transmit Power Electronics

In terms of power electronics limitations our Flyback Converter was only 86% efficient and the transducer draws a lot of power when it vibrates thus limiting our bit rate. One improvement that can be made is electrical impedance matching on the H-bridge load (transducer) using an inductor. The transducer has a capacitance of around 2 nF. At 200 kHz this corresponds to an impedance $Z_C = -j2.5k\Omega$. Thus if we attach an inductor such that its impedance cancels Z_C our load will dissipate less power during the transmit stage and we may be able to improve on our bit rate.

Our implementation of the Flyback Converter is also very basic. Some immediate improvements would be adding an RC snubber circuit on the primary side to protect the switching MOSFET. Calculations can also be done to select the optimal transformer leakage inductance and rectifying capacitor value to maximize efficiency. Refer to these websites for Flyback design guidelines: How to Design a Flyback Converter and Flyback Converter. Upgrading the general purpose gate driver chip (IR2184) on the Flyback to one designed specifically for Flyback converters (UCC28781) with feedback should also improve efficiency. The Forward Converter is another more complex but more efficient DC-DC converter topology that can be explored.

4.1.3 Modulation Schemes

The On-Off Keying (OOK) modulation used in the project is simple and low-cost but more susceptible to interference and noise compared to other defined modulation schemes. Frequency modulation, phase-shift modulation, or other amplitude modulation techniques like amplitude shift-keying (ASK) should be investigated to optimize for power consumption and a faster bit rate while maintaining the same error rate. None of these were tested due to time limitations, as they may require more complex transmit/receiving circuits.

Our team recommends testing out frequency modulation in particular. The transducers chosen were not characterized, so we were unable to drive at different frequencies beyond 200 kHz due to not knowing the transducer's mechanical bandwidth. The choice of better characterized transducers can allow more tests and optimizations for modulation techniques.

4.2 Receiver

The incoming signals at the receiver will vary greatly in amplitude therefore, an automatic gain control amplifier should be placed before the microcontroller to ensure the incoming voltages are always suitable. Similarly, to protect the low voltage electronics on the receiver side, a diode protection circuit should be placed before the sensitive electronics such as op-amps and the microcontroller. This serves to prevent large voltage spikes from damaging the components.

4.3 System

4.3.1 Nodal Mesh Network

This initial prototype would need to be developed further to be integrated as a larger mesh network communication system. The device would ideally be able to transmit and receive in multiple directions. Since the transducer used for this initial prototype was very directional, it is recommended to either source a new transducer or have multiple external transducers to face multiple directions.

To prevent crosstalk between devices, we recommend assigning each message with a unique message ID thus when a device transmits a message, it will remember the previous messages sent and will only send messages that have not yet been transmitted from itself.

4.3.2 Mechanical Enclosure

To improve upon the design and allow it to be integrated into a full system, we recommend designing a waterproof enclosure for the electronics, that would allow the device to float half above and half below water and using a waterproof sealant for wires that would need to run externally to the transducer. In addition these modules would need to be designed to be portable and easily attachable for rescuers to carry

4.3.3 Implement in Air RF Module

The purpose of the project is to create a communications module capable of communicating in air and underwater in a cave context. There are existing research and products like the HeyPhone that showcase RF communications in cave conditions, so the design should be well researched. Work will need to be done to connect these two channel links together and develop a robust system for cross-interface communications (ie. water-air, air-water).

Table 4: System Test Plan

Parameter	Distance
Distance	Bring the system to a pool or a large body of water up to 100m (range of fish finder transducer). Test to find the absolute max distance where message no longer transmit correctly.
Obstacles	Investigate the error rates that arise in the presence of obstacles (rocks, turns, changing cave cross section). This is related to diffraction and signal reflection.
Echos	Investigate the presence of echos in the signal and how that might contribute to cross talk. Implement error correction or electronic filtering to remove echos.
Noise	Generate high frequency noise (in the range of 40 kHz to 300 kHz) that could be created by animals or mechanical sources. See if this affects the signal picked up by the transducer.

4.3.4 Testing in the Field

We demonstrated that our system works in a medium sized storage container (1.0m x 0.5m x 0.5m). In this environment we saw no transmission errors even if the transducers were not facing each other and when people were trying to cause interference by splashing the water or partially blocking the transducers.

Obviously this is not an accurate representation of a cave environment where our system would actually operate. So it will be important for future teams to develop a series of tests that can systematically characterize the performance (speed and error rate) of the device in more cave like situations. Some test recommendations are briefly discussed in Table 4.