Wireless Trout Locating System

A Major Qualifying Project
Submitted to the Faculty of Worcester Polytechnic Institute

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Abstract

The goal of this project is to develop a prototype system with a self-powered transmitter that can be eventually used to continuously track and record the position of the Gillaroo trout species along the River Shannon without human interaction. This is achieved by harvesting energy from the fish and its surroundings, implementing a tracking method specific to the aquatic environment of the River Shannon, and by communicating the location of the fish to a command center.

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Executive Summary

The environment has undergone many changes in recent years. Some of these changes have caused problems, which includes a decreasing number of wildlife species. More specifically, fish have been affected by these changes. Global warming has decreased the number of fish available for food because the high levels of pollution in the water have caused death for many species of fish. In addition to environmental effects, the use of many modern technologies for mass fishing has caused overfishing and even harm to the fish.

The decreased numbers of fish and the overfishing problems have spiked interest in the ability to track the fish, more specifically the Gillaroo. The Gillaroo is a type of trout found in Ireland. Years ago, this fish could be caught easily and was plentiful, now this fish is scarcely seen. There is a current need to find a way to accurately track the fish and discover its breeding ground. If the breeding ground could be found, the fish could be more protected, or the area could be sanctioned as a “No Fishing” zone. Overtime, this could help increase the number of Gillaroo in the River Shannon and save the species from extinction.

The first steps to solving the problem were to research existing technologies and methods currently available for fish tracking, as well as research technologies that had the potential to be applied to underwater fish tracking and energy harvesting. One technology currently on the market is catch and release fishing, where a fish is caught and tagged. This method relies on the fish being caught again, data recorded and then transferred to the correct organization. Another technology in use for tracking is Radio Frequency Identification (RFID). This method relies on tagging the fish but records its passage through an RFID antenna placed at choke points in rivers, without human interaction. Closed circuit television (CCTV) systems are also used and function in choke points similar to RFID, but the fish does not have to be caught and tagged, the downfall

is the lack of a distinct identification for each fish. A more complex acoustic system using active tags that emit an ultrasonic signal has had success in open water, but in shallow or obstructed waters the signals can be distorted or lost. A more temporary technology available, due to the tags short lifespan, uses archival tags which are attached to a fish and record various pieces of information, such as water temperature and depth at set intervals. When finished, the tag automatically detaches from the fish and transmits the information via satellite. A simpler method of tracking the population of fish is called electrofishing, which uses electric fields to force fish to a confined area or the surface in order to be counted. Conversely, this method can only give a sample of the population at a given time and can be deadly to the fish. Alternative methods that were also researched include the use of directional antennas, Global Positioning Systems (GPS), thermal imaging and various proximity sensors. The possible advantages and disadvantages to applying these technologies to underwater tracking were further analyzed.

In order to accurately track fish along the River Shannon, an integrated approach was chosen because most tracking methods that function effectively in open waters are often less effective in shallow waters, and methods that work well in shallow waters do not have the range to be effective in larger open waters. The integrated approach uses two different systems, allowing for each method to compensate for the deficiencies of the other. The two methods chosen are an acoustic tracking system for the open areas, and an RFID system for narrow and shallow areas. The acoustic tracking system is effective up to 100 meters from each listening stations, but can be unreliable in obstructed areas. In contrast, the RFID system has a limited range, 20 centimeters, but is extremely reliable regardless of obstruction. By combining these two tracking methods, the system is able to have a large range from the acoustic system, and high reliability in shallow obstructed areas because of the RFID system, producing a superior system to either individual part.

The wireless trout locating system satisfied the overall design objectives. When the bender is tuned to oscillate at a frequency of 18 Hz, the energy harvesting subsystem is able to charge the receiver module to 3.6 V in less than 1 second. The RFID system can successfully detect a tag whenever a fish passes through the RFID antenna. The acoustic system can detect any fish within 100 meters with a direct line of sight, and can also detect the strength of the signal received at each listening station. The successful function of the RFID and acoustic system allows the location of the fish to be determined and the tracking information of the fish obtained to be encoded in a parallel binary sequence for transmission to the mission control. The mission control has the capability of reading the four signals, one from the RFID reader and three from the acoustic listening stations, and outputs the correct sequences on the LEDs of the FPGA evaluation board.

Though the project was successful, the project was considered a proof of concept, and therefore there are several areas of future work that the team considered. Overall, the system could be implemented in smaller form factor using surface mount technology and board layouts. The energy harvesting module could be further developed before being implemented on a live fish by using a piezoelectric bender that can be more easily bent, increasing the ability to harvest energy and power the transmitting device. Implementing a microcontroller to replicate most of the circuitry in the RFID subsystem would increase overall operation of the system. Adding the ability to transmit wirelessly from water to air for the communications part of the system would increase usability of the overall system. Lastly, the mission control could be refined by using a microcontroller and adding an SD card for the data storage. Improvements in these four technical areas will greatly enhance the marketability of the system as a whole.

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1.0 Introduction

1.1. Motivation

The world, its atmosphere and its ecology have greatly changed over the past decade. Scientists have noted that more animals have become endangered, extinct, or more in danger of being extinct. Many animals have been traveling further and looking longer for a food source and many have not been able to find the food they typically eat [1]. As seen in Figure 1.1-1, many individual ecosystems have been impacted by this global change. Everything within a specific ecosystem is interconnected and thus affected by any type of change [2].

One type of animal that has been greatly affected by this global change has been fish. Fish have undergone several changes over the recent decades. Given these global climate changes, the temperature of the water has been greatly affected, causing many species of fish to move and change migration patterns. Fish have had to swim further and dive deeper to find food

[3]. The temperatures of the streams and rivers have increased such that cold-water fish, such as trout, can no longer survive in these warmer waters [4]. Consequently, the species of marine animals seen on the coastlines of places such as Ireland have changed over the past several years. There have been reports saying there was a large increase in the number of jelly fish, a danger to both swimmers but also many other marine animals. This has caused their search for food to change, and anything that might eat these fish has also had to change its behavior to find food as well. In addition, the increased amount of pollution, such as carbon dioxide, in bodies of water such as ocean and rivers, has resulted in large death tolls in many fish species [5]

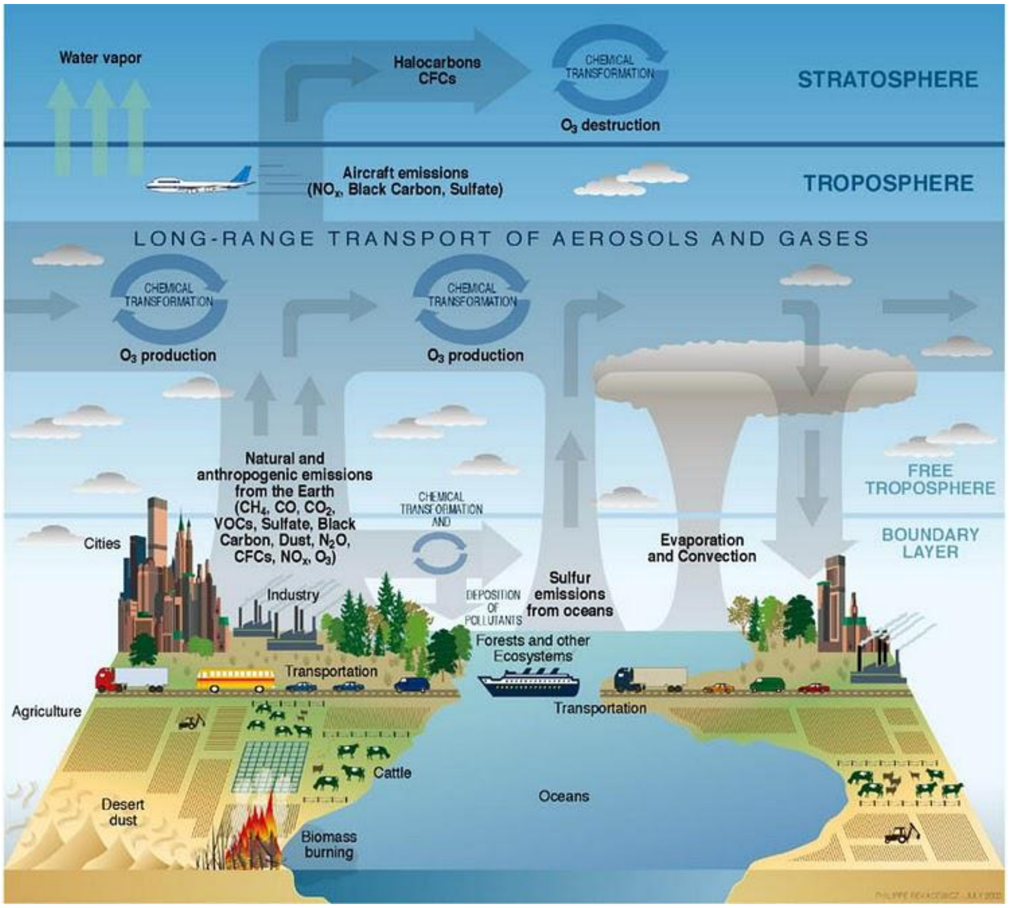

Figure 1.1-1 Global Warming [2] The above chart shows how everything in the environment can easily be affected by one simple change, such as the addition of aerosols and gasses into the environment. Consequently, this one change can result in the water, animals and agriculture being negatively affected.

Finally, overfishing has caused a significant decrease to the population of many fish species [1]. Due to the high demand for fish and the constantly decreasing number of fish, fishermen have resorted to using nets with smaller and smaller openings. This causes smaller fish that have yet to breed to die prematurely [1]. With overfishing, which is estimated to be equal to 33% in Ireland [6], and a loss of opportunity to breed, the number of fish will inevitably continue to decrease unless changes are made.

Changes in both land and water have caused a negative effect on many animals. Fish have been negatively affected by these changes as well. Fish provide a source of food for both humans and other larger water animals. All of these negative effects have resulted in the decrease in the number of several species [1]. In Ireland, the fish stock is currently declining and is not being sustainably harvested [7].

1.2. Gillaroo Tracking

The River Shannon and its tributaries stretch throughout Ireland. The river stretches for over 259 km and is a barrier between the east and west parts of Ireland flowing into the Atlantic Ocean [8]. Along this river there are many species of fish and wildlife. Many of the fish present in the Shannon travel from ocean to river throughout the seasons. However, there are several fish species that reside only in the freshwater of the Shannon, such as the Gillaroo [9], [8]. The Gillaroo is a specific species of trout that is believed to only exist in a very confined area of the Shannon River [9]. Scientists believe that the Gillaroo exist and breed in a 28 km region of the River Shannon between an area around Castleconnel and Lough Derg [9] ,[17], as shown in Figure 1.2-1. The Gillaroo was only declared a distinct species 25 years ago, as previously, it was thought to be a trout that had changed its physical characteristics to fit its new surroundings. Scientists have now begun DNA testing from the adipose fin on many fish in this small area in hopes of uncovering more information about the Gillaroo [9].

Figure 1.2-1 Section of the River Shannon where the Gillaroo is found, the highlighted section is where the Gillaroo inhabits.

There is very little information available on the Gillaroo. However, local residents that live along the River Shannon have recognized a significant decrease in the number of Gillaroo over the past ten years [4], [9]. Ten years ago, people would fly fish for the Gillaroo in late fall, and they were plentiful but presently, it is hard to find Gillaroo in the previously mentioned section of the River Shannon at all [9]. There is little knowledge of the Gillaroo's breeding location and although 28 km is a small portion of the River Shannon, it is still too large to cover using any of the available tracking approaches. In order to save the Gillaroo, there needs to be a way to find its breeding grounds and track its behavior to help provide protection and perhaps even rehabilitation of the Gillaroo.

1.3. Current State-of-the-Art and Problems

One method of fish tracking currently being used is catch and release fishing. In catch and release fishing, fish are caught and tagged with a plastic strip that has a phone number and identification number for the fish, as shown in Figure 1.3-1. If fishermen re-catch the fish, they can call the phone number on the plastic strip and report the location where they caught the fish, along with its size and weight if possible. Though this method can show overall patterns of fish movement, there are several issues. This method relies on the fish being re-caught for any tracking to be recorded and for some species the return rate is less than 1%. Moreover, this method relies on the fact that those that catch the fish will actually call [10].

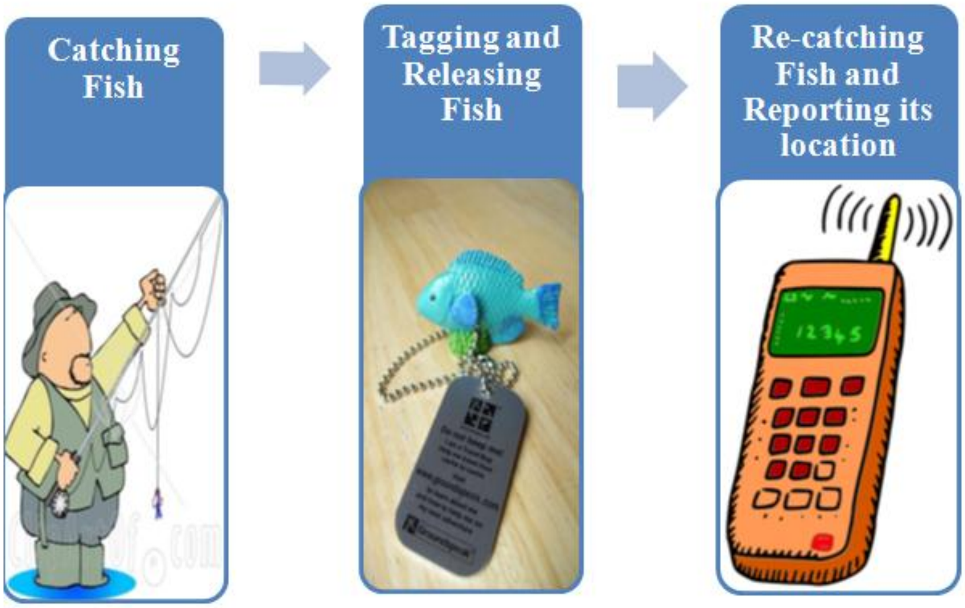

Figure 1.3-1 Catch Release Fishing. The Catch Release process consists of catching the fish, tagging it with a phone number and an identification number, and then releasing the fish back into the water. The fish location gets reported once a fisherman re-catches the fish and gives the fish identification number by calling the phone number on the fish.

Presently, one way to track fish is to use the Radio Frequency Identification (RFID). The RFID tracking for fish is done by injecting tags known as Passive Integrated Transponders (PIT) into the abdomen of young fish [11]. Migrating fish, such as Salmon, are easy to detect when they pass through a narrow point, such as a river mouth. However, this technique is not well suited for non-migrating fish, such as the Gillaroo, because this technology is dependent upon the fish passing through the RFID antenna array, as shown in the middle photo in the figure below [12]. In Figure 1.3-2 below, the overall function of an RFID system is shown, showing how the tag interacts with the antenna of the reader in order to get data to both the reader and the host computer [13].

Figure 1.3-2 RFID concept diagram showing the tag, on the left, that would be inserted into the fish in order to communicate with the antenna array which is in the center and the reader, the photo on the right, receives the transmitted information. [13]

Closed Circuit Television (CCTV) systems are essentially a camera or system of cameras that are positioned across a river or other waterways, typically at a natural choke point to view the passing of fish as shown in Figure 1.3-3. The cameras can be placed above or below the surface of the water to record the video of the fish as it is passes by the camera [14]. Closed Circuit TV can be used to confirm the reliability of counters or act as counters themselves. The cameras can be used in conjunction with another system such as RFID to record whenever the counter records a fish to provide visual verification, or the cameras themselves can provide some image recognition to identify fish shapes of a specified size in order to count the fish passing [15].

Figure 1.3-3 CCTV System Diagram. The cameras are placed in an area where the river narrows. As the fish passes this area, the cameras record the fish [16].

Acoustic tracking involves placing a tag on or in a fish that emits an acoustic signal typically between 30 and 80 kHz. This signal can be heard by acoustic receivers, which then determines the location of the fish. Depending on the frequency used, acoustic tags can have a range of over 1km [17]. The tags send out encoded signals at preset time intervals that can be heard by listening stations set up in known locations or on a boat following the fish. This concept can be seen in Figure 1.3-4, which shows each of the listeners attached to floating balloons and the tag attached to the fish. The listeners pick up the signal as the fish travels within range of the listener network. Boats are typically used for tracking in the ocean, while listening stations are typically set up in lakes and rivers [18].

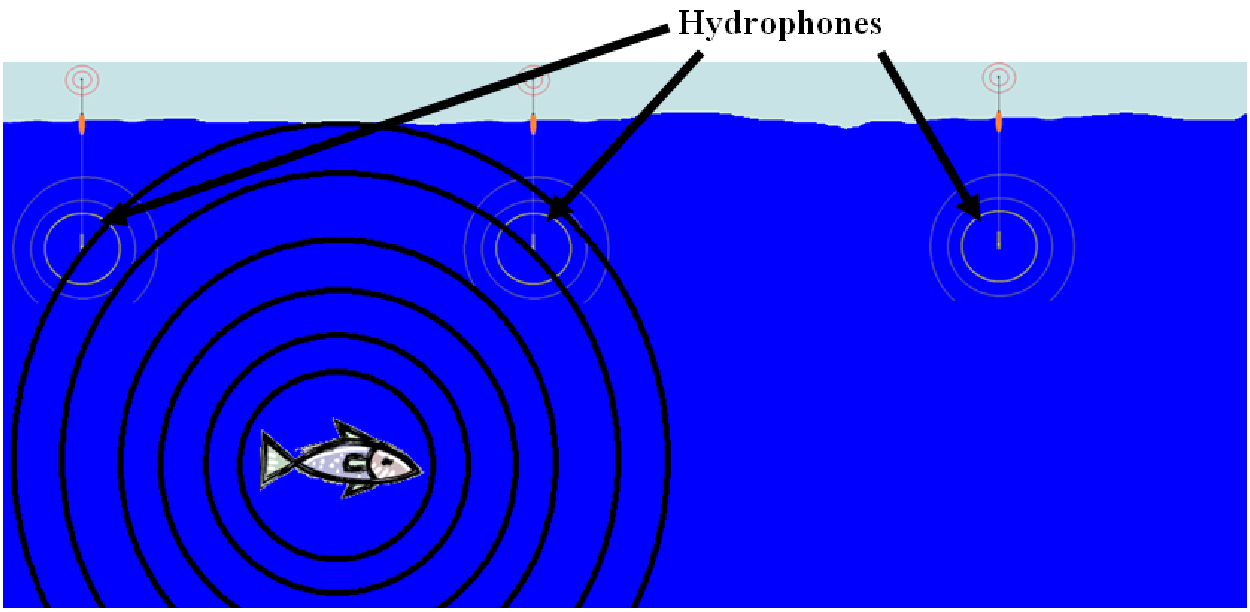

Figure 1.3-4 An example of a fish that has an acoustic tag. The tag sends out acoustic waves, which are received by hydrophones, positioned throughout the area. When these hydrophones receive a signal from the fish, they process the information contained in the signal and use the time that the signal arrived to calculate the position of the fish relative to each hydrophone. All this data is collected together, and the position of the fish, along with any other information the tag is collecting is known.

Archival tags are another system that has been used to track fish, typically in the open ocean. Figure 1.3-4 shows a system diagram of an archival tag system. The basic design is a positively buoyant tag attached to the fish, which records specified data, such as temperature or pressure of the water around the fish, at set time intervals as the fish travels. Once the tag has recorded enough data it is released from the fish and floats to the surface, where it transmits its stored data via satellite [19]. These tags have a very limited lifespan, typically between 3 and 30 days [20].

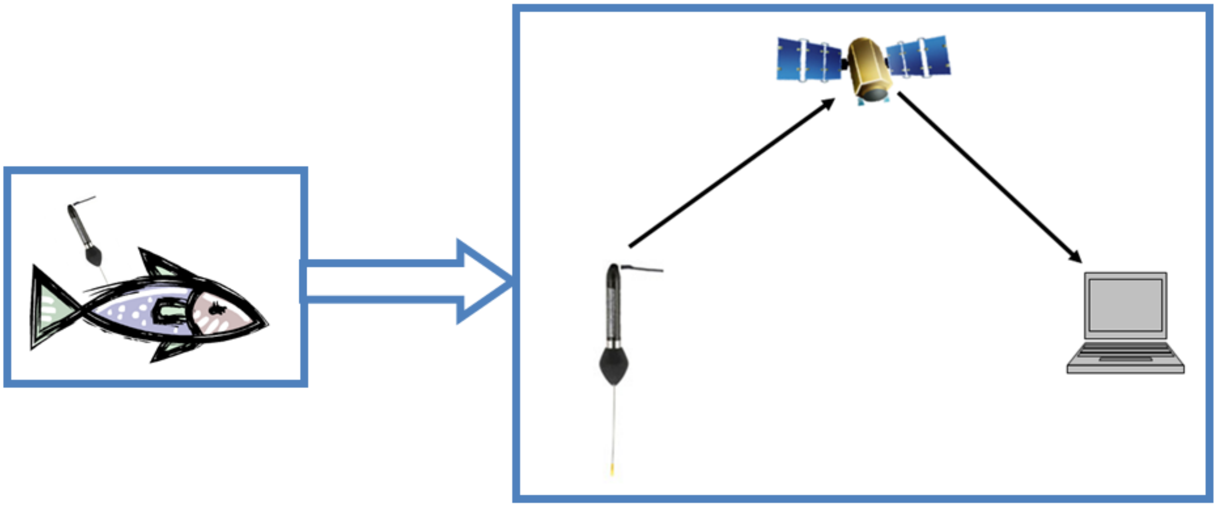

Figure 1.3-5 An archival tag is attached to a fish, which is then released into the river. The tag collects information over time such as temperature, position, and depth. Once the memory capacity of the tag has been filled, the tag detaches from the fish, floats to the surface of the water, and transmits its information via satellite to a predetermined location [21].

Electrofishing methods are being employed by fishery biologists in some countries including Ireland for approximation of fish density of particular species in rivers [17]. The typical practice is to select an area along a river where electrodes can be immersed, as shown in Figure 1.3-6. The electric shock stuns the fish which causes them to rise up to the water surface as a result. The fish density in the river is then based off the number of fish of a particular species found in the test site [17]. Although electrofishing is very convenient for humans, it has significant harmful effects to the fish, such as spinal injuries and bleeding in the gills.

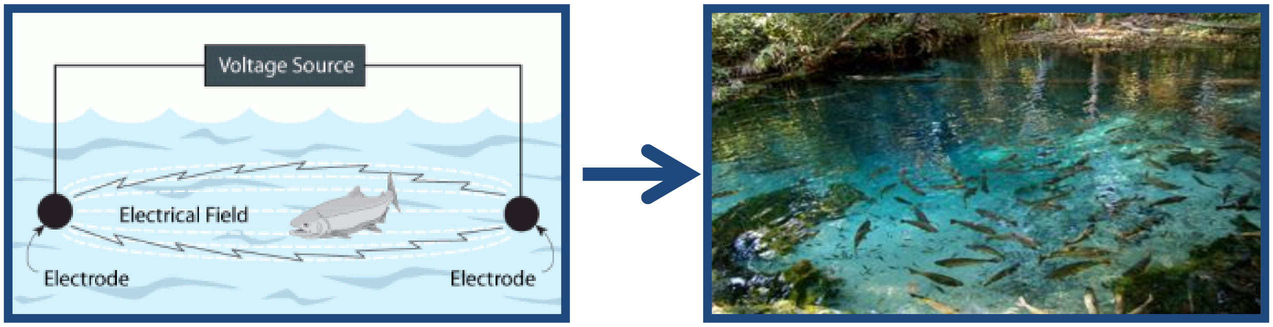

Figure 1.3-6 Electrofishing [22]. The electric field is generated by applying a voltage source between two electrodes. The resulting shock stuns the fish which rise up the water surface.

Directional antennas are also being used to track wildlife. The transmitter is connected to the animal under investigation. The transmitter sends out a Very High Frequency (VHF) signal which is received by the directional antennas [23], as shown in Figure 1.3-7. Although this method is effective, the approach is labor intensive because it requires manual tracking. The manual tracking using directional antennas becomes more difficult underwater, in addition, the usage of VHF underwater would be impractical because VHF radio signals are significantly attenuated in water. Therefore, if this method were to be used, the person tracking the fish would have to be within close range of the fish [24].

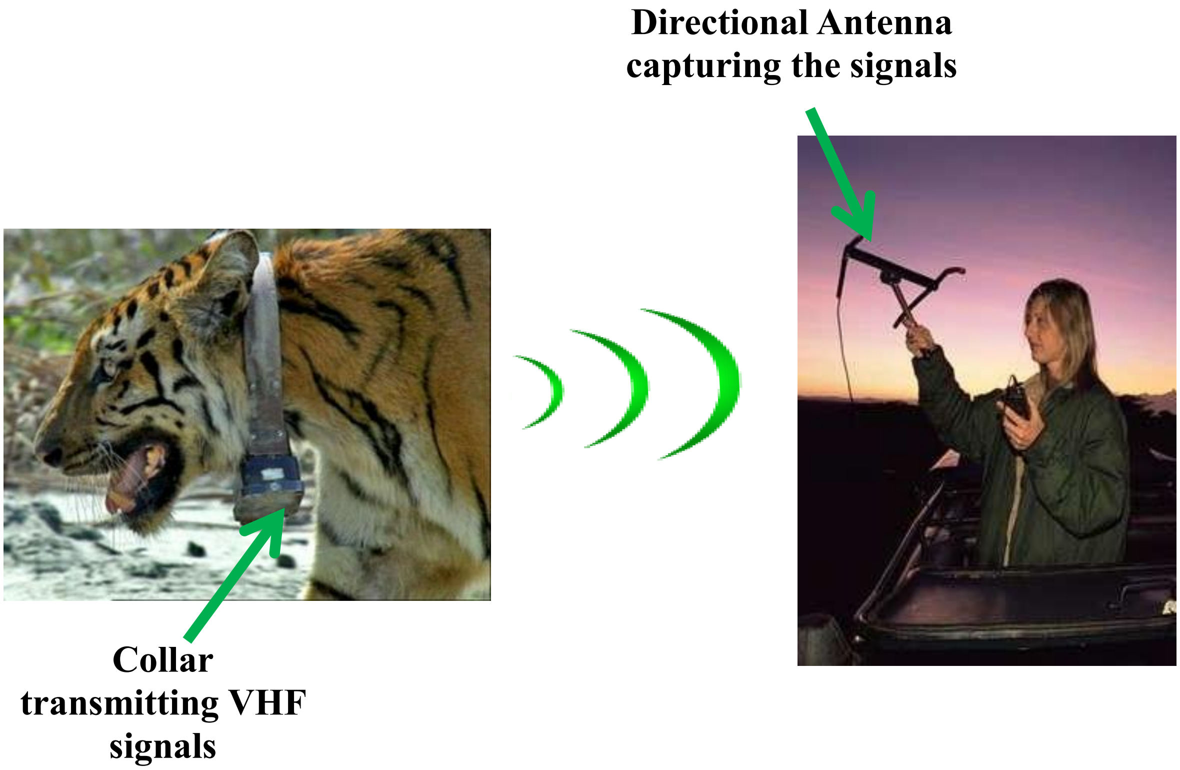

Figure 1.3-7 VHF tracking. To locate the animal, a scientist uses a directional antenna that picks up the signal coming from the transmitter placed on the animal's collar.

1.4. Proposed Design

The project's aim is to develop a self-powered underwater wireless tracking system. The system consists of two main modules as shown in Figure 1.4-1. The first module is an energy harvesting device which will generate electrical power from the Gillaroo. This energy will be derived from the energy of the Gillaroo, such as its swimming motion or thermal energy. This power will be used to operate the wireless communication device, which will provide a long lasting tracking system. The energy harvesting device will be attached to the fish in a manner that will not cause any harm to the fish based on biological studies done previously.

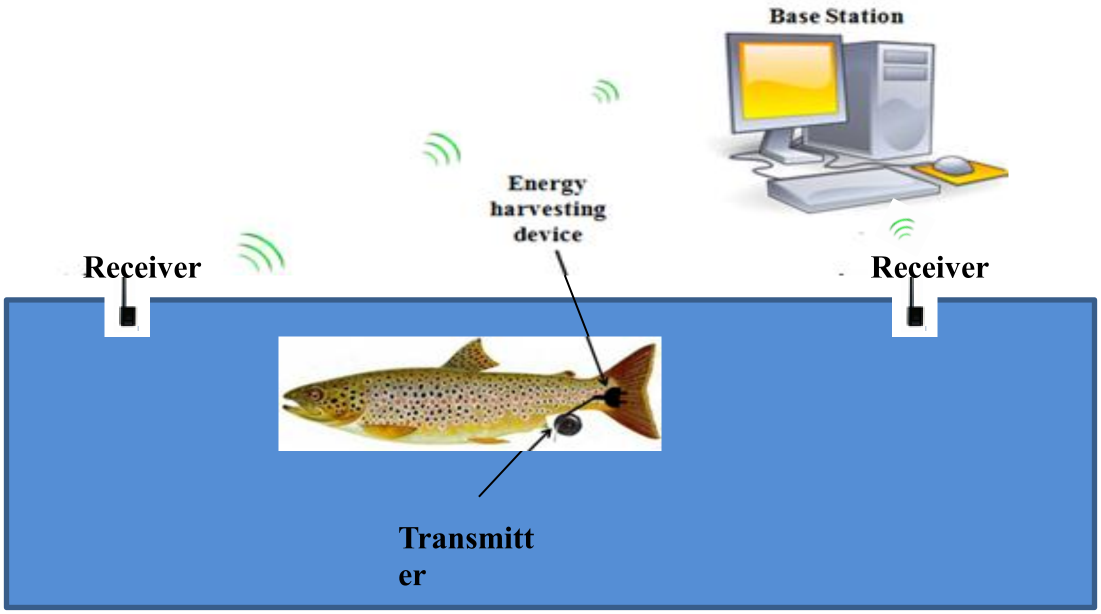

Figure 1.4-1 Concept Diagram. The fish is equipped with a self-powered transmitter which is constantly sending the identification number to listening stations along the river. The data from the receivers is then transmitted to a base station to determine the location of the fish.

The second module consists of an underwater wireless communication device. This device will be based on a transmitter sensor on the fish that sends underwater signals to an underwater receiver. The data acquired from the receiver will be then transmitted to an onshore base station. The location will be determined using localization techniques such as the received signal strength indicator (RSSI). The system has to compensate for the physical limitations imposed by the properties of water, such as the propagation of wireless signals and the attenuation. This attenuation can be high and can cause a reduction of range and performance.

Note that the proposed system will be designed such that the device will not attract the attention of predators or impact its physical behavior

This project advances the current state-of-the-art by continuously tracking the fish and using an energy harvesting concept to increase the device's lifespan. This project is neither fish nor environment dependent, and thus it can also be adaptable to other species of fish and implemented at other locations. The tracking system will be beneficial to biology research communities, commercial fisheries and the agriculture sector, since this system will be both mobile and modular and also have a longer lifespan by harvesting energy from the fish, allowing continuous recharging of the battery. This will increase the understanding of the behavior of the Gillaroo but can be expanded to other fish as well.

1.5. Report Organization

The structure of the report is detailed in this section. Chapter 2 provides a literature review of necessary background knowledge to build the desired modules for each technical concept. This chapter gives a description of the Gillaroo and the river Shannon. It then outlines the different methods of energy harvesting, tracking and communication. Chapter 3 states the specific design choices that were made based on the information from the background research. Chapter 4 provides a technical analysis of the subsystems integration to provide the overview of the design. Chapter 5 investigates the system results and functionality. Chapter 6 delivers the conclusions and future recommendations for improvement. Lastly, appendices are attached at the end of the report. They document supplementary information that is too large to include in the main text.

2.0 Energy Harvesting and Communication Tracking Methods

Gillaroo is a species of fish that has started to significantly decrease in numbers over the past years. For this reason, there is a need to track the Gillaroo in order to uncover what has happened to this species of fish. The Gillaroo that this project is concerned with only lives in certain sections of the River Shannon, narrowing down the area where tracking is necessary. Due to the fact that fish are always swimming, this chapter will explore the various opportunities to harvest energy from the fish and its surroundings. Though there are many different methods to track an animal, such as the Gillaroo, water increases the complexity of the tracking problem. This chapter will identify the various methods for tracking animals and show whether the application for a fish is feasible. Finally, this chapter will discuss the options for communicating both above and below water. This chapter will provide all the necessary information to understand both the overall problem and its complexity.

2.1. Environmental Considerations

When designing a system that will be implemented on an animal, the effect that the device will have on the animal and its habitat must be considered. A tracking device that causes the Gillaroo to die sooner than it would have otherwise makes the device itself disadvantageous to the survival of the Gillaroo, as it will not be able to observe the animal behaving normally. Additionally, if the device pollutes, or otherwise upsets the ecosystem that the animal lives in, the goal of the system, to protect the Gillaroo from extinction, cannot be achieved. To ensure that the device will not negatively impact the Gillaroo's lifestyle, or have a negative impact on the River Shannon, the Gillaroo and the river must be understood.

2.1.1. Gillaroo

The Gillaroo is a species of trout that is unique to the west of Ireland. Lough Melvin is considered to be its home in Ireland and the only lake where it has been regularly captured. Although the existence of the Gillaroo in other Irish lakes has been reported, the Gillaroo's unique gene does not match the 200 other species of trout found in Ireland and Britain. In addition, it has been established that the progeny of the Gillaroo of Lough Melvin keeps its feeding habits and coloration when displaced to a different body of water. The Gillaroo is generally found in shallow areas of the water along rocky shores, and in sandy bays and has not been seen in deep or open water [25].

The Gillaroo's name comes from the red flecking on the fish, as shown in Figure 2.1-1. The name is translated from "Gil" and "roo" in Gaelic to "The Red One" in English [26]. The Gillaroo is considered a bottom-feeding fish and feeds almost exclusively on animals, such as snails and freshwater shrimp. However, in the late summer they come to surface in order to feed and can be caught on the dry fly. Besides its deep red spots, the Gillaroo is characterized by a "gizzard" to help with the digestion of hard food such as water snails. As for their lifecycle, Gillaroo rarely live longer than five years [25].

Figure 2.1-1 Ireland's Gillaroo trout [27]

Trout are considered to be cold-blooded creatures, which mean that they take on the temperatures of their surroundings. Studies have shown that in temperature ranging from 40 to 65 degrees F, trout preserve their normal routine and are actively feeding. When the temperature fluctuates outside the trout's range, it affects their activity and feeding levels. They become slow-moving and can even die. Trout possess an extremely developed set of senses, as with most animals. These senses help the trout navigate, locate food and avoid predators. Trout have dual hearing systems: hearing receptors and a lateral-line system. The hearing receptors in the trout's head allow them to hear sound frequencies outside the human hearing range. The lateral-line system on each side of the trout's bodies picks up frequency vibrations [28] as shown in Figure 2.1-2. Trout also use the earth's magnetic field to navigate. A team of scientists in New Zealand found magnetite in the fish' head close to the never fibers, which they believe is the fish' internal compass [29].

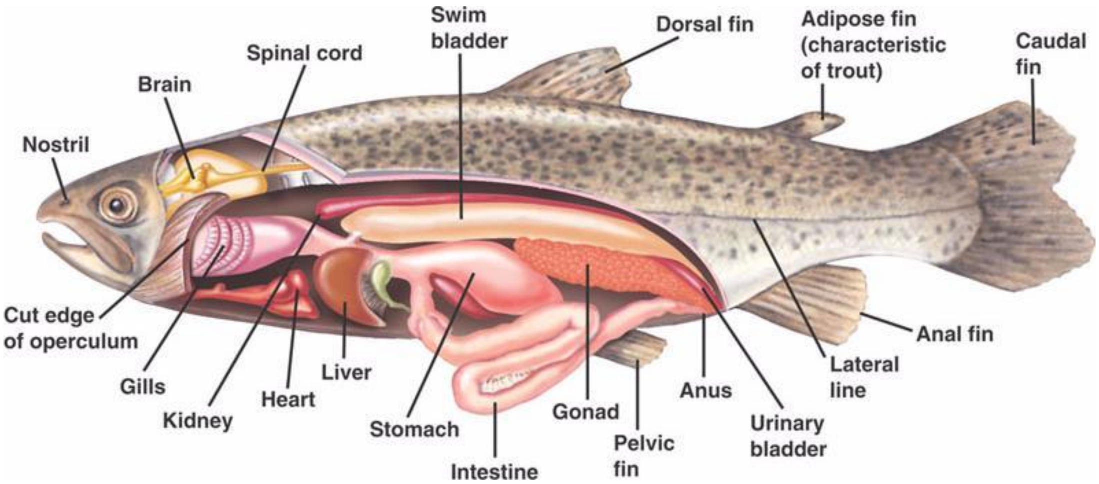

Figure 2.1-2 – Trout Anatomy [30]

2.1.2. The River Shannon

The River Shannon begins at the bottom of Tiltanbane Mountain and flows 386 kilometers to the Atlantic Ocean [31]. Along the river are several large lakes, such as Lough Derg and Lough Ree. The geography of the river varies along its path. Some areas are slow moving and surrounded by marshlands particularly in the area north of Shannonbridge. After Shannonbridge, the River Shannon is joined by the River Suck and flows into Lough Derg. From Lough Derg to the sea, the river falls 109 feet, and is used to generate electricity at the Ardnacrusha hydroelectric power station [8]. At this point, the river is divided and about 2/3 of the river is diverted for the power station. The remaining third is fairly fast flowing but has sections which have islands and forks that divide the river into smaller streams at times. This section varies between 1 and 3 meters in depth [17]. There is also a fish ladder at the power station to allow fish such as salmon to pass upstream. Pollution along the river is very limited because it has been primarily used for private boating after commercial shipping was replaced with railroads in 1850 [8]. The area the project will be focusing on is a 7 km section between Lough Derg and Castleconnell, highlighted in yellow in Figure 2.1-3, which is at times broken by a number of islands and other barriers.

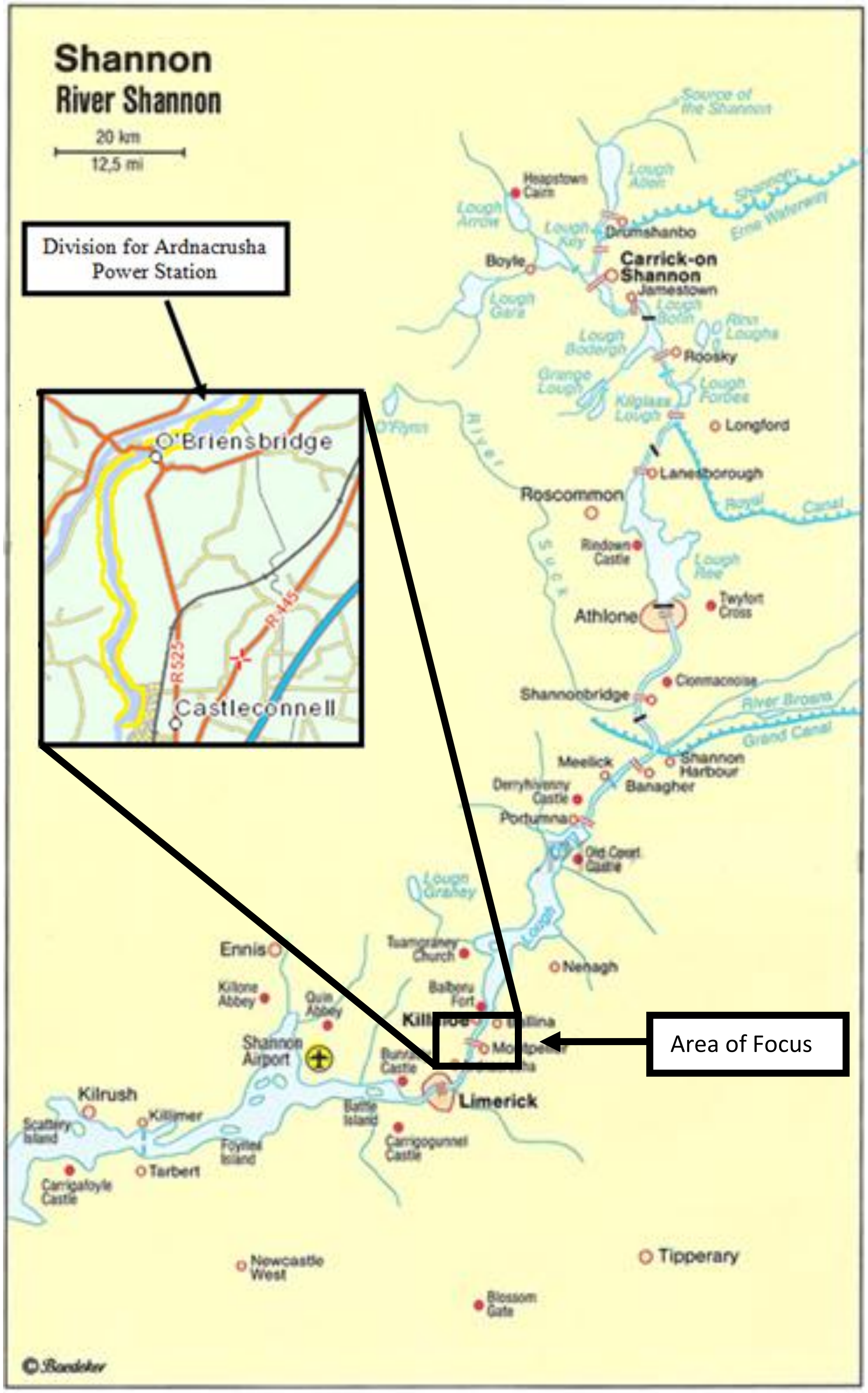

Figure 2.1-3 A map of the River Shannon showing in detail the section through which this project will track the Gillaroo. The Area of focus is highlighted in yellow [32], [33].

Having examined the Gillaroo and its environment, the next step in design can be considered. With the information about the Gillaroo and the River Shannon, different design options can be examined in relation to both their technical merit, and their potential impact on the Gillaroo.

2.2. Underwater Energy Harvesting

In order to choose the most suitable form of energy, several energy harvesting techniques were considered for possible implementation in the project. The system needs to have a long lasting tracking system, which implies a self-powered transmission method. In this section of the background, these different energy harvesting techniques are presented.

2.2.1. Thermal Energy

Thermal energy is the internal energy present in a thermodynamic system that is derived from the system's temperature, an important component of alternative energy [34]. Thermal energy is generated by the kinetic energy of the system's particles. The movement of the molecules in substances causes collisions and generates heat. The laws of thermodynamics describe how the energy in the form of heat is an exchange of energy between two systems, or a system and its surroundings. For example, when placing a pot of water under fire, the water heats up by the transmission of the thermal energy of the fire to the water. Thermal energy can be captured from many natural sources such as solar heat, ocean heat, geothermal heat and even body heat [35]. Most animals create heat from their metabolic activity which includes breaking down food and movement. However, this metabolic heat is regulated differently from one animal to another animal. Based on the preceding, animals are grouped into two different categories: warm-blooded and cold-blooded animals. Cold-blooded animals rely on external means from their surroundings to adjust their temperatures. For example, to increase their metabolism, reptiles bask in the sun, expand their surface area and darken their skin to take in most of the sunlight. Warm-blooded animals, on the other hand, rely on their internal means to manage their temperature, such as shivering, sweating and consuming high-energy food. Since warm-blooded animals depend on their bodies' activity, they have to eat much more than cold-blooded animals. Conversely, cold-blooded animals convert more food into body mass [36]. Fish are considered cold-blooded animals since they lose most of their metabolic heat through the gills. The blood passing through gills is in close contact with the colder outside water and the heat gets lost into the water [37].

Thermoelectric generators (TEGs) can be used to draw electrical energy from thermal energy by sensing differences in temperature. They consist of pairs of p-type and n-type semiconductor materials connected in series or parallel forming an array of thermocouples. An n-type semiconductor is a type of semiconductor that has an excess of electrons, while a p-type has an excess of positive ions [38]. When there is a different temperature on each side of the junction, a proportional voltage can be measured across their terminals [39]. The thermocouple is based on the Seebeck effect, which is described in Figure 2.2-1. When heat is applied to one of the two junctions, it causes a flow of the electrons in the n-type material and the holes in the p-type. In the n-type, the energetic electrons move toward the cold junction, creating an opposite current flow to the p-type toward the metal plate. The preceding causes the holes in the P junction to flow in the direction of the current [38].

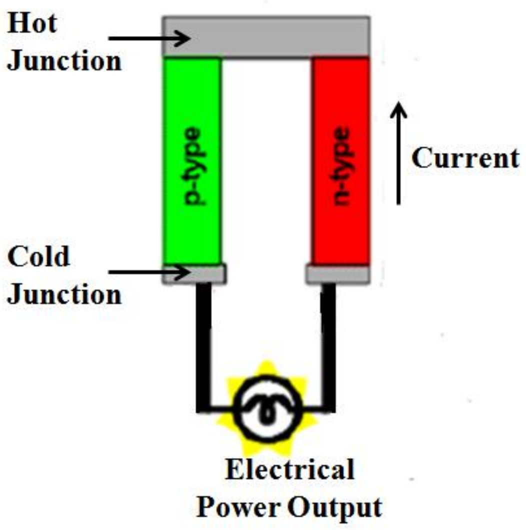

Figure 2.2-1 Seebeck Effect [40]. When there is a temperature difference, a proportional electric potential is created, which drives current to flow from the n-type to the p-type.

One of the early employments of the thermal harvesting method is the Seiko Thermic watch. The watch is powered solely by the body heat on the wrist. With a temperature difference of 3˚C between the environment and the body, the thermoelectric generator in the watch produces a power of 1.5 µW [41].

2.2.2. Rotational Energy (Turbine)

One way to generate electricity is through electromagnetic induction. Electromagnetic induction occurs when a conductor, like a wire, is moving across a magnetic field. As the wire passes through the magnetic field, a small Electro Motive Fields (EMF) is induced in each wire that not parallel to the magnetic field lines, as long as the wire is moving [42]. The amount of electricity generated is dependent upon the field strength, velocity of the conductor in relation to the magnetic field, and the number of turns in the conductor [43], [84].

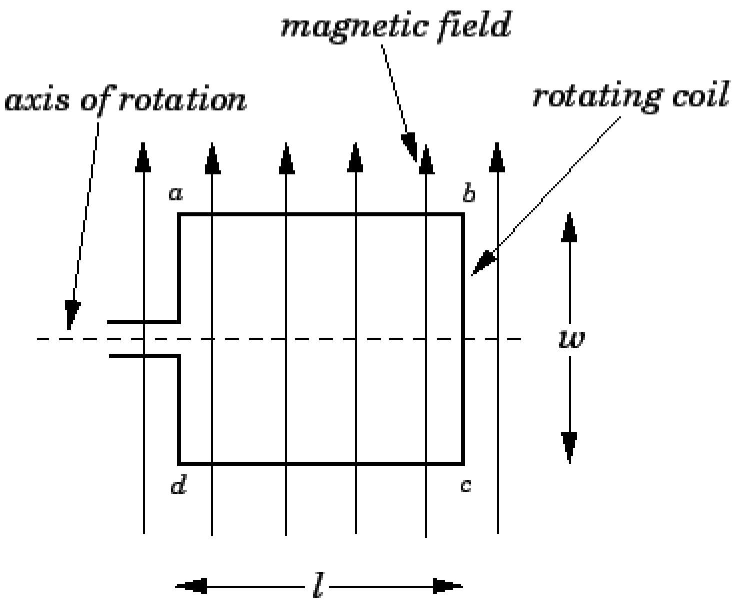

Figure 2.2-2 A single turn rectangular coil of wire in a uniform magnetic field. The length and width of the coil are given as l and w respectively and the magnetic field flows from the bottom of the figure to the top. This represents the concept behind a motor [44].

The formula for the EMF induced in a straight conductor moving linearly through a field is:

$$\boldsymbol{E = B * l * v}$$

Equation 1 EMF induced in a straight conductor

where B is the magnetic induction of the field, l is the length of the wire moving through the field, and v is the velocity of the wire through the field, as long as the wire is moving perpendicular to the magnetic field [84]. For a rotating coil in a uniform magnetic field, the EMF is:

$$\boldsymbol{E = n * B * l * w^2 * \sin(2 * \pi * f * t)}$$

Equation 2 EMF induced in a coil rotating in a uniform magnetic field

where n is the number of turns in the coil, B is the strength of the magnetic field, l is the length of the coil as shown in Figure 2.2-2, f is the frequency of the rotations, and t is time. Thus the EMF of a generator varies in time, with a peak value of:

$$E = \pm n * B * l * w^2$$

Equation 3 Peak EMF induced in a coil rotating in a uniform magnetic field

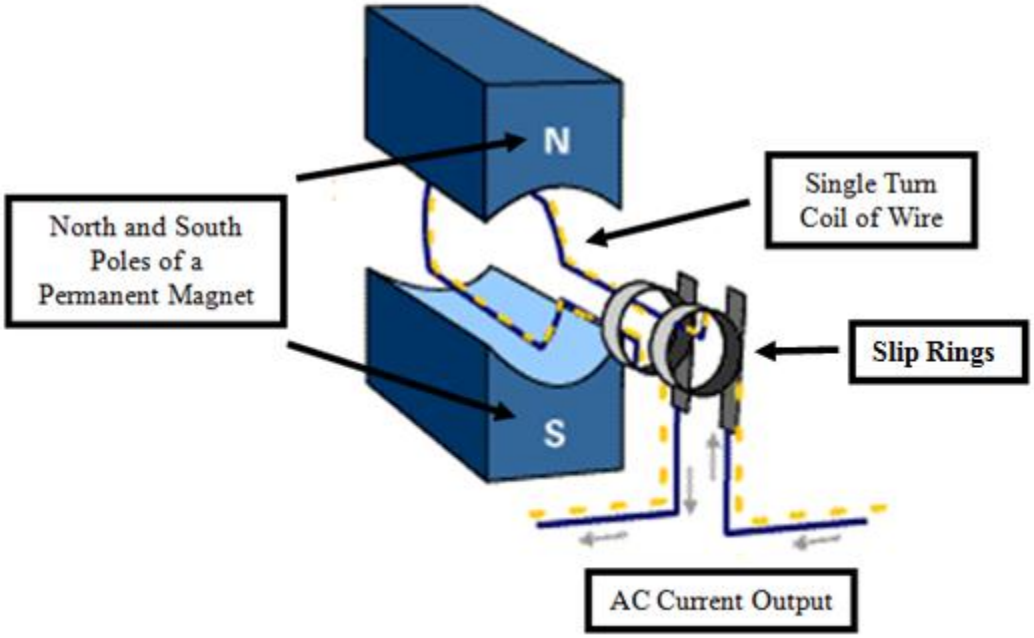

Figure 2.2-3 An example of a single turn AC generator operating in a single magnetic field. The magnetic field is generated by a permanent magnet, and the slip rings on the end allow the coil to freely rotate [45].

A simple example of a generator is shown in Figure 2.2-3. This figure shows a generator with one coil and one pair of magnetic poles connected in a way to generate alternating current (AC). An external force is required to rotate the coil of wire and produce a voltage across the two wires. Rotational generators can produce either alternating current (AC) or direct current (DC) depending on the structure of the generator. Most rotating generators will produce alternating current. However, devices such as slip rings can mechanically rectify the alternating current inside the generator so that direct current appears at the output [84].

In Figure 2.2-4, a method of connecting a generator to produce AC or DC is shown. The DC connector alternates the connection so that the top side of the wire always connects to A and the bottom side to B. As the top wire moves through the field it produces a current in one direction, and as the same wire rotates through the field on the bottom in the opposite direction, then it produces a current in the opposite direction. However, by switching the wire's connection from A to B at the same time that it would change, the original orientation is preserved and the voltage seen looking in at A and B remains constant.

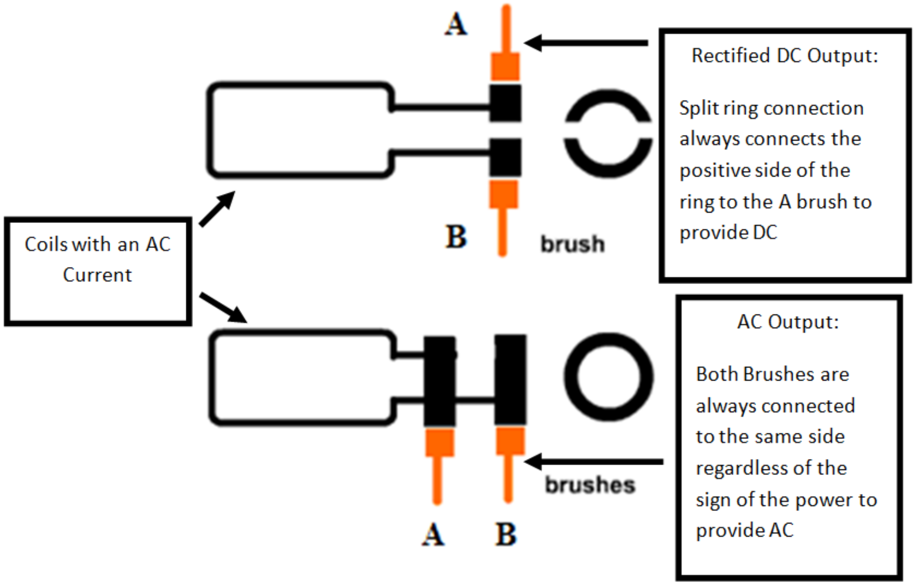

Figure 2.2-4 This diagram illustrates the difference between DC And AC slip rings. DC slip rings rectify the AC voltage produced by the generator by switching the connection every time the voltage changes form positive to negative, hence the gaps in the ring. The AC slip rings are continuous, to provide a constant connection to the AC voltage being produced by the generator [46].

The AC connector shown in the previous figure does not alternate the connections, and instead only allows the system to freely rotate by having brushes A and B slide across the slip rings so that the wires do not get tangled. Thus, as the top wire rotates through to the bottom and crosses the magnetic field in the opposite direction, the direction of the current changes producing an AC voltage when looking at A and B. Alternatively, the output of the generator can be electrically converted from AC to DC using any number of circuits such as half-wave and full-wave rectifiers [84].

Rotational energy and electromagnetic induction could be adapted for our project similar to the manner by which hydroelectric plants use the flow of water to spin turbines and generate electricity. In a hydroelectric plant, the flow of water over a drop converts the potential energy stored by the height difference into kinetic energy as the water falls through the turbine causing it to spin. If this idea was scaled down, then the flow of the river past the fish, either from the natural flow of the river, from the fish moving through the water, or a combination of the two could be used to turn a propeller attached to the shaft [84].

2.2.3. Piezoelectricity

Piezoelectricity is the charge generated by certain materials when placed under stress. In other words, piezoelectric sensors convert mechanical strain into electricity. The strain can come from different sources such as acoustic noise, human motion or seismic vibrations. The piezoelectric effect is reversible, which means that a change in voltage causes a mechanical deformation in a piezoelectric material [47]**.** Harvesting energy from piezoelectric materials has recently grown in popularity. Train stations in Japan are currently using piezoelectric elements to collect power from the commuters' footsteps as they pass through the gates [48].

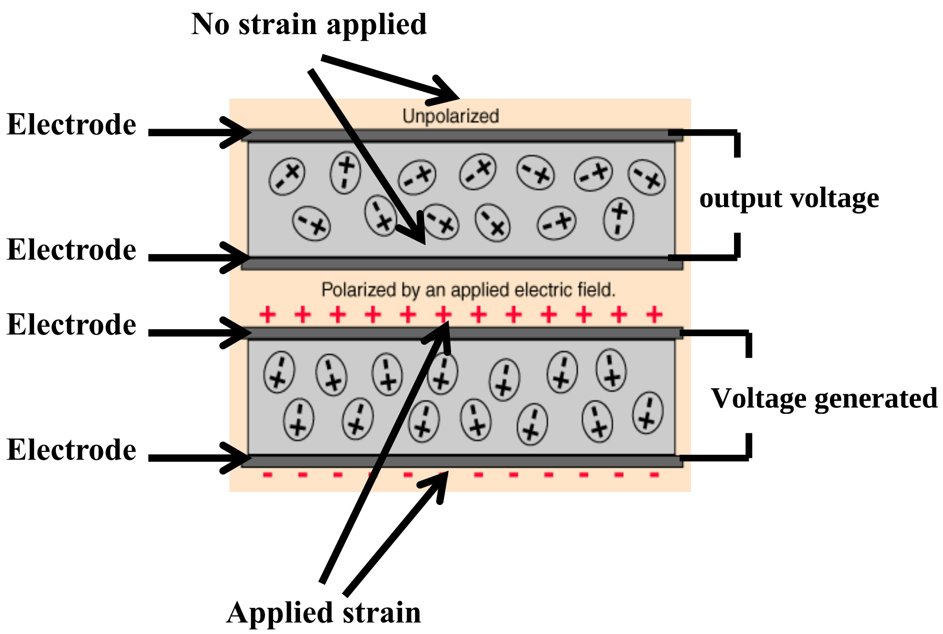

Figure 2.2-5 Polarization of a material [49]. When stressed, the piezoelectric material gets heated, causing the molecules to move freely in the direction of the resulting magnetic field, creating an electric voltage between the two electrodes.

A piezoelectric element consists of a polarized material with electrodes attached to its opposite faces. When a voltage is applied across the material, a resulting magnetic field causes the polarized molecules to align with it as shown in Figure 2.2-5. This alignment of the molecules causes the material to change its dimensions which translates to the mechanical deformation [50]. The two main materials that are used for piezoelectric sensors are piezoelectric ceramics and crystal materials. The ceramic materials have higher sensitivity while the crystal materials have higher long-term stability [51].

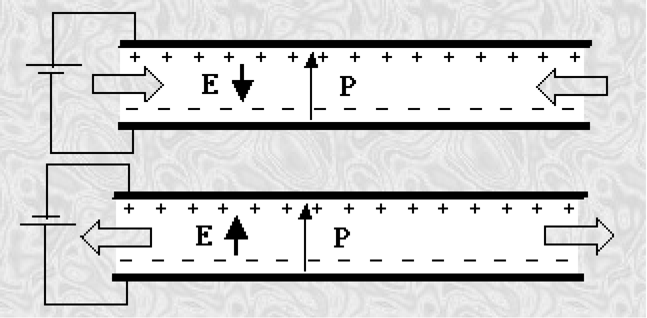

Figure 2.2-6 - Piezoelectric film [52]. When the film is contracted or expanded, a magnetic field is generated by the attraction and repulsion of the diploes in the molecules of the film, creating an output voltage between the electrodes.

The piezoelectricity effect can be used to capture the motion of the fish, for instance the bending of its tail using a bimorph. A bimorph is composed of two piezoelectric films. The piezoelectric film can be formed from a polyvinylidene fluoride (PVDF) which is a plastic that is mechanically strong and resistant to a range of chemicals [53]. The piezoelectric film is composed of two electrodes, as shown in Figure 2.2-6, which behave as capacitor plates to hold the charge when a stress is applied. The polarity of the output voltage depends on the direction of the resulting magnetic field from the contracting and expanding of the film. The piezoelectric film can be modeled by an AC voltage source in series with a capacitor. The voltage source is directly proportional to the applied force [54]. The capacitance of the piezoelectric film can be found using Equation 4:

$$C = \varepsilon * \frac{A}{t}$$

Equation 4 Capacitance of a PVDF film

where ε represents the permittivity of the PVDF, A is the area of the film's electrodes and t is the film thickness. From Equation 4, it is concluded that a large sheet of thin film will have the largest capacitance [55].

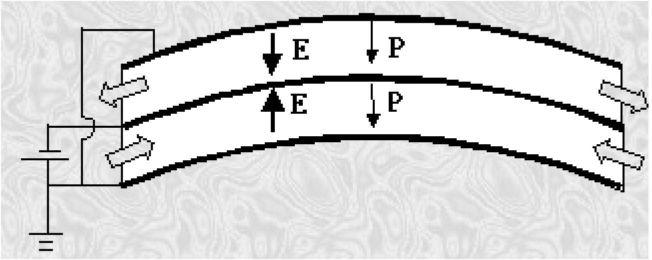

Figure 2.2-7 Bimorph [52]. With two piezoelectric films glued in opposite polarities, the deflection of the bimorph is achieved.

To obtain the bending motion, two piezoelectric films of opposite polarities are glued together as shown in Figure 2.2-7. The outer electrodes are grounded and the output voltage is measured at the center electrode [52]. When an electric field is applied to the bimorph, it causes one of the piezoelectric films to contract and the other one to expand which results in the material bending. The amount of tip deflection in the bimorph and the corresponding voltage is given by Equation 5:

$$x = \frac{3}{4} * d31 * \left(\frac{l^2}{t^2}\right) * V$$

Equation 5 Tip deflection of the bimorph [56]

Where d31 is the piezoelectric coefficient for length change, l is the bimorph's length, t is the bimorph's thickness and V is the applied voltage.

2.2.4. Acoustic Energy

Acoustic energy is the mechanical energy contained in vibrations generated by sound waves. Underwater, these sound waves are transferred by the compression and decompression of water molecules [57]. This mechanical energy can be converted into electrical energy using either a piezoelectric material or a magnet and coil. As the piezoelectric material or the magnet/coil are compressed and allowed to return to neutral they generate an electric potential which can be used to charge some type of energy storage device, or power a device outright [58].

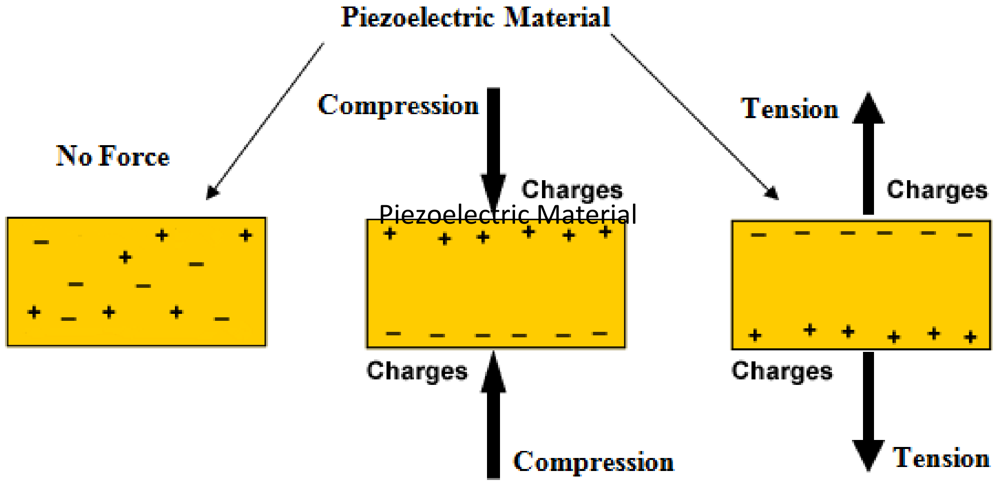

Figure 2.2-8 The effect of compression and tension forces on a piezoelectric material. When no force is applied to the piezoelectric material the charges are scattered randomly throughout the material. When either a tensile or compressive force is allied, the charges align on opposite ends of the material, and create an electric potential [46].

As previously discussed, piezoelectric materials convert mechanical strain into electrical energy. In an underwater acoustic energy harvester, the compression of water molecules applies the pressure on the piezoelectric material, as shown in Figure 2.2-8, and thereby generates electricity. For piezoelectric materials, the higher the frequency of the vibrations, the more power will be produced. This is because each oscillation produces the same amount of energy, assuming everything else constant an increase in frequency will increase the number of oscillations per second [58]. However, piezoelectric acoustic generators can be difficult to implement on a small scale. Though typical electromagnetic converters generate too small of a voltage for most applications, some electromagnetic converters have been developed to produce a high voltage [59].

The magnetic field surrounding a permanent magnet induces an electric potential in the coil proportional to the strength of the field, the number of turns in the coil, and the speed at which the two move in relation each other. The equation that governs this behavior is:

$$E = B * l * v$$

Equation 6 The electromotive force generated by a conductor moving linearly through a magnetic field

Where B is the strength of the magnetic field, l is the length of wire in the magnetic field, and v is the velocity of the wire in relation to the magnetic field [84]. Since the wire is coiled in the magnetic field, the length of the wire is proportional to the number of turns in the coil. The function is identical to a rotational motor in concept, except the motion is entirely linear as shown in Figure 2.2-9. The figure shows how the sound waves push the coil through the magnetic field to the right and then the diaphragm pulls the coil back through the magnetic field.

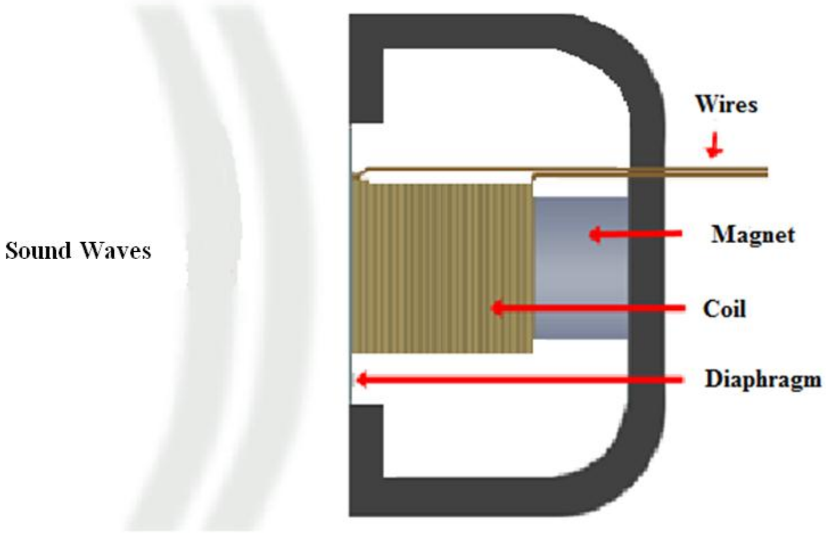

Figure 2.2-9 A microphone shown receiving sound waves. The waves will move the diaphragm which is attached to the coil. When this happens the coil will be moving through the magnetic field produced by the magnet. This will induce a voltage in the wires, generating energy [60].

In the case of vibrations, the higher the frequency, the faster the magnet must be moving, and the more energy generated. For vibration harvesting devices, a resonating cantilever beam can be attached to the magnet so that the magnet will resonate after the initial sound wave to generate more energy [61]. Both of these methods generate alternating current because both flex one direction with the sound wave to generate a peak voltage, and then return to neutral, generating a peak equal to the first, and opposite in direction. In an underwater application, the sound could come from the flow of the river, the motion of other animals, or even the noise from boats passing.

2.2.5. Solar Energy

Solar energy can be utilized in two main forms. The first is using the heat from the sun, the thermal energy. Using this thermal energy is mainly used for smaller domestic purposes, but it can also be used to heat larger bodies of water that are used to drive large turbines to generate power. The other method is using photovoltaic (PV) energy, which uses semiconductors [62]. The semiconductors come in many different form factors and are made out of many different materials, each with its own set of properties, efficiencies and downfalls, but all convert the sun's energy into electricity [63]. Solar panels use the photovoltaic effect to collect renewable energy. As shown in Figure 2.2-10, the solar cell absorbs photons in order to start an electric current. This is done when the photons strike the surface of a solar cell, which allows electrons to exit their orbits. The electrons are released, creating energy, and the solar cell uses all of the free electrons and forms a directional current [64]. These PV cells are made out of two or more thin layers of semiconductors, as shown in Figure 2.2-10, with the N type silicon and P type silicon layers, and when the sun hits the cell, the energy can be taken away as direct current. PV cells are combined to create a panel to produce up to several watts because the electricity generated by a single cell is small [65].

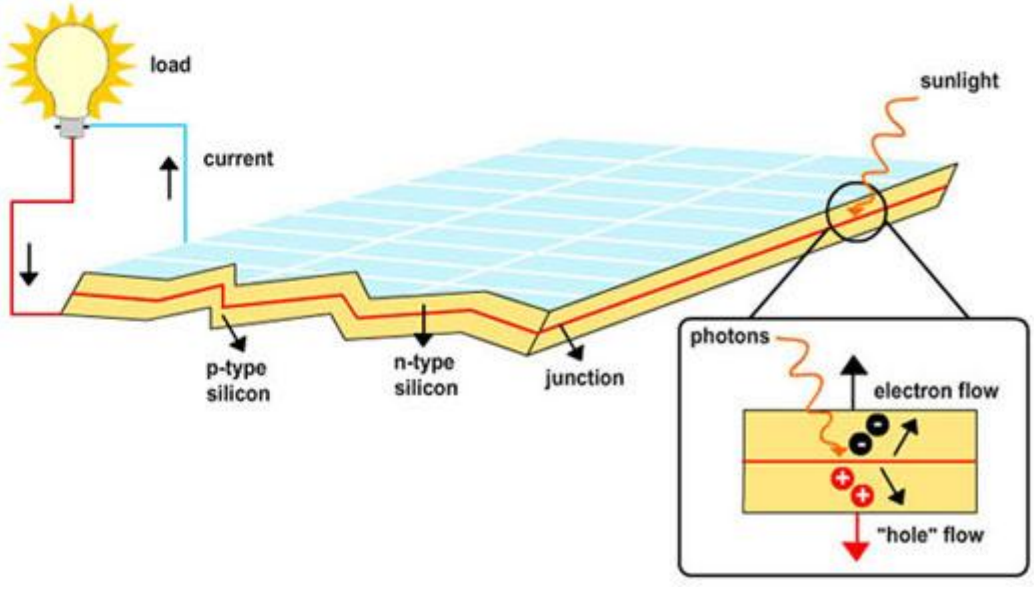

Figure 2.2-10 Solar Panel operation. Solar panel receives energy from the sun and uses the semiconductors to transfer the energy into electrical energy. [66]

Though solar energy is widely available and free to use, the PVs have yet to be developed to create both a device that is cheap and efficient. PVs are normally used to relieve the stress of the main grid, not as a replacement because PVs cannot provide all of the electricity necessary, in addition, the sun only shines for a portion of the day, and most PVs only work with direct sunlight [62]. In addition, PV is made out of the semiconductor material, so there are no moving parts. This means that the life of the system is longer and there is minimal maintenance required for the system.

PV cells in water have not undergone extensive research. However, there have been several smaller projects to create cells that can work underwater. Renssellaer Polytechnic Institute created a robot that works in the water. However the PV floats on top of the water, as seen in Figure 2.2-11. Therefore the PV is indeed waterproof, but does not work underwater [67]. PVs need contact from direct sunlight, and when underwater, the light from the sun is refracted and changed, causing the efficiency to significantly decrease. Solar panels, if waterproofed, could work in up to one or two feet in completely clear water, but is not practical for deep or murky waters [68]. A solar cell is only fully active on average for five hours a day. With this average of five hours a day, a solar panel can produce 8-10 Watts per square foot. The amount of energy produced is proportional to the area of the panel used. Therefore, the smaller the panel, the smaller the amount of energy produced [64].

Figure 2.2-11 RPI underwater robot operated by solar panels on the surface of the water. The PVs are surrounded by the yellow framing of the robot.

2.2.6. Summary of Underwater Energy Harvesting

The many different types of underwater energy harvesting in the context of this project has both advantages and disadvantages. Table 2.2-1 summarizes the differences between the different types of underwater energy harvesting techniques. Also from the table, some types of techniques can be immediately excluded because they do not work underwater, such as thermal. While solar and acoustic could work underwater, both have many more disadvantages than advantages. Finally, piezoelectricity is the only technique that has more advantages then disadvantages which could lead to a realistic approach for the energy harvesting part of the project. These different techniques will be used to help power the different tracking methods researched.

Table 2.2-1 Comparison of Underwater Energy Harvesting Techniques

Underwater Energy Harvesting			
Type	**Application**	**Advantages**	**Disadvantages**
Thermal	Metabolic Heat	Fish is always moving No moving parts	Trout is cold blooded Loss of heat through gills
Rotational	Water Flow	Currents in river	Attract other fish Large and heavy
Piezoelectricity	Fish Movement	Easily attached to fish Constant fish movement High voltage output	Low current output
Acoustic	Ambient Noise	Inexpensive	Unreliable Tuned to specific frequency Inefficient
Solar	Sun	No moving parts	Only operates when sun available Inefficient underwater Large form factor Expensive Difficult attachment to fish

2.3. Tracking

The underwater energy harvesting, discussed in the previous section, will be used to power the tracking device or devices discussed in the following chapter. Though animal tracking has been explored and had success, this project presents several different problems associated with tracking. The Gillaroo lives completely underwater and in more shallow areas that are traversed by boats and fisherman. Any tracking device or infrastructure that is implemented cannot impede the fish or the people traveling through the river. In the section to follow, the options for tracking a fish are discussed in detail.

2.3.1. GPS and Multilateration

Multilateration is a method of determining the position of an object by measuring its distances from multiple reference points. Multilateration is used in several systems such as the Global Positional System (GPS) and Enhanced 9-1-1 to locate wireless phones in emergencies. The distance is measured by computing the time difference of arrival (TDOA) instead of directly measuring the distance from the received signal strengths (RSS) as shown in Figure 2.3-1. Since the radio signal velocity is the speed of light, knowing the time is the same as knowing the distance. The distance is derived by multiplying the speed of light and the travel time [69].

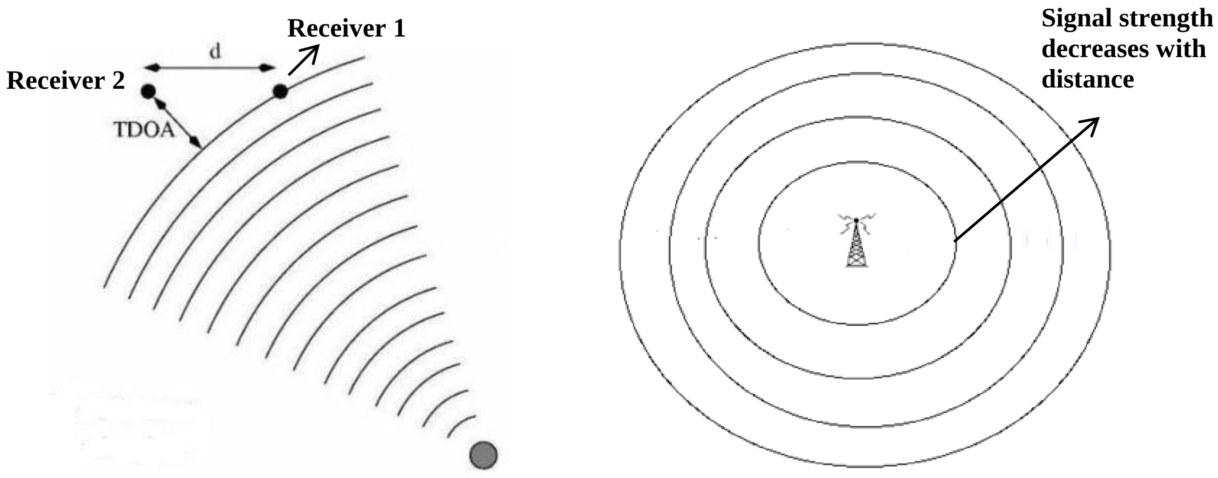

Figure 2.3-1 TDOA VS RSS. The figure in the left illustrates the TDOA concept. The distance between the two receivers can be computed since the signal arrives at the receivers at different times. Meanwhile, the figure in the right illustrates the RSS concept. The measurement of the propagation path loses and the transmitter output power, allows the receiver to calculate its distance from the transmitter.

GPS is a satellite-based positioning system. It is made up of 27 satellites of which three are extras in case one fails. Each one of these satellites circles the globe twice a day and transmits two low power radio signals. One of these signals is designated for the civilian usage and operates at 1575.42 MHz and the other signal is for military usage and the operating frequency is 1227.60 MHz. The signal contains three different bits of information: the I.D. of the specific transmitting satellite, the state of the satellite, and the orbital information of all the satellites. All GPS satellites synchronize their activities so that these repeating signals are transmitted at the same time as shown in Figure 2.3-2. The GPS receiver's mission is to locate at least four of these satellites. Using multilateration, the receiver estimates its distance to the GPS satellites by using the different travel times from the four satellites. GPS is more suitable for outdoor environments and will not normally work indoors, underwater or underground due to attenuated signals [70].

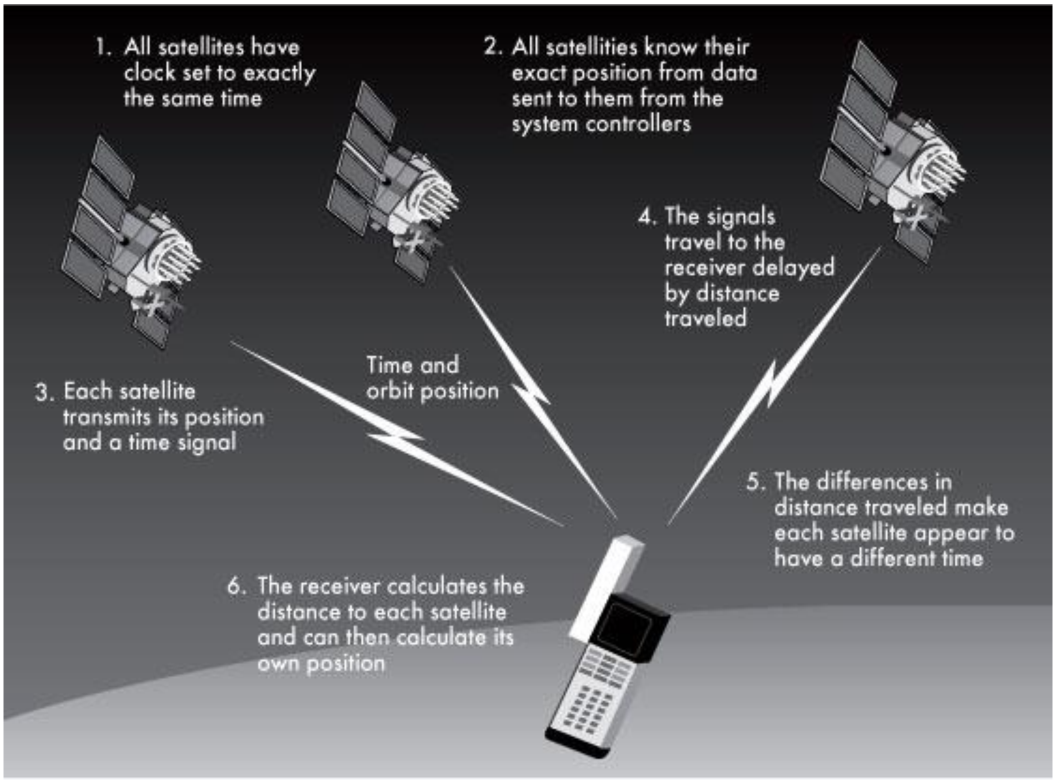

Figure 2.3-2 GPS operation. The GPS satellites are continually synchronized before sending any signals. Each satellite transmits its position and the signal's time. The receiver gets these signals at different times and converts them into distances since the speed is known, by using multilateration, the receiver calculates its own location from the distances of the satellites [71].

To navigate underwater, a scuba diver often uses a waypoint and lets the GPS float on the surface to attain a signal and records the location by pulling the GPS down underwater [72]. Another way to obtain a signal is to have a floating antenna attached to a GPS receiver which can be strapped to the diver's hand, as shown in Figure 2.3-3 [73].

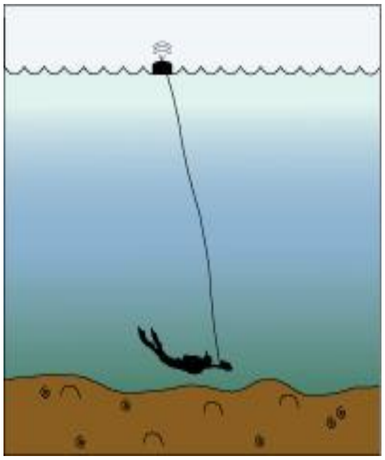

Figure 2.3-3 GPS underwater [74]

2.3.2. Triangulation and Directional Antenna

Triangulation is the process of determining the location of a point by creating a triangle with two known points and the unknown point as the vertices [75]. By measuring the angles from the two known locations, and knowing the distance between those two points, the location of the third point can be calculated relative to the known locations. The calculation is based on the mathematical principle that for any triangle, if two angles and the side between them are known, then the length of the other 2 sides can be calculated [76]. These angles are used to determine the location of the unknown point constrained in two dimensions. Triangulation can use line-of-sight, RF signals, or acoustic signals to find the angle of the point.

Figure 2.3-4 shows a simple example of triangulation using two points (1 and 2) to determine the position of a third (x). Using a line drawn between 1 and 2 as a base line, and knowing the angles a and b, then using the formulas:

$$L/\left(\left[{}^{\tan b}/_{\tan a}\right]+1\right)=L2,\text{ where } L=L2+L1$$

Equation 7 the length L1 in terms of L, b, and a.

$$c=L1\tan a$$

Equation 8 A reorganized version of the tangent formula.

Then the distance along the base line and the distance from the base line to location x can be calculated. Then using polar coordinates with 1 as the origin and a line from 1 to 2 as the axis, the position of x is known to be ($\sqrt{L1^2 + c^2}$, a) [76].

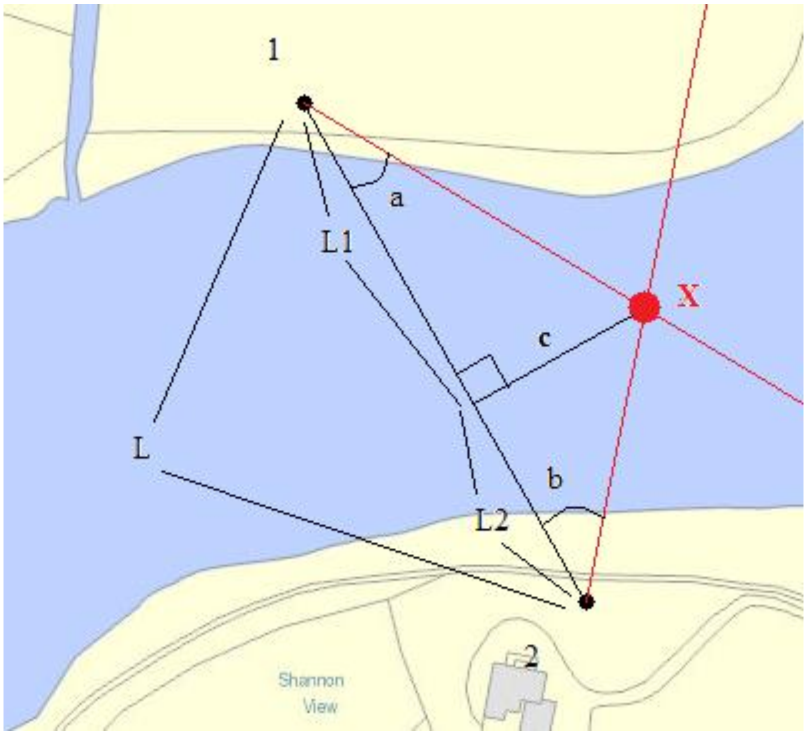

Figure 2.3-4 A mathematical representation of triangulation. The points one and two represent receiving stations, and the point X represents the transmitting tag.

A simple way to measure the angle to an RF or acoustic signal is by using directional antennas. A directional antenna is an antenna that is configured to provide gain to the signal in a specific direction or directions and to attenuate signals from other directions [77]. Some common examples of RF directed antennas are Yagi-Uda antennas, loop antennas, and corner antennas.

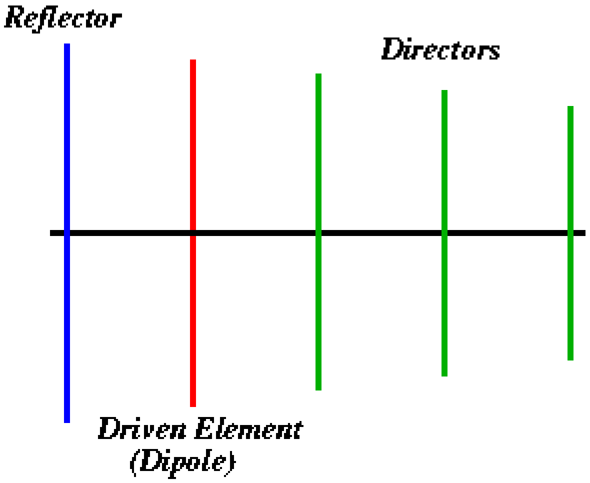

Figure 2.3-5 An example of a Yagi-Uda antenna. The red element is the driven element which either transmits or receives the signal. The blue and green elements are reflectors and directors, both of which focus the signal into the driven element [77].

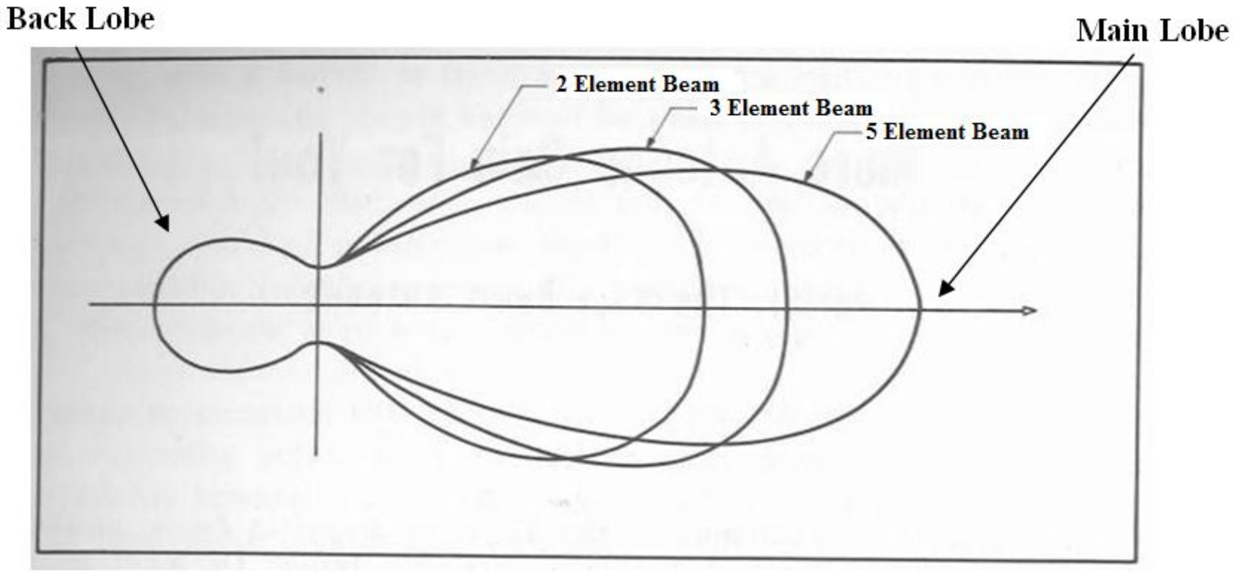

Figure 2.3-6 A five element Yagi-Uda Antenna, and the receiving patterns for a two, three and five element antenna. The Receiving pattern shows two important points, first that increasing the number of elements in the antenna will increase the focus of the antenna, and second, that there is a back lobe which will pick up signals from directions other than the direction the antenna is pointed [78].

Figure 2.3-6 shows the receiving pattern for a Yagi-Uda antenna, and shows how the antenna receives signals from a single direction far better than it can receive signals from any other direction. All other signals will suffer more attenuation, and therefore will be weaker than direct signals from the same distance away. Thus, the antenna will receive the strongest signal when it is pointed at the source of the signal [77]. Alternatively, an antenna with equal gain in every direction except one would be able to use the point where the signal strength is weakest, representing the direction to the signal. For example, a loop antenna could be rotated and when the signal strength is lowest, the loop would be in line with the signal source. This type of setup can have inaccuracies as low as 1 to 2% [79]. Alternatively, multiple directed antennas could be used together, and then the antenna receiving the strongest signal would be the one pointed toward the source of the signal. In this case, the focus of the antenna will determine the precision of the result, the tighter the angle that the antenna observes, the more precise the angle. If these arrays of directed antennas are placed in pairs on either side of the river, together they could divide the river into a grid, with the ability to pinpoint the fish to any of the sections. The tradeoff is that narrower bands will require more antennas to monitor the entire river.

2.3.3. Proximity Sensors

A proximity sensor is a sensor that can detect an object without physical contact. There are many different types of proximity sensors which use the different properties of the material that needs to be sensed (i.e. conductive, inductive etc.). The sizes of the proximity sensors vary based off the target of the sensor. Most times the sensor head is flat and either round or square depending on the application. The range for detection again depends on the type of sensor, but the range is normally less than 2 inches [80], [81]. The sensor sends out a signal and the detection is based off what the plate receives back and the level of energy it receives back [80]. An inductive sensor is an example of a proximity sensor which detects metal objects. An inductive proximity sensor is made up of four components: a coil, an oscillator circuit, a detection circuit and an output circuit. There are two main types of inductive proximity sensors: shielded and unshielded. The shielded has the coil in a metal encasing, which allows the sensor to be less sensitive to other metal around, but the sensing distance will be less. The unshielded does not encase the coil, which means that the sensor is more affected by other metals present. However, the unshielded will have a longer sensing distance. Figure 2.3-7 shows the general functionality of the inductive sensor. The oscillator circuit is used to induce a magnetic field in the coil. The coil will produce a field, as seen above, in the shape of a doughnut. With the induced magnetic field, Eddy currents will form on the object that is being detected, when the object is in range. Eddy currents form when a conductor experiences a change in magnetic field, this change induces a current in the conductor. Each Eddy current that forms has inductance and creates a magnetic field. The reason that the inductive sensor will detect metal objects is because the Eddy currents will build up on the detectable object. This will dampen the oscillators own magnetic field. The output circuit is triggered when the magnetic field is dampened enough [82].

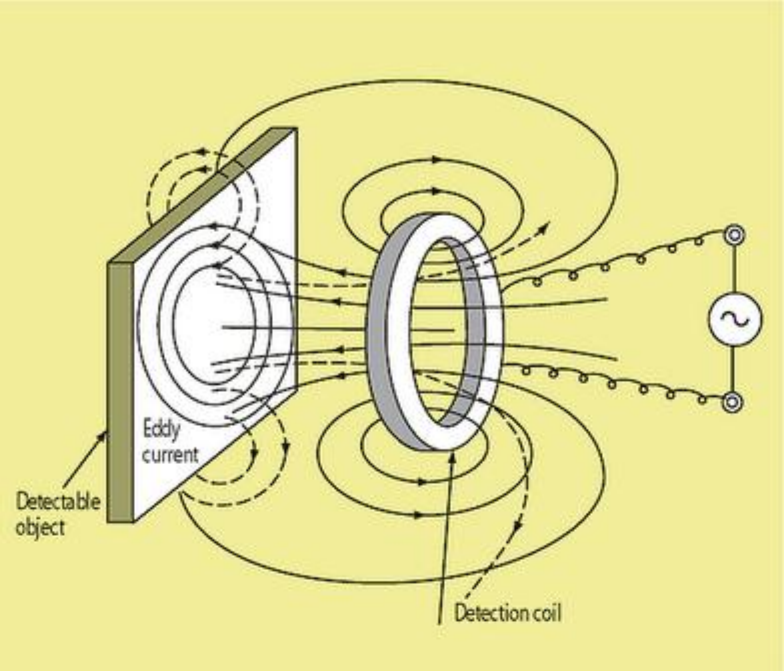

Figure 2.3-7 Inductive Proximity Sensor Diagram. Currents are induced when the object moves within range, the object is detected [83].

Inductive sensors rely on the laws of electromagnetic. There are several basic equations derived from Maxwell's equations that are used to help analyze a system containing an inductive proximity sensor. The magnetic flux density is given in Equation 9 where B is the magnetic flux, H is the magnetic field intensity and u is the permeability of a vacuum and the ratio between the permeability of the medium and a vacuum.

$$B = \ H\mu_0\mu_r$$

Equation 9 Magnetic Flux Density

The next equation is to find the magnetic flux, or $\Phi_{B.}$

$$\Phi = Ba$$

Equation 10 Magnetic Flux

Where B is the magnetic flux density and a is the area. And finally Equation 11 is used to calculate the inductance.

$$\varepsilon = \frac{d\Phi}{dt}$$

Equation 11 Electromagnetic field.

Where E is the electromagnetic field induced. In addition, in some special cases when a coil is being used, the number of coils, N, factors into Equation 12.

$$\varepsilon = \ -N\frac{d\Phi}{dt}$$

Equation 12 Electromagnetic field induced through a coil.

These equations can be used to fully analyze an inductive proximity sensor.

A capacitive proximity sensor is also a popular form of proximity sensors. Instead of producing an electromagnetic field, capacitive proximity sensors induce an electrostatic field. Capacitive sensors will sense both metal and nonmetal targets. To determine the capacitance between two objects, Equation 13 is used where a is the area of the plates, E_0 is the permittivity of free space and d is the distance between the plates.

$$C = \frac{a}{d} \epsilon_0$$

Equation 13 Capacitance between two objects

Like the inductive proximity sensor, the capacitive sensor is made up of four main parts: a coil, an oscillator circuit, a detection circuit and an output circuit. The capacitive sensor uses a dielectric plate to sense the capacitance. As the target enters the electrostatic field, the capacitance is changed in the oscillator circuit, causing the oscillator to oscillate. The trigger circuit reads the amplitude of the oscillator circuit. The output is activated when the amplitude reaches a certain point. When the target moves away from the sensor, the amplitude of the oscillator circuit will decrease and the output will return to its original state. Capacitive sensors are more likely to see a target with a higher dielectric constant, such as water or metal. The sensing distance, %S_r, is directly dependent on the dielectric constant of the target, as seen in the figure below [84].

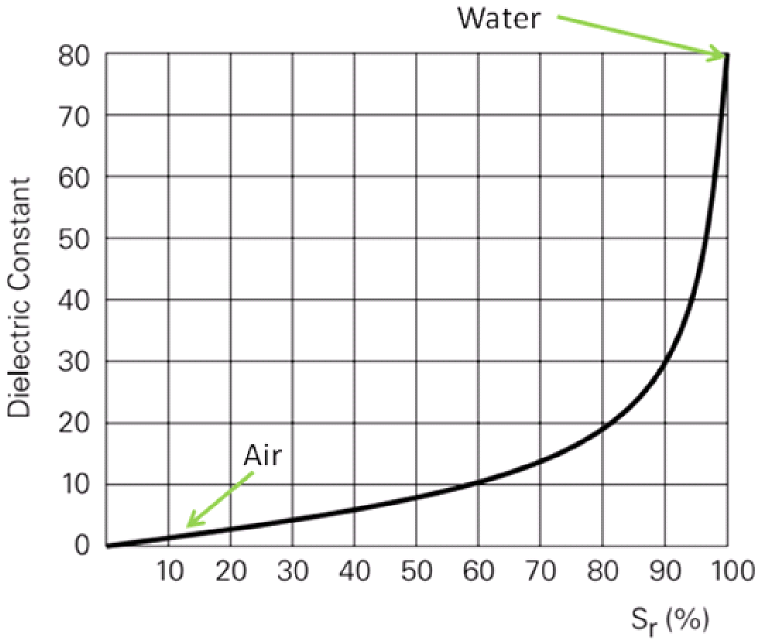

Figure 2.3-8 Capacitive Sensor -Sensing Distance vs. Dielectric Constant. Water has the highest dielectric constant, and air has the lowest. This means that water will have the longest read range while air will have the shortest read range for a capacitive proximity sensor [84].

Many proximity sensors will not work underwater. However, inductive proximity sensors are insensitive to many liquids, such as water [85]. The main issue of using an inductive sensor, if used in water, is that an inductive sensor produces a magnetic field [80]. As previously mentioned, many fish and sea animals use the magnetic fields to navigate and find food. Producing a magnetic field may disrupt the lives of the fish. In addition, the range for the sensors is very small and the sensors cannot differentiate between two different objects based on the sensor information alone [81].

2.3.4. Thermal Imaging

One method of tracking is the employment of thermal imaging. Thermal imaging is used to display the heat emitted from an object without directly coming in contact with the object. The heat is captured using a camera that detects infrared radiation and produces images from that radiation without the need of illumination. Thermal images allow a visual of the fluctuations in temperature since the amount of radiation diffused by an object increases with temperature. Humans and warm-blooded animals stand out against cooler environments since they maintain their body temperature above their surroundings [86]. Figure 2.3-9 is an example of a thermal image captured in a zoo. The thermal image reveals the hot spots of the zebra [87].

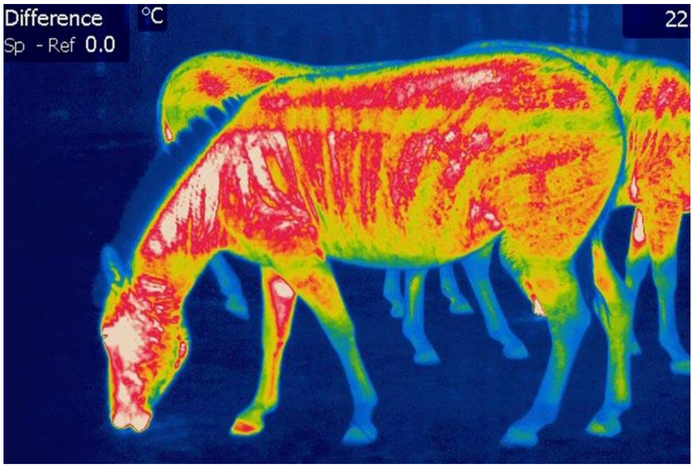

Figure 2.3-9 Thermal image of a zebra [87]

Thermal imaging uses a camera which consists of a lens, an array of infrared detectors, and a signal processing unit. The lens focuses the infrared radiation that is emitted by the objects within the view of the lens, and then it passes the radiation to the infrared detectors [88]. These detectors read the focused radiation and translate it to electric signals using the pyroelectricity effect. Pyroelectricity is the charge generated by certain materials when placed under a different temperature [89]. The signal processing unit converts the electric signal into usable data then sends it to a display so it can be visible to the user. Thermal imaging could be a viable solution for tracking fish underwater by attaching a unique tag to the fish that would make it stand in the image, as the fish itself is a cold-blooded animal and would not show much variation to the background [88].

2.3.5. Radio Frequency Identification

Radio Frequency Identification (RFID) is a system that can wirelessly transmit the identification number of an object using radio waves. A well known example of an RFID system is the tolls that allow cars to pass without stopping. RFID, like proximity sensors, does not require contact, and is not affected by non-metallic materials. There are two main components of an RFID system: Tag and Reader. There can be many different tags and each tag has a unique ID. When the tag is detected by the reader, using an antenna, the reader will receive the data from the tag and pass the information to the computer system for further processing [90]. This process can be seen in Figure 2.3-10. The range of the reader is dependent upon the operating frequency of the system [91]. The higher the frequency, the longer the read range because it is easier to build an antenna that is directionally selective at the higher frequencies, like the UHF bands mentioned below. RFID systems have many uses such as asset tracking, supply chain management and payment systems [90].

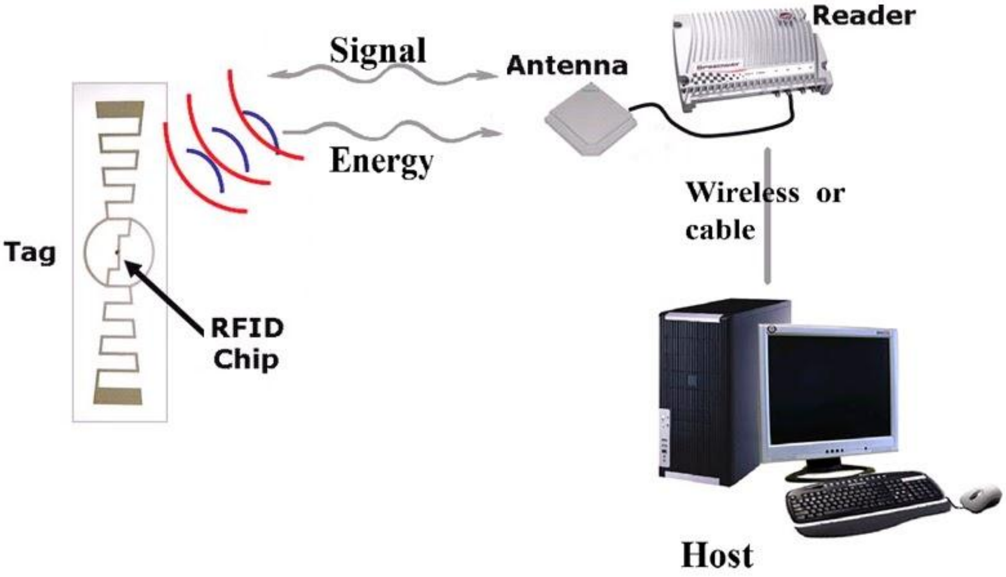

Figure 2.3-10 RFID System. The tag receives the reflected energy from the antenna connected to the reader when it is in proximity of the antenna. When the energy is exchanged, the reader receives the ID number of the tag. The reader will then communicate the inform to the host computer

As mentioned before, an RFID system has two main components. The first is the tag. The tag of the RFID system is application specific. There are three main types of tags. The first tag type is passive meaning that there is no source of energy on board the tag. The tag will only transfer data when it is within the range of the reader. The reader sends out electromagnetic waves, and when in range of the antenna of the tag, will induce a current in the tag. The tag will use this power to reflect the signal sent and then add information to the reflected signal modulation.

The second type of tag is an active tag. This tag has a source of energy, such as a battery, on board the tag. This battery will power the transmitter on the tag, and any additional circuitry, such as a microchip to store information. These tags will have a longer range because the signal is being pushed out by the tag, rather than reflected by the tag to the reader. However, these active tags can be more expensive and require replacement of the battery.

The last type of tag is a Semi-Passive tag. These tags still use the same form of data transmission as the passive tags, however they have a source of energy, like a battery to power a chip to maintain memory. In addition to the power of the tags, tags may be Read only or Read-Write. Read only, like in a computer system, means the tag cannot be programmed and has a limited storage area. Read only tags are normally cheaper and easier to integrate into a system. Read-Write tags have the ability to be programmed. These tags are normally more expensive, but can store much more data.

Finally, a tag can transmit data in two different ways: propagation or induction. Propagation uses Low Frequency (LF) (125-134 kHz) or High Frequency (HF) (3-30 MHz) bands and uses close proximity electromagnetic or inductive coupling, shown in Figure 2.3-11. Induction uses electromagnetic waves and operates on the Ultra High Frequency (UHF) (433MHz, 865–956MHz and 2.45GHz) or microwave bands, shown in Figure 2.3-12 [92].

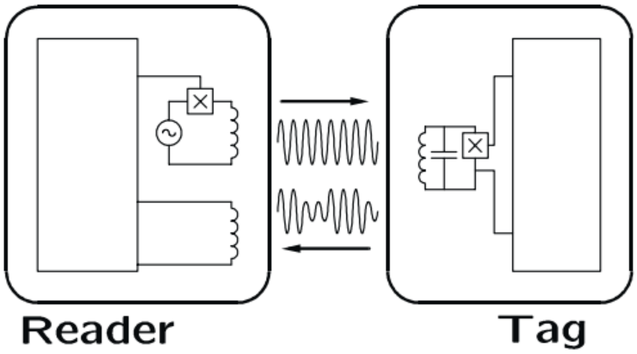

Figure 2.3-11 Propagation. This process uses inductive coupling to determine the distance between the two objects. The signal that is returned determines detection of the tag or no detection. [92]

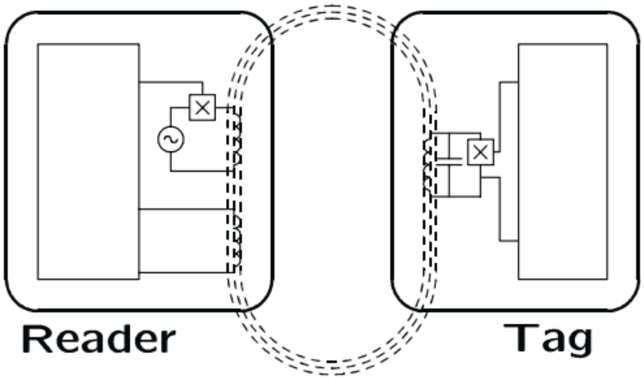

Figure 2.3-12 Induction uses electromagnetic waves, operating at a high frequency. This induces a field between the tag and reader. The field strength changes as an object moves through it [92].

The second part of an RFID system is the reader, like tags, readers are not all the same. A reader can be either read only or Read-Write. This is also dependent on the tag being used. If the reader is Read only, then the reader simply takes the data from the tag and records it. If the reader is Read-Write, and the tag is as well, then the reader can write data to the tag and store the data in the tags memory. In addition, readers come in two main form factors: mobile or fixed. The mobile readers are normally handheld and can be easily moved. These readers can be more expensive than the fixed readers. Fixed readers are fixed in one location and are not meant to be moved. These can be placed where the tags will go through, such as the toll gates [92].

RFID systems have become more popular in the last 10 years due to two main reasons: need and cost. The cost of the tags has decreased significantly between 2003 and today. Due to the cost decrease, more applications that possess the potential to employ an RFID system have been identified.

One application that this project will further explore is tracking. However, instead of tracking inanimate objects, this project will explore the tracking of animals. Recently, there have been more studies of RFID using animals. In Australia and New Zealand, an RFID tagging system was implemented for the Sheep and cattle by attaching a tag to the animal's ears. Like branding the animal, the tag gives each animal a number or name, and will also provide additional statistical information, such as its whereabouts and traveling habits. This system uses a low operating frequency of 134.2 kHz. The range of the system is low, but a high range is unnecessary as there are common points where cattle have to be ushered through [93]. A low operating frequency system can be used on mediums with higher water content. This will allow penetration through some of the water because at lower frequencies there is less attenuation through water [91]. RFID could possibly be used in places where fish are forced to jump out of the water, or are in very shallow waters.

2.3.6. Sonar

Sonar stands for sound navigation and ranging. There are two types of sonar: active and passive [94]. Passive sonar detects vibrations in the water and uses them to find the location that the sound originated from. Passive sonar has been used to track and identify submarines, as different propellers make slightly different sounds, as well as to track whales by the distinct sounds that each individual whale makes [95], [96]. If each fish had a tag that produced a distinct acoustic signal, then by listening for those signals, the positions of the fish could be found using a tracking method such as multilateration, or triangulation. Hydrophones spaced along the river would receive the acoustic signals, filter out any noise, and then the position of the fish could be calculated.

Active sonar sends out a sound wave, or ping, and listens for the response. Since sound waves travel at a fairly constant speed of 1482m/s in fresh water, the time between when the first signal is sent and when the reflection of the signal is received gives an accurate measure of the distance to any objects, and the way the sound reflects gives the general shape of objects in the path of the sound wave [97] , [98], [99]. For example, if the ping is sent out and a reflection is heard one second later then the wave traveled 1482m to get to the nearest object and return, meaning the object is 741 m away. Active sonar is typically used to navigate around objects in the ocean or to follow ships and submarines [94].

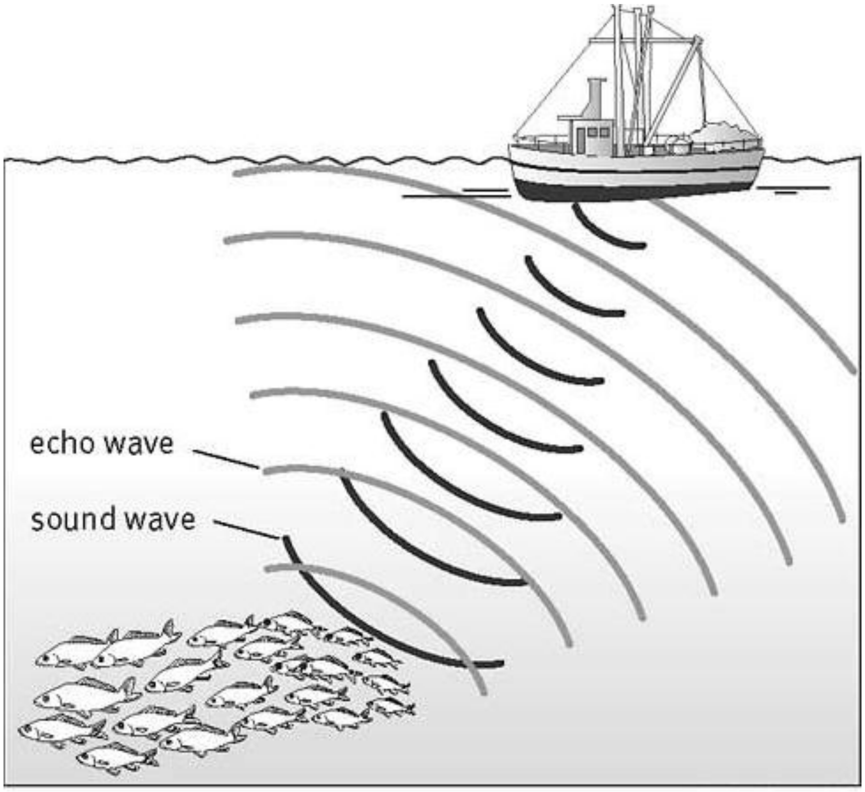

Figure 2.3-13 In this example of active sonar, the boat in the top right is sending out a sound wave. When the sound wave reaches the school of fish, part of the sound wave is reflected, and travels back to the boat. Equipment on the boat receives and processes this echo wave, and can determine the distance and direction from the boat to the fish [100].

Active sonar has also been adapted to fish finders to aid fishermen by finding the depth that the fish are at. In Figure 2.3-13, the boat is sending out an active sonar ping, the sound waves are shown reflecting off of the school of fish, and the sound waves return to the boat different from when they were sent out. Equipment on board the boat analyzes the incoming sound waves and produces an image with the location of the fish. A problem with active sonar tracking is that there is no way to distinguish objects based on anything besides size, and general shape, although modern advances in micro-processing have enabled fish finders to track speed and direction as well [101]. Every trout would come up as essentially the same object and no specific fish could be tracked unless it was the only fish in the river.

2.3.7. Summary of Tracking Methods

The various tracking methods that have been discussed each have advantages and disadvantages. The detailed analysis of various tracking methods that was provided in the previous section has allowed the team to carefully consider all available options. Table 2.3-1 summarizes the advantages and disadvantages of each method.

Table 2.3-1Comparison of Tracking Methods

Tracking Methods			
Type	**Application**	**Advantages**	**Disadvantages**
Multilateration	GPS	Highly accurate Infrastructure in place	Does not work underwater
Multilateration	Telephony	Highly accurate	Need access to provider base stations
Multilateration	Independently Manufactured	Control operation frequency	Complex calculations
Triangulation	Directional Antenna	Simple calculations	Reliance on signal strength Higher accuracy requires more antennas
Proximity	Capacitive	No advantages	Does not penetrate through water Limited range Differentiation between fish difficult
Proximity	Inductive	No advantages	Field produced might affect fish Differentiation between fish difficult Only detects metal
Thermal	Infrared Camera	No advantages	Expensive Reflects off of water Differentiation between fish difficult
RFID	Passive	No on board power required for tag Unique identification included	Limited range
RFID	Active	Longer range than passive Unique identification included	On board power required for tag
Sonar	Passive	Unique identification included	On board power required for tag Requires multiple listening stations
Sonar	Active	No on board power required for tag	No unique identifier for individual fish

2.4. Communication

Communication is a way of transferring and receiving information using various methods. Wireless communication methods will be employed to transmit useful information obtained by the tracking system of the project to a user interface. Before designing communication methods for the project, several areas had to be researched to get familiarization of the current communication technologies. Main communication methods such as cellular telephony, radio and acoustic were studied thoroughly for the determination of the viable communication method for the scope of the project.

2.4.1. Radio Transmission

Radio is defined as "the transmission of data by modulating electromagnetic waves at frequencies below visible light" [102] and the radio spectrum covers a frequency range from 3 KHz to 40 GHz and wavelength range of 1 cm to more than 1 km [103]. Radio is used in many forms, such as wireless networks, mobile communication and broadcasting. Radio wave propagation is greatly affected by the medium in which it is travelling which is an important factor in the applications of the radio frequency.

The attenuation factor of radio is significantly affected by the operating frequency and conductivity of its propagating medium. Radio waves become increasingly attenuated in water more so than in air because water has a higher conductivity than air. Therefore, the range of radio communication underwater is far less compared to the range in air, for the same operating frequency. The following formula gives the relationship between attenuation and frequency of the carrier wave and conductivity of the medium.

$$Attenuation\left(\frac{dB}{m}\right) = 0.0173 * \sqrt{f * \sigma}$$

Equation 14 is used for the determination of attenuation of radio waves and in which, f represents frequency in Hz and σ represents conductivity of the medium in S/m [104].

$$Attenuation\left(\frac{dB}{m}\right) = 0.0173 * \sqrt{f * \sigma}$$

Equation 14 The radio attenuation. The equation shows the relationship of attenuation vs. combined effect of frequency and conductivity of radio waves [104].

The attenuation of radio waves increases with frequency as well as the conductivity of the medium. Fresh water has a lower conductivity than seawater due to its lower salt content. Therefore, radio attenuation is lower in fresh water than in sea water for the same operating frequencies. A common value for the conductivity of fresh water is 0.001 S/m. Based on the average conductivity value of fresh water, and using the attenuation equation mentioned above, Figure 2.4-1 was constructed [104], [105].

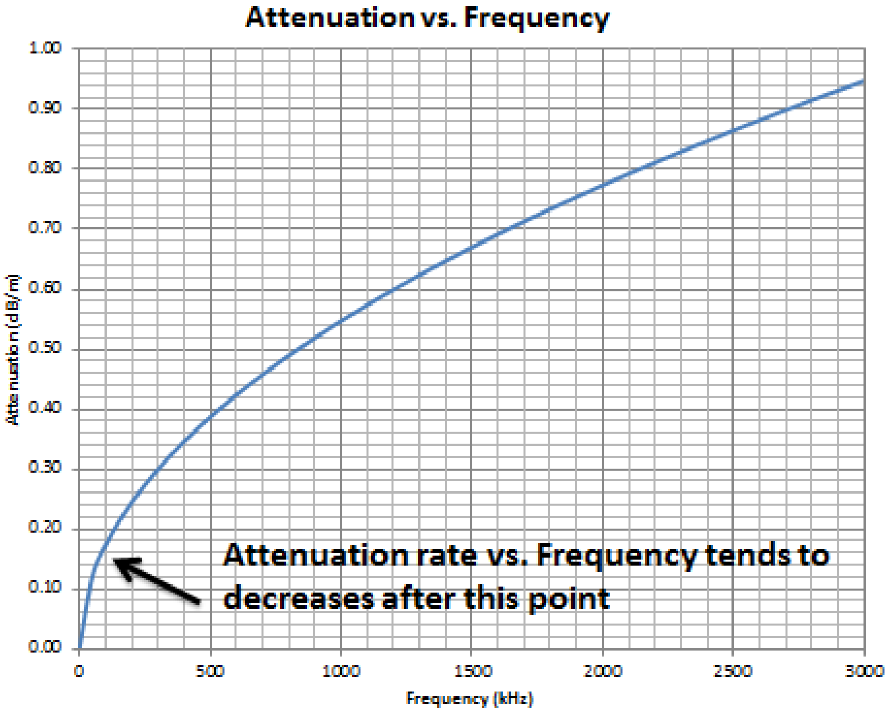

Figure 2.4-1 Attenuation vs. Frequency of radio in fresh water. The graph has information about a trend in the relation between the two axes. The attenuation rate vs. frequency tends to decrease after 100 kHz

In radio communication, the information is modulated onto a carrier wave by varying its amplitude, frequency or phase. The information is then filtered out from the modulated signal using various techniques at the receiver. Radio communication is used in cellular telephony for the transmission and reception of data wirelessly. Radio is also used in communication of information using analog or digital form [106].

Cellular telephony

Cellular telephony is a method which employs the use of cell phones to transmit and receive information wirelessly. Cellular telephony is based on a series of contiguous radio cells. Cells are land areas where the radio network is distributed. The size of a cell is dependent on the power of the antenna and the medium in which the radio signals will propagate. There are various types of cellular network configurations such as macro-cells, micro-cells, and pico-cells [107].

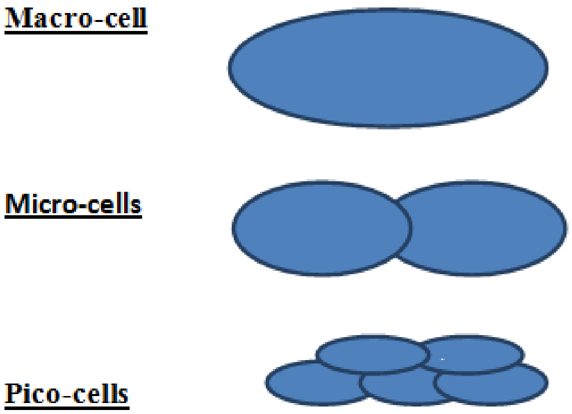

Figure 2.4-2 Cellular network comparison. The network ranges of the three types of cells are based on the antenna sizes that are used. Amongst all three cell types, largest antenna sizes are used for macro-cells.

Figure 2.4-2 shows network coverage comparison between three types of cells. In a macro-cell setup, large radio antennas are positioned above average roof-top level. The covered network area can vary from a few kilometers to around 35 km. Its network coverage is the largest amongst the three types of cells. In a micro-cell setup, the radio antennas are positioned below the average roof-top level and thus the network coverage area is smaller compared with the macro-cell setup. The range can vary from a few hundred meters to a few kilometers. A pico-cell setup is usually used indoors as their network coverage range is quite small. This is because the size of the antennas in pico-cell setup is the smallest of all the three cell types [107].

Cellular telephony was primarily used for voice calls and text messaging. With the development of technology Over time, cellular telephony now also provides services such as picture messaging, wireless internet browsing, mobile TV along with voice calls and text messaging. The two most popular systems which employ cellular telephony are Second Generation (2G) cellular system and Third Generation (3G) cellular system. One of the popular 2G cellular systems is (GSM) and one of the popular 3G cellular systems is UMTS [108].

GSM

Global System for Mobile Communications (GSM) is a popular cellular telephony system that is used in 2G network. As the demand for the cellular telephony increased, there was a need to create a system to increase network capacity and thus accommodate the increased demand. Radio frequencies that are used for wireless communication have a limited bandwidth of 25 MHz [104]. To create more radio channels for wireless communication, GSM technology was invented. GSM operates in the 850 MHz or 1.9 GHz bands in US and the 900 MHz or 1.8 GHz bands in Europe. 80% of world’s population is now covered by terrestrial GSM networks [109]. GSM technology divides the 25 MHz bandwidth of the radio frequencies by using combination of the Frequency Division Multiple Access (FDMA) and the Time Division Multiple Access (TDMA) [110]. Using these multiple access methods, a GSM radio frequency has the ability to be shared for communication between different cell phones which are located in different cellular network areas and this in turn satisfied much of the increased demand for the use of cellular telephony [111].

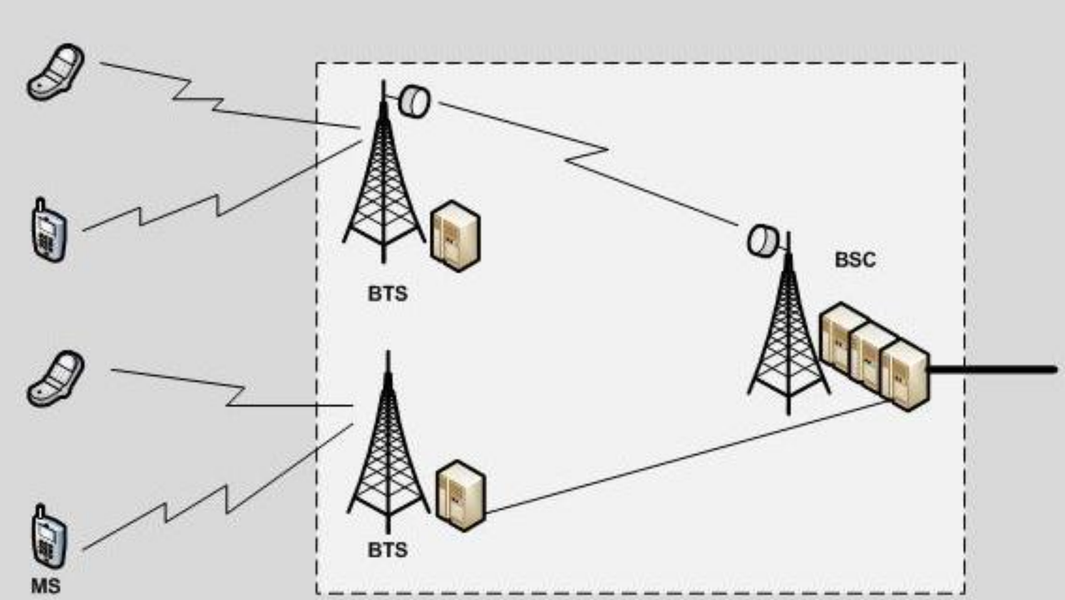

Figure 2.4-3 Radio links between the Base Station and cell phone. The Base Stations is comprised of BTS and BSC which are antennas and call control centers respectively. The antennas are used to transmit and receive signals from the mobile station (MS) [112].

The operation of GSM can be divided into three broad categories: the Mobile Station (MS), the Base Station Subsystem (BSS) and the Network Subsystem (NSS) [112]. Figure 2.4-3 shows radio links between the mobile station and the Base Station Subsystem. The Mobile Station consists of a cell phone and a Subscriber Identity Module (SIM) card. The cell phone contains a radio transceiver, a display and a digital signal processor. The SIM card contains the user's subscription information [112]. The Base Station Subsystem manages radio links with the Mobile Station. It consists of two parts: the Base Transceiver Station (BTS) and the Base Station Controller (BSC). The BTS is a radio transceiver that interacts with the Mobile Station by transmitting and receiving signals from the Mobile Station as shown in Figure 2.4-3. The BSC manages the quality of the radio channel by operating with the radio transceiver stations. The BSC connects the NSS and the Mobile Station. The NSS carries out the call switching between the mobile network users. The NSS is also responsible to manage authentication of the mobile services [112].

UMTS

Universal Mobile Telecommunications Systems (UMTS) is a popular cellular telephony system that is used in 3G network. With an increase in demand for faster data rates and better quality of service in cellular telephony, a 3G cellular network system called UMTS was invented. UMTS uses a 5 MHz carrier channel width to transmit high data rates. UMTS supports four different types of quality of services. First is the conventional class which is voice exchange between humans. Second is the streaming class whose typical applications are audio and video streaming. Third is the interactive class which is the use of wireless internet by a user. Fourth is the background class which is typically used for file downloads [108].

Figure 2.4-4 shows the UMTS architecture. There are certain terms that have been used in the picture such as Uu, IuB, IuR, IuCs and IuPs which represent interfaces between different certain protocols. The Uu term represents the interface between the cell phone and the Base Station. This is an air interface which supports data rates up to 2 Mbps. The IuB term is the interface between the Base Station and Radio Network Controller (RNC). The IuR term represents the interface between RNCs which enables in a better resource management of calls especially if the user is not stationary. RNC prioritizes the radio links according to quality of service levels that is being received by cell phones. In this way, a cell phone receives data from multiple base stations and it combines all the data to improve the quality of service of the call. UMTS analyzer checks the consistency of all the protocols involved in UMTS network. Circuit-Switched Domain and Packet-Switched Domain, which have interface terms of IuCs and IuPs with RNC, are responsible for switching and control of the wireless radio links that are used by a cell phone for communication [108], [113], [114].

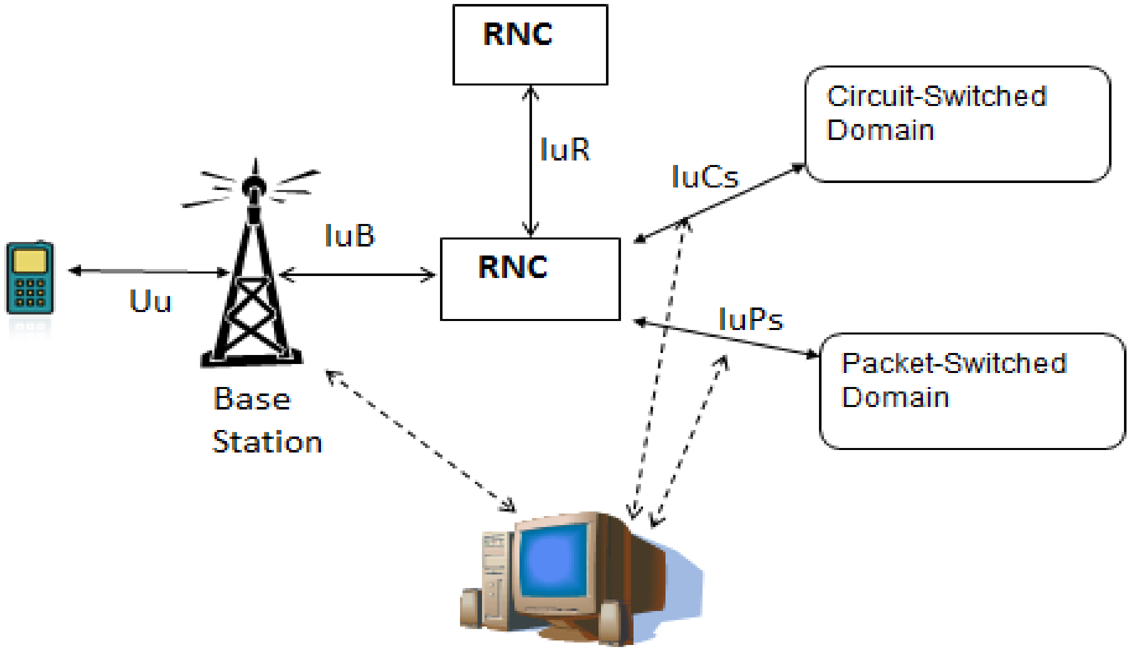

Figure 2.4-4The UMTS architecture. The symbols Uu, IuB, IuR, IuCs and IuPs are the terms that represent interfaces between each protocol [114].

Analog Radio Communication

In Analog Modulation, a continuous modulation is applied to transmit an analog signal. The properties of the carrier wave, such as amplitude and frequency, change with respect to amplitude variations of the analog signal that needs to be transmitted. The frequency of the carrier wave is higher than the frequency of the analog signal. Analog Modulation is mainly comprised of Amplitude Modulation (AM) and Frequency Modulation (FM) [106].

Amplitude Modulation and Demodulation

AM is the transmission of data by modulating the carrier wave with different amplitude levels while the transmitted frequency remains unchanged [103]. AM commercial broadcasting needs licensing from the authorities of the country for example in United States, the Federal Communications Commission (FCC) license range for AM broadcasting is from 535 kHz to 1700 kHz [115].

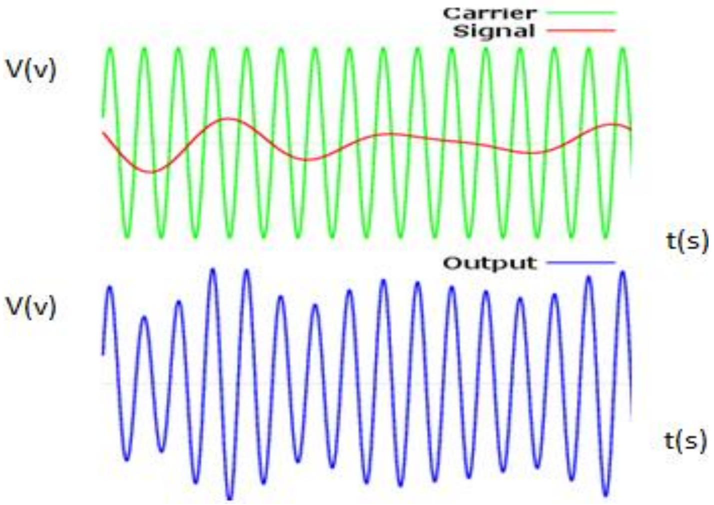

Figure 2.4-5: The AM generation. The graph represents the generation of amplitude modulation. The top graph shows a sinusoidal carrier signal as well as the data signal. The bottom graph shows the AM output [116]

Figure 2.4-5 shows a graphical view of AM generation. The amplitude levels of the output AM waveform changes by an amount which corresponds to the variations in the amplitude levels of the signal. The path along the peak points of the output waveform represents the variations in the signal [116].

The demodulation process of AM uses certain components. The output from demodulation of an AM signal is the original analog signal that was modulated on a carrier wave at the transmitter. There are several methods used for the demodulation of an AM but most common one employs the use of an envelope detector.

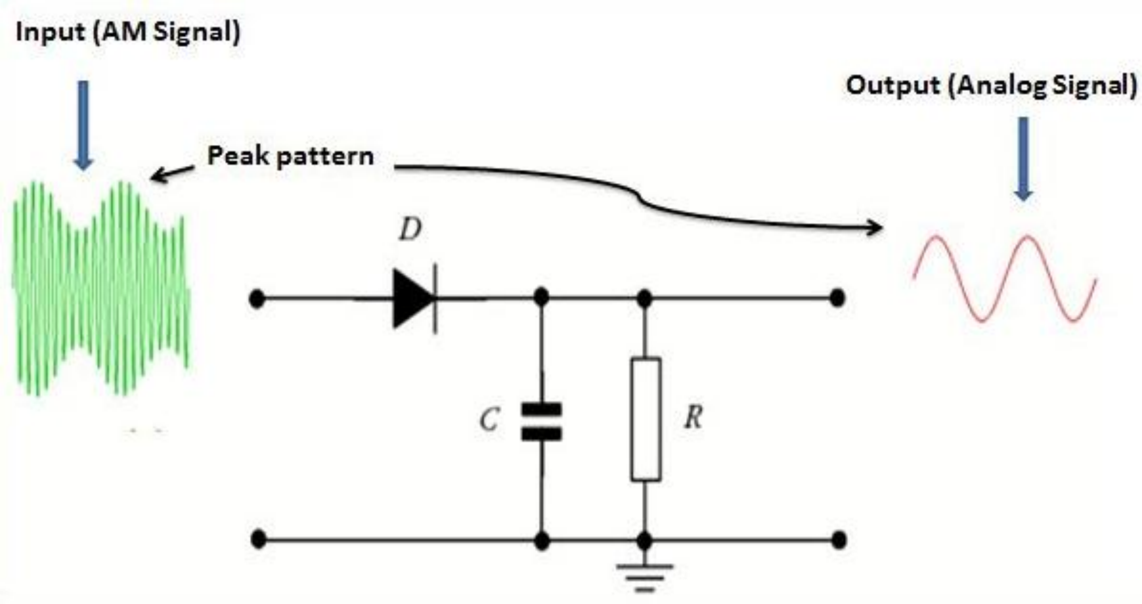

Figure 2.4-6 An envelope detector. The envelope detector performs the rectification and filtration of the modulated signal. The information embedded in an AM signal corresponds to the peak pattern of an AM signal. Therefore, the output waveform in the figure has the shape which corresponds to the peak pattern of the AM signal [117].

The schematic of an envelope detector is shown in Figure 2.4-6. The diode in the circuit rectifies the incoming signal by allowing current to flow in only one direction. When the input signal amplitude increases, the capacitor gets charged to the peak voltage of the incoming waveform. When the input signal changes its direction, the diode blocks the passage of the current and the capacitor gets slowly discharged by the resistor attached to it in parallel. When the input waveform changes its direction again, the procedure gets repeated. The rectified signal is then fed to a low pass filter which is comprised of a capacitor and a resistor in a parallel configuration. This generates a waveform that follows the peak pattern of the high frequency AM signal. The low pass filter filters out the high frequency signal and thus the demodulated information is obtained [117]. Therefore, the usage of both rectifier diode and low pass filter is necessary for the demodulation of an AM signal.

Frequency Modulation and Demodulation

In FM, the frequency of the carrier wave modulates with respect to the variations in the amplitude level of the signal waveform while the amplitude levels remain the same for the modulated output.

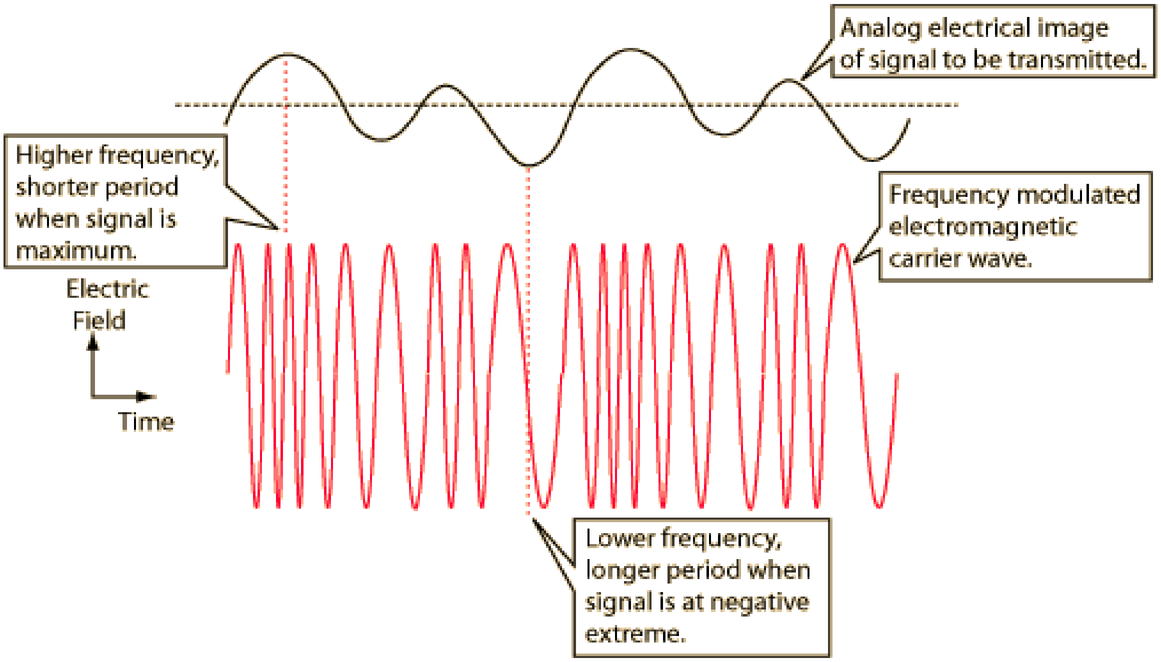

Figure 2.4-7 The FM generation. The bottom waveform represents the FM wave. When the amplitude of the input analog signal shown as the middle waveform increase, the frequency of the carrier wave increases and vice versa [118].

Figure 2.4-7 shows a graphical representation of FM generation in which, the carrier wave modulates with higher frequencies for higher amplitude levels of the signal and the carrier wave modulates with a lower frequencies with lower amplitude levels of the signal [119]. The licensed range under the FCC for FM broadcasting is from of 88 MHz to 108 MHz [115].

One of the methods to demodulate an FM signal is by using the slope detection technique which involves three parts: a differentiator, an envelope detector and a DC blocking capacitor. In this method, the FM signal is first converted to an AM signal using a differentiator and then the signal is applied to an envelope detector to discern the information signal from the carrier wave. The signal is then passed through a DC blocking capacitor to remove the DC component of the signal.

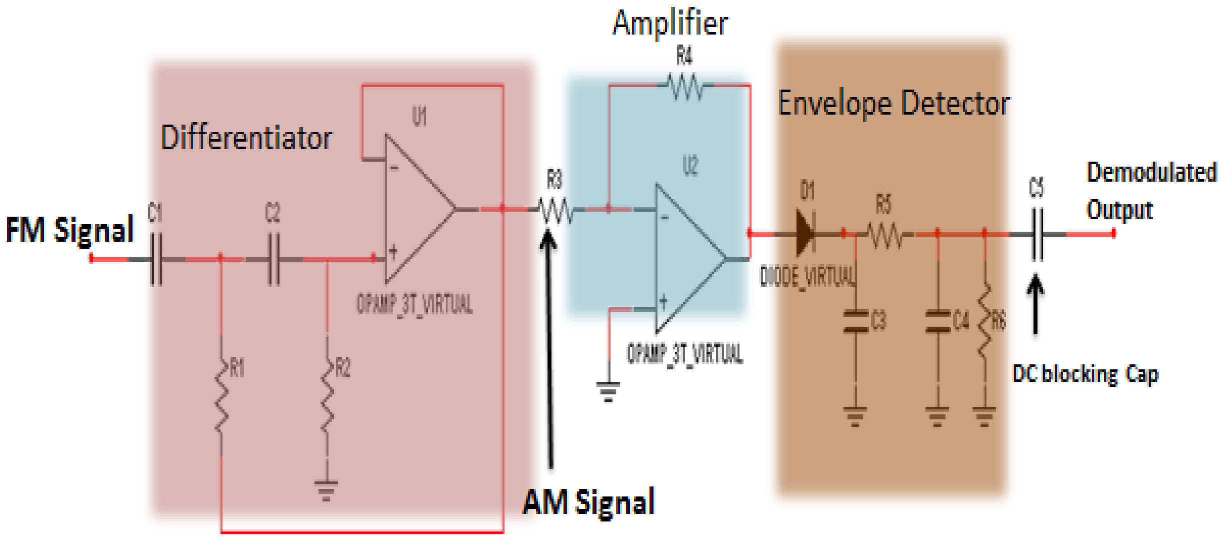

Figure 2.4-8 The FM demodulation. The figure shows the diagram of FM demodulation method. It involves the use differentiator circuit to convert FM signal to an AM signal. An amplifier is then used to amplify the signal to user defined amplitude level. An envelope detector demodulates the AM signal. Capacitor labeled C5 then removes the DC component from the signal [120].

Figure 2.4-8 shows the FM demodulation method. An FM signal is fed to a differentiator which converts the FM signal into an AM signal. The purpose of the differentiator is to convert the frequency variations in a signal to amplitude variations. The differentiation circuit consists of combination of resistors and capacitors with an op-amp. The signal is then fed to an op-amp to amplify the signal. The signal is then fed to an envelope detector. An envelope detector is made up of a diode rectifier in series with a parallel combination of capacitors and resistors as shown in figure above. When the input signal amplitude increases, the capacitor gets charged to the peak voltage of the incoming waveform. When the input voltage decreases, the capacitor gets slowly discharged by the resistor attached to the capacitor in parallel. The output from the envelope detector is then fed to a DC blocking cap to remove the DC component of the signal [120], [121].

Digital Radio Communication

Digital modulation includes Amplitude Shift Keying (ASK), Frequency-Shift-Keying (FSK), Phase Shift Keying (PSK), and On-Off Keying (OOK). A discrete modulation is applied to transmit information. The properties of the carrier wave, such as amplitude and frequency, change with respect to binary logic levels that need to be transmitted. Digital Modulation is mainly comprised of Amplitude Shift Keying (ASK), On-Off Keying (OOK) and Frequency Shift Keying (FSK) [122].

Amplitude Shift Keying/On-Off Keying

In ASK, different voltage levels of the information signal get encoded on a sinusoidal carrier wave by varying its amplitude levels to two or more discrete levels while keeping the frequency to a constant value. The voltage levels of the information signals get encoded into their binary values and that binary information is stored in different amplitude levels of the ASK signal. One of the methods for ASK generation involves a Dual Analog Switch Module, a Sequence Generator and a sinusoidal oscillator [123].

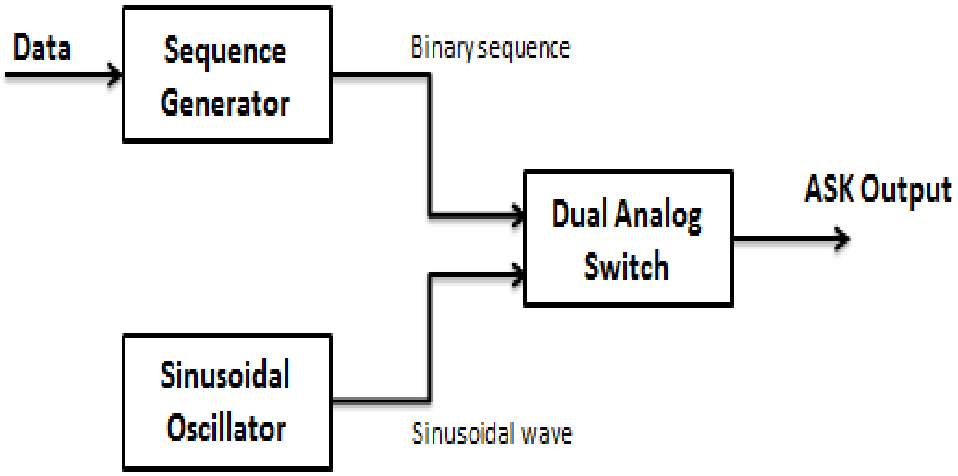

Figure 2.4-9 The ASK generation method. It involves 3 main components to transmit data in ASK modulated form. The dual Analog Switch convolves the input from the Sequence Generator and the Audio Oscillator and outputs an ASK modulated signal [123]

Figure 2.4-9 shows an ASK generation method [123]. In this method, an oscillator feeds a sinusoidal carrier signal to the Dual Analog Switch (DAS). The DAS is a type of a switch that can handle both analog and digital signals [124]. The data that needs to be transmitted is fed to the clock of a sequence generator. The sequence generator converts the data input into binary logic levels. The output from the sequence generator is fed to the DAS. The DAS convolves the binary logic signals with the carrier wave. This leads to the generation of Amplitude Shift Keying signal [123].

OOK is the simplest type of ASK modulation. In OOK modulation, a logic 1 bit would modulate the carrier wave from the transmitter to a specific amplitude level and a logic 0 bit would modulate the amplitude level of the carrier wave from the transmitter to zero level. This is different from ASK in which there are multiple amplitude levels assigned to the carrier for the transmission of information [122].

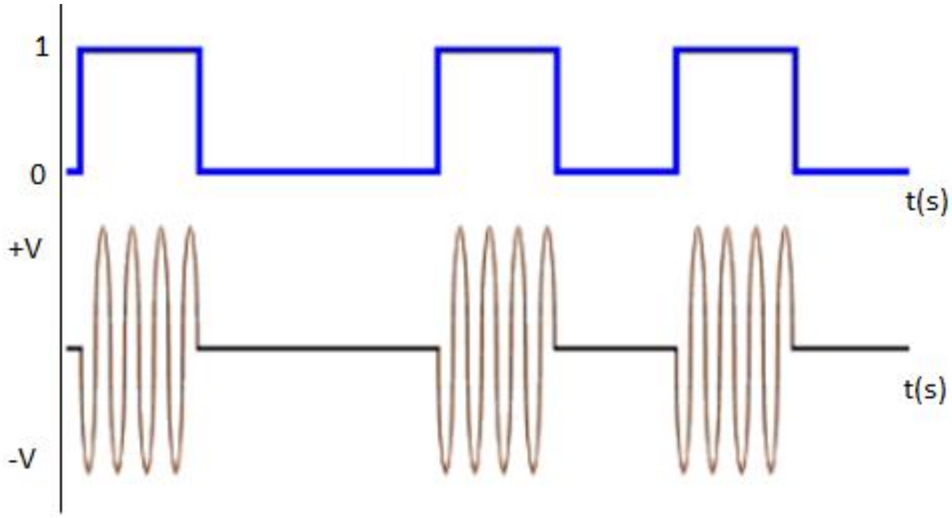

Figure 2.4-10 The OOK generated output. The top waveform is the input binary sequence fed to a transmitter. Based on the binary sequence, the transmitter generates OOK modulation shown in 2nd waveform [125]

Figure 2.4-10 shows the effect of the input binary sequence on the modulation of the carrier wave. When there is a logic 1 at the input, an OOK modulated wave takes the shape of the carrier wave with a particular amplitude level and when there is a logic 0, the carrier wave does not get transmitted. The following mathematical equation shows the OOK generation principle [122]. In the equation below, s(t) represents logic data which is shown as the first waveform in Figure 2.4-10, sin(2*π*f*t) represents the carrier wave, t represents time in seconds and f represents frequency in hertz [122].

$$OOK(t) = s(t) * \sin(2\pi f t)$$

Equation 15 The OOK generation. This equation represents the OOK generation method. It involves the convolution of sinusoidal waveform and the logic data [122].

The demodulation of ASK typically involves three steps: filtration, envelope detection and comparison of signal levels. By the use of band-pass filter, the concerned carrier frequency can be filtered from a broadband input noise signal. The input band pass filter is constructed by using a combination of a capacitor, inductor and resistor.

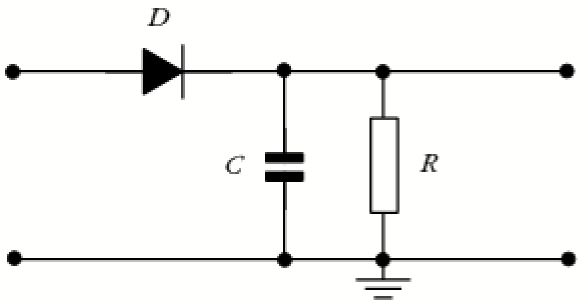

Figure 2.4-11 An envelope detector. The envelope detector performs the recitification and filteration of the modulated signal [117]

The signal is then fed to an envelope detector [126]. The schematic of an envelope detector is shown in Figure 2.4-11. The diode in the circuit rectifies the incoming signal by allowing current to flow in only one direction. The rectified signal is then fed to a low pass filter. A low pass filter is comprised of a capacitor and a resistor. When the input signal amplitude increases, the capacitor gets charged to the peak voltage of the incoming waveform. When the input signal changes its direction, the diode blocks the passage of the current and the capacitor gets slowly discharged by the resistor attached to it in parallel. When the input waveform changes its direction again, the procedure gets repeated [117].

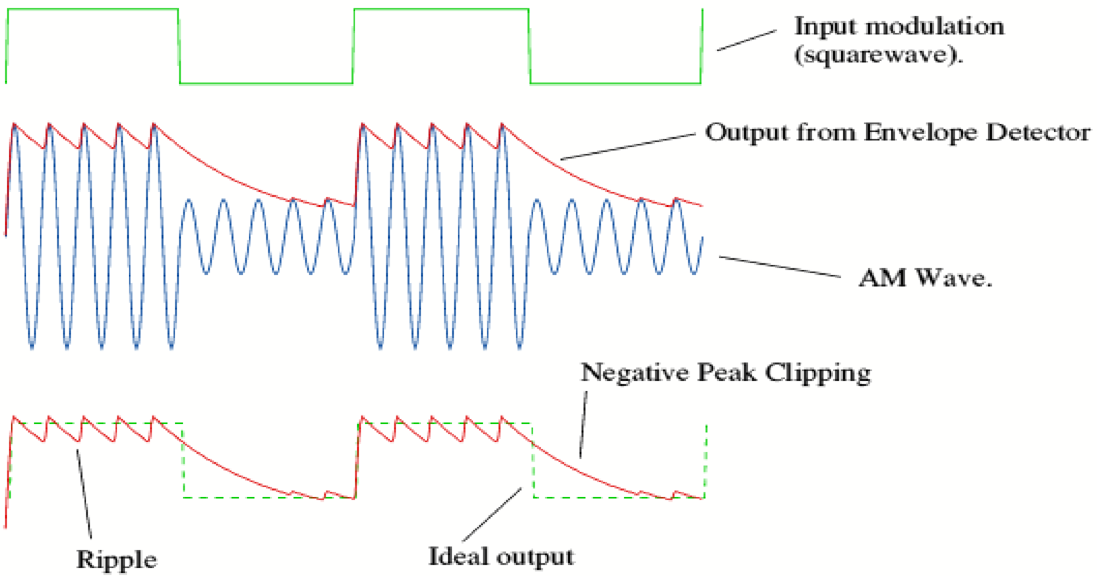

Figure 2.4-12 The figure shows waveforms from the ASK demodulated method. The top waveform is the input binary sequence and the middle waveform represents the effect of an envelope detector on the ASK waveform [117].

The effect on the signal by the application of an envelope detector is being shown in Figure 2.4-12. The output from the envelope detector will have the shape close to the original transmitted binary data signal shape but its logic 1 level will have ripples as shown in Figure 2.4-12 [117]. To get a binary data output, the signal is then fed to a comparator. The comparator then obtains the binary output by comparing the output signal from the envelope detector with its threshold input [126].

Frequency Shift Keying

FSK, a digital version of FM, is another form of digital modulation that is used in radio communication. In FSK, multiple frequencies are assigned to represent different digital information. This digital information is in the form of a combination of binary numbers, '1' and '0'. In the simplest form of FSK, a particular frequency gets assigned for logic 1 and a different frequency gets assigned for logic 0. The following equations govern the FSK modulation principle [122]. In the above below, t refers to time in seconds, f1 and f2 represents two different frequency levels

$$FSK(t) = sin(2 * pi * f1 * t) \quad for\ bit\ 1$$

$$FSK(t) = sin(2 * pi * f2 * t) \quad for\ bit\ 0$$

Equation 16 The FSK generation. These equations represent the FSK generation method which is dependent on the frequency [122].

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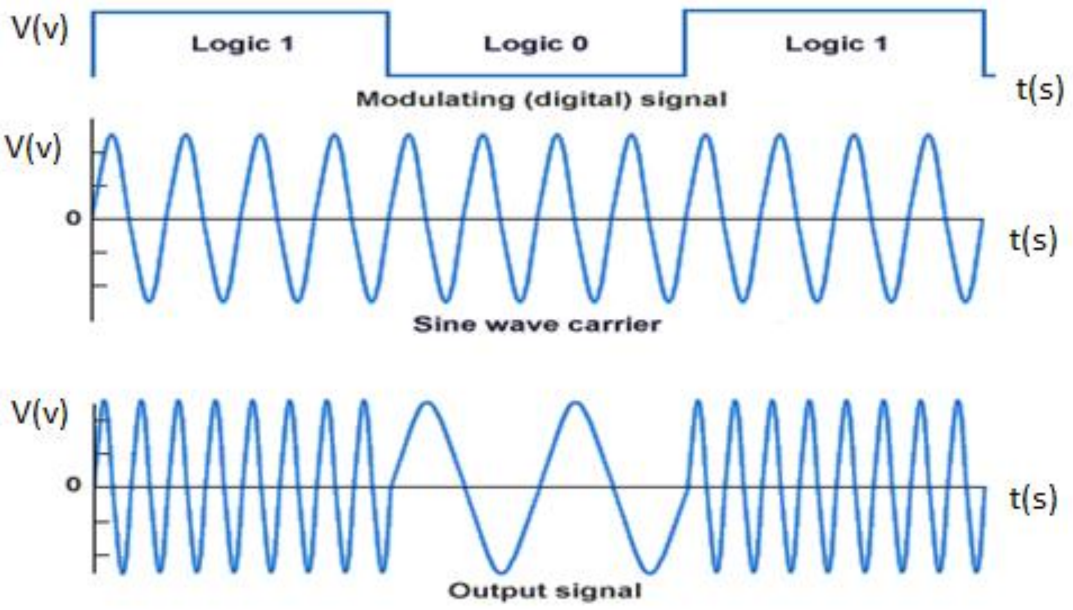


Figure 2.4-13 The first waveform represents the logic data. The 2nd and the 3rd waveforms represent carrier waves and FSK generated output respectively [127]

Figure 2.4-13 shows the FSK generated waveform for an input binary sequence. To transmit a logic 1, a carrier wave of a particular frequency gets transmitted, and to transmit a logic 0, a carrier wave of a different frequency gets transmitted [122].

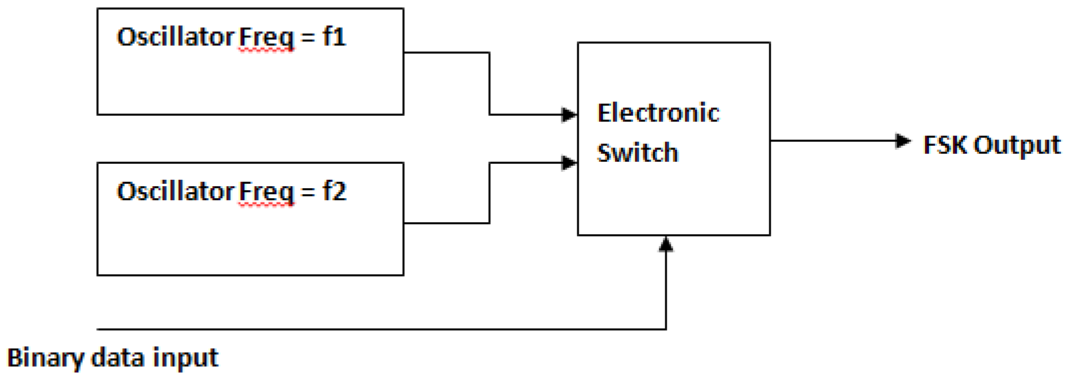


Figure 2.4-14 The FSK generation. The block diagram shows the FSK generation method. It involves the use of oscillators, electronic switch and binary input data [128].

Figure 2.4-14 shows one of the methods employed in FSK generation which uses an electronic switching technique. The control line of the switch connects to the binary data input. The switch also has a connection with either of the two oscillators which have different frequencies. Binary data is fed to the switch and depending on the input logic, the switch transitions between the oscillators [128].

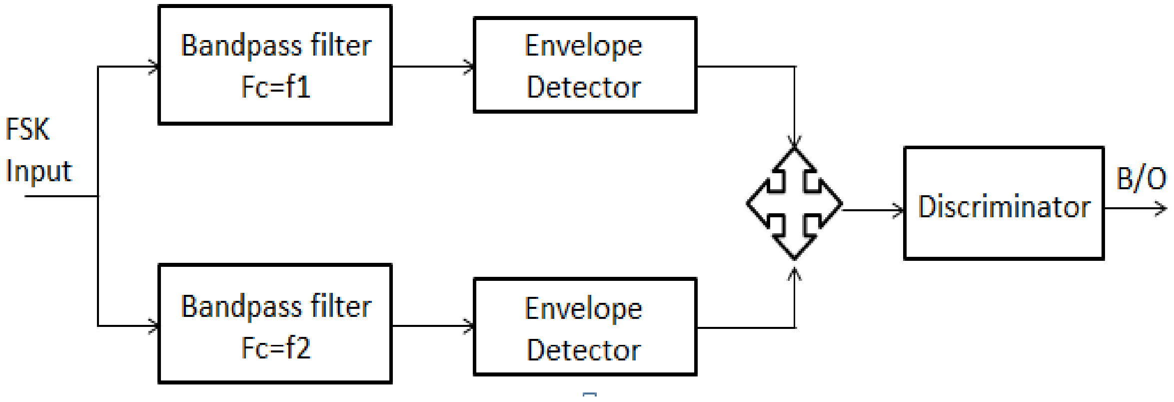


Figure 2.4-15 The FSK demodulation. The block diagram represents the steps that are involved in FSK demodulation. A bandpass filter discerns the frequency information from the carrier waveform. This output is then fed to other components to obtain the binary output [129].

Figure 2.4-15 shows the block diagram of FSK demodulation. The demodulation of FSK involves a frequency detector circuit which is composed of two bandpass filters that are centered on the two FSK frequencies such as f1 and f2. The output from the respective bandpass filters is then fed to its respective envelope detector. The output waveforms from the two envelope detectors, which will have ripples with different frequencies, are then fed to the discriminator. The discriminator circuit is composed of a sample and hold circuit and a comparator [129]. The sample and hold circuit takes samples of the input signals and then holds these sampled voltages for a set amount of time. This sample and hold circuit gives enough time to the comparator to discern the input signal. The comparator then obtains the binary information by comparing the frequency levels of the waveforms such that if f1 is greater than f2 then the comparator generates a logic 1 and if the comparator detects that f1 is less than f2, then it generates a logic 0 [129], [130], [131].

Radio communication is one of the important methods for the transmission of information. Radio communication involves transmission of data on a carrier wave by employing either an analog or digital modulation technique. Both analog and digital modulation techniques have their advantages and disadvantages in different applications involving wireless communication [132].

2.4.2. Acoustic

Acoustic communication is signal transmission in the form of sound waves [133]. Depending on the acoustic communication application, the typical frequencies assosiated with acoustic communication underwater range from 10Hz to 1 Mhz [132]. The attenuation of an acoustic signal underwater is dependent on the signal frequency. The path loss that occurs in acoustic communication underwater over a distance, d, is given by the following Equation 17 in whichd is the distance in km, k is the path loss exponent, a(f) is the absorption factor in dB/km and f is the frequency in Khz [134].

$$A(d,f) = d^k * a(f)^d$$

Equation 17 The path loss. The path loss equation is dependent on the frequency, distance and path loss exponent [134].

Thorp’s formula can be used to find the absorption factor where symbol f is refering to frequency in kHz, as shown in Equation 18 [134].

$$10 \log * a(f) = 0.11 * \frac{f^2}{1+f^2} + 44 * \frac{f^2}{4100+f^2} + 0.000275 * f^2 + 0.0003$$

Equation 18 The thorp's equation. The equation is used to find the absorption factor in acoustic communication. This is dependent on the frequency level of the acoustic signal [134].

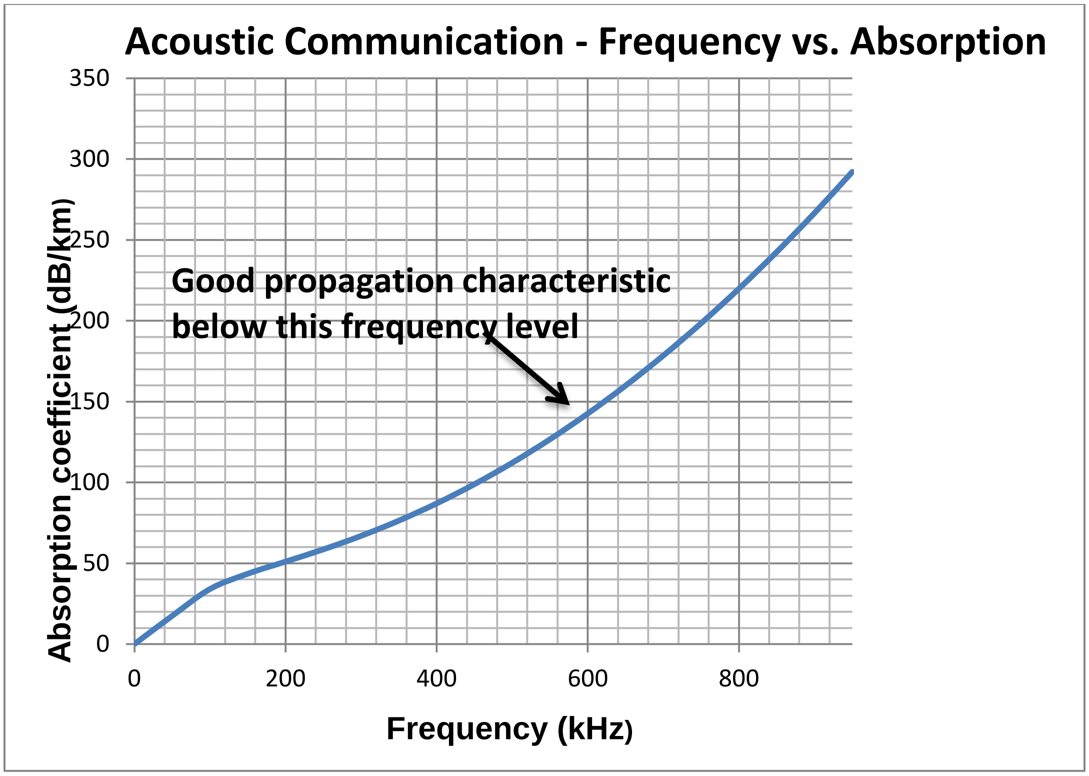


Figure 2.4-16 The graph shows the relationship between frequency and absorption for a frequencies less than 900 kHz. For higher frequency values, the absorption coefficient increases with a greater rate in comparison with frequency values [134].

Figure 2.4-16 shows a graphical representation of absorption vs. frequency in acoustic communication [134]. There are some important trends in the graph. The slope of the line decrease slightly around 200 kHz and then slope of the graph tends to increase more from frequencies above 600 kHz. Underwater acoustic communication typically uses FSK techniques for modulation and detection purposes at low bit rates. The concept behind FSK modulation has been discussed in section 2.4.1. Acoustic signals underwater are detected by using hydrophone which combined with some additional circuitry demodulates the FSK acoustic signal and then feeds the data for digital signal pocessing in which the data is recorded for the user interface [135].

Acoustic signal transmission is less attenuated in harsh mediums compared to radio transmission. This property makes acoustic signals effective for long distance communications in mediums such as water. However, there are certain limitation associated with acoustic communications underwater. Acoustic transmissions have lower bandwidth and higher propagation delays [133].

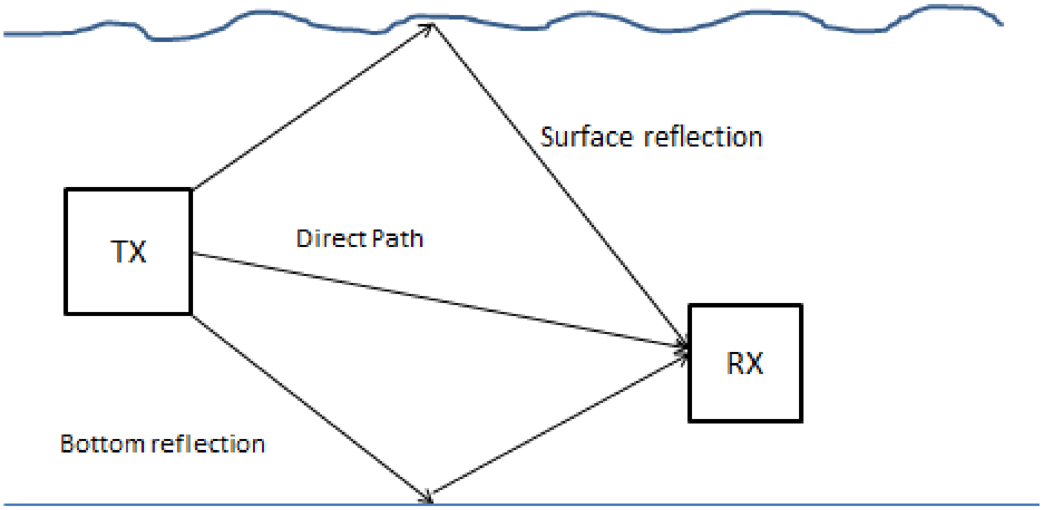


Figure 2.4-17 The multipath effect. Signals transmitted from TX reach the receiver RX with three different routes with certain time delays. Direct path takes the least amount of time to reach RX. The unwanted signals in the form of the surface and bottom reflections distort the signal processing at the RX [135].

In addition, acoustic communication is limitated by multipath loss as shown in Figure 2.4-17 [135]. The acoustic waves from the transmiter (TX) arrive at the receiver (RX) by following three different paths: direct, surface reflection, and bottom reflection. The direct path is the strongest signal received from the transmitter. This signal path takes the least amont of time to travel between the reciever and transmitter. The surface reflection reaches the transmitter after being reflected from the water surface and this signal arrives at the reciever later than the direct path due to a time delay. The bottom reflection reaches the transmitter after being reflected from the bottom. The multipath effect is more prominent in shallow waters, because the time difference between the arrival of the signals to the receiver is less which can lead to distorted results in detection of the transmitting object [135].

Acoustic communication is one of the important means of communication underwater. Even though it has its limitations, such multipath effect and propagation delays, an acoustic signal is less attenuated in water and there is still being used for long distance communication and underwater tracking [132].

2.4.3. Communication summary

Section 2.4 had a thorough analysis of two means of communication: radio and acoustic. All the modulation methods used in these communications were researched and their advantages and disadvantages were thoroughly analyzed. Table 2.4-1 also has some information regarding advantages and disadvantages of applications of the communication methods.

Table 2.4-1 Comparison of communication methods

Communication methods			
Type	**Application**	**Advantages**	**Disadvantages**
Radio (Cellular Telephony)	GSM	Divides B.W of RF ->Provides more radio channels	Lower data rate
Radio (Cellular Telephony)	UMTS	Faster data rate Better quality of service	More power consumption
Radio (Analog)	AM	Simple circuitry	Limited bandwidth
Radio (Analog)	FM	Higher bandwidth	Complicated circuitry
Radio (Digital)	OOK	Simple to implement Less power consumption	Signal more prone to noise
Radio (Digital)	FSK	Signal less prone to noise	Complicated circuitry More power consumption
Acoustic		Less attenuated in water	Slow data rate Multipath effect Path loss

2.5. Summary

This chapter presents the necessary background research to make the design decisions covered in the next chapter. It lays out different options for energy harvesting, tracking methods and communication technologies. Section 2.1 Environmental Considerations gives an overview of the Gillaroo and the river Shannon to gain a better understanding of the target and its surrounding. Section 2.2 Energy Harvesting discusses all the possible energy harvesting ways that can be used to capture power from the fish or its surroundings. Section 2.3 Tracking covers several tracking methods that are considered for the project and their associated current State-Of-The-Art to develop an efficient tracking system. Finally, section 2.4 Communication lists the communication technologies that can be employed underwater. This module's mission is to deliver the data from the tracking system to a mission control center where the location of the fish is determined. The discussion of these different topics is essential to make the critical design approach.

3.0 Proposed Design and Project Logistics

3.1. Main Goal

Current fish tracking methods range from simple tag and re-catch, to complex systems utilizing multilateration, and in some cases, satellites to collect data about the behavior of various species of fish. These systems run on battery power and as a result, all have a lifespan limited by the size of the battery the fish can carry, and how frequently the tags transmit information. The less frequently the tags transmit, the longer the tags can last, but the less precise the tags are. Some systems allow adjustments to be made to the overall system so that the precision can be tailored to each individual need. However, if the transmitting device could be powered by the fish or its environment, then the sacrifices in precision to increase lifespan would no longer be an issue, and the life of the tag would be limited only by the life of the fish.

The goal of this project is to develop a system, which will successfully track fish, and increase the tag's life span by checking the feasibility of developing a self-powered transmitting tag. The project should combine the energy efficiency of a passive RFID tag system in appropriate shallow and narrow areas, with an active acoustic signaling system designed to function in waters one to three meters deep. The acoustic signaling will be powered by an energy harvesting system that converts the mechanical energy of the fish into electrical energy. This energy harvesting system will include a backup battery unit to supplement the system if ambient energy ceases. This can then be used to send an identification number through the water using acoustic signal. The information collected by both RFID antennas and listening stations would then be wirelessly transmitted to a central location, hereafter referred to as the mission control center.

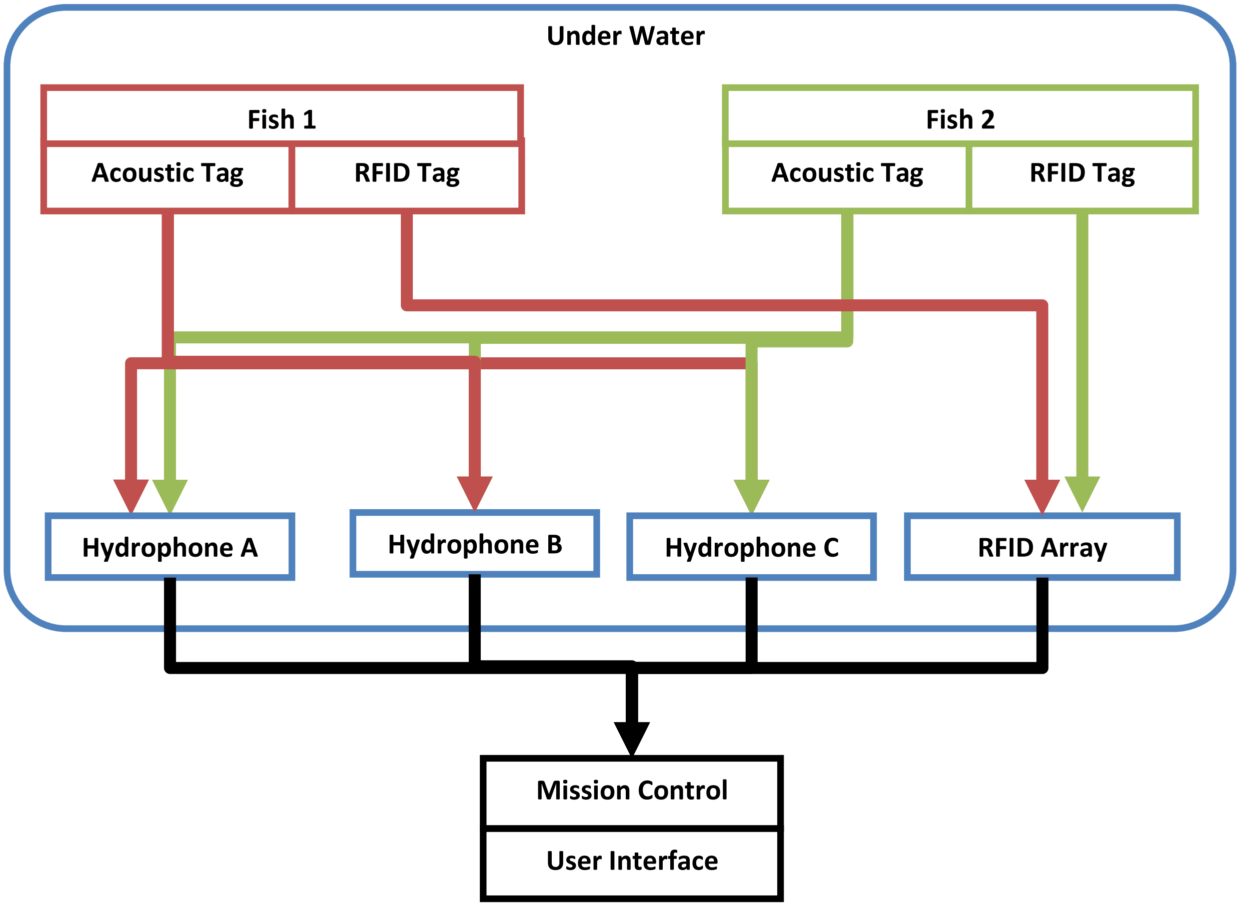


Figure 3.1-1 Overall System Design which shows how the tags will interact with both the RFID and the acoustic hydrophones and finally how all information will be communicated to Mission Control. In order to complete all testing, there needs to be at least two tags present to show functionality.

Figure 3.1-1 illustrates an overall system diagram of the system the team plans to develop. The concept will be implemented using two fish tags, three hydrophones and one RFID reader. There will be two fish tags used to demonstrate that the system can be scaled to include numerous tagged fish. There will be three hydrophones so that the team can observe and correct for any signals observed by the hydrophones adjacent to the one that should record the location of the fish. There is only need for one RFID array because in the implementation, multiple arrays will not be close enough for interference to occur, and therefore the system will function in the same manner regardless if there is one RFID array or ten RFID arrays. As seen above, each fish tag will contain an acoustic and an RFID component. When the tag passes through an RFID array, the RFID portion of the tag will receive power and transmit the fish' ID number. Also, as the fish swims through the rest of the river, the tag will transmit an acoustic signal that can be received by the hydrophones. The station will transmit the fish' unique ID number as well as the station's ID number to the centralized location known as the mission control center, when either a listening stations or an RFID array receives a signal. Once the signal is received at the mission control center, it is processed and stored, and then sent to the user interface which will display the last known location of the two fish.

The design has several technical challenges to address. These challenges range from self-powering a fish tag to wirelessly integrating data from multiple sources, and include:

- **Harvesting Energy from the fish or its environment to power a transmitter:** Currently, all fish tracking systems are powered by conventional batteries, giving them a limited lifespan. The team will develop a device that can harvest the energy produced by the fish and uses it in concert with a battery to extend its life. The device will be carefully designed to avoid negatively impacting the fish' life.
- **Tracking the location of the fish through the different areas of the river despite the changes in the river topology:** The River Shannon contains a varying geography that can make traditional tracking methods difficult to implement or in some cases useless.
- **Communication from water to air:** There are numerous complications that arise when transmitting radio signals from water to air. One example is the losses caused by the reflection of part of the signal at the boundary of the two mediums.

- **Communicating the information about the location of the fish to a central location:** The information gathered by the different detectors scattered throughout the river needs to be centered in one location to allow easy, real time access to the information.

3.2. Project Objectives

The main objective of the design is to continuously provide the location of the Gillaroo along the River Shannon through the use of the energy harvesting concept and efficient underwater tracking methods without human interaction. In order to do so, the system must meet the following requirements:

- The system needs to harvest power from the fish or its surroundings to activate the transmitting device periodically which will send the fish's ID number to the stations. In case the energy harvester fails to deliver the power needed, the system needs to draw power from a battery unit. This will provide a long lasting system that does not solely rely on external power to constantly send a signal. The energy harvesting device will be cautiously attached to the fish to prevent any harm or discomfort to the fish.

- In order to employ suitable tracking methods in sections of river that have similar topologies, the system needs to have corresponding tracking methods so that maximum coverage of the river is provided. The different receivers will be constantly seeking the fish ID number from the transmitter attached to the fish.

- The system needs to wirelessly communicate the data acquired from the receivers to an on-shore mission control center. This process involves encoding the fish's identification, the receiver's identification, and a parameter showing the strength of the received signal within range of the fish. The preceding information which will be encoded in a format that is compatible with the radio transmitter and receiver chipsets will be continually transmitted and received wirelessly and then fed to the mission control center for further processing of information.

- The mission control center needs to be able to process all the data from the receivers, and output the location of the fish based on localization techniques, such as received signal strength indicator.

These objectives are achieved though the development of individual subcomponents which will be integrated into a complete system prototype. The subsystems consist of the power management subsystem, the tracking subsystem, the communication subsystem, and the mission control subsystem. These specifications of these modules are covered in section 3.4.

3.3. Project Management and Tasks

The time limitation, as well as the complexity of the problem, necessitates an efficient time management plan to ensure successful completion of the MQP. The project was split into three main parts that could be worked on simultaneously and a forth section to be completed during integration by all members of the team. The three main implementation parts are defined in 3.4.1 Energy Harvesting, 3.4.2 Tracking and 3.4.3 Communication followed by the last section to be completed as a team, section 3.4.4 Mission Control Center.

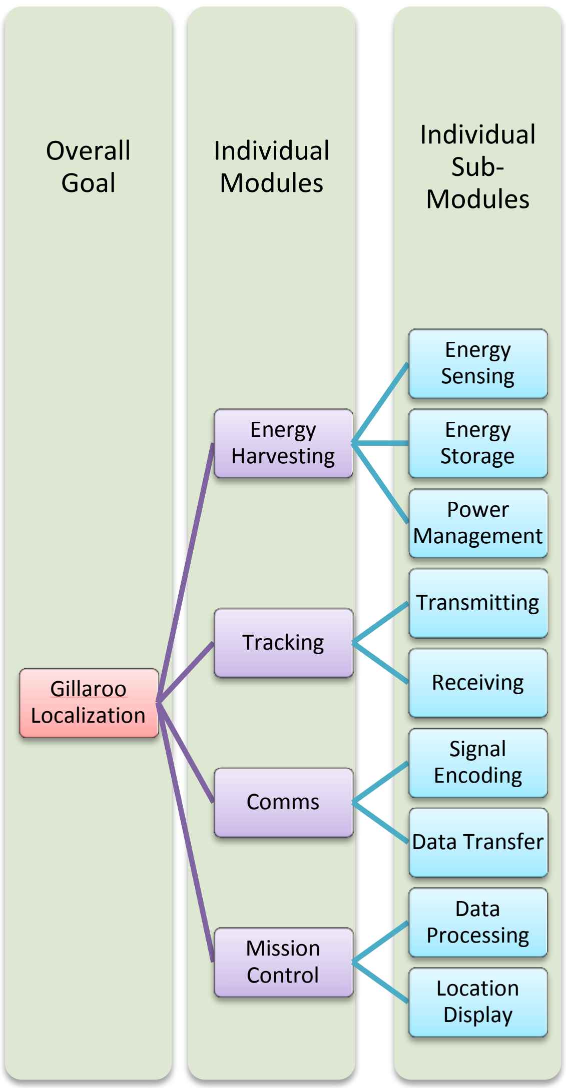


Figure 3.3-1 This shows the project management and how the overall goal of the project of tasking fish is split into four main goals. From the four goals there are several objectives. Each of the goals is completed by an individual to contribute to the team's overall effort of tracking the Gillaroo.

The team required extensive knowledge in three main areas: energy harvesting, tracking and communications. One member of the team focused on the energy harvesting area, researching and developing several different methods. Two individuals were assigned to this area to figure out several options for tracking of the fish because tracking was the area of the least amount of knowledge. Finally, one member focused on the different methods of communication, for the wireless transmission and the reception of the information. The team decided integration would be done as a team. As part of integration, there is a forth part to the project which is the mission control center. This is the final piece to the project which will pull together all three main components. The mission control will collect all of the location data as well as do the final calculations to determine the fish's location. Figure 3.3-1 illustrates the team's organization and duties, showing the three main areas of the project, as well as the mission control and what are necessary for each area.

The team created a Gantt chart to keep the project on schedule. Below in Figure 3.3-2, the Gantt chart illustrates the overall schedule. The Blue boxes are the overall objectives, while the gold boxes detail each task to complete the objective. The black boxes show the major deadlines to be met before moving on in the project.

The second chart is the actual schedule, as described below. The team had several changes in the project which caused a change in schedule. Originally, the goal of the project was to complete an actual product that could be attached to the fish. Due to time constraints the goal switched to a proof of concept during week seven. In addition, the original plan was to complete the project within the ten weeks, because of integration problems, the original ten weeks had to extend to the following seven weeks. Integration marked the largest milestone for the team, and when it was pushed off in Ireland due to the delay in parts orders, this left very little time for debugging. Once given enough time and the proper equipment, integration was possible. Though this set the team back, several other studies were able to be conducted as well as an increased amount of testing. Though the original goal was not completed, a well documented proof of concept was completed in the newly allotted time.

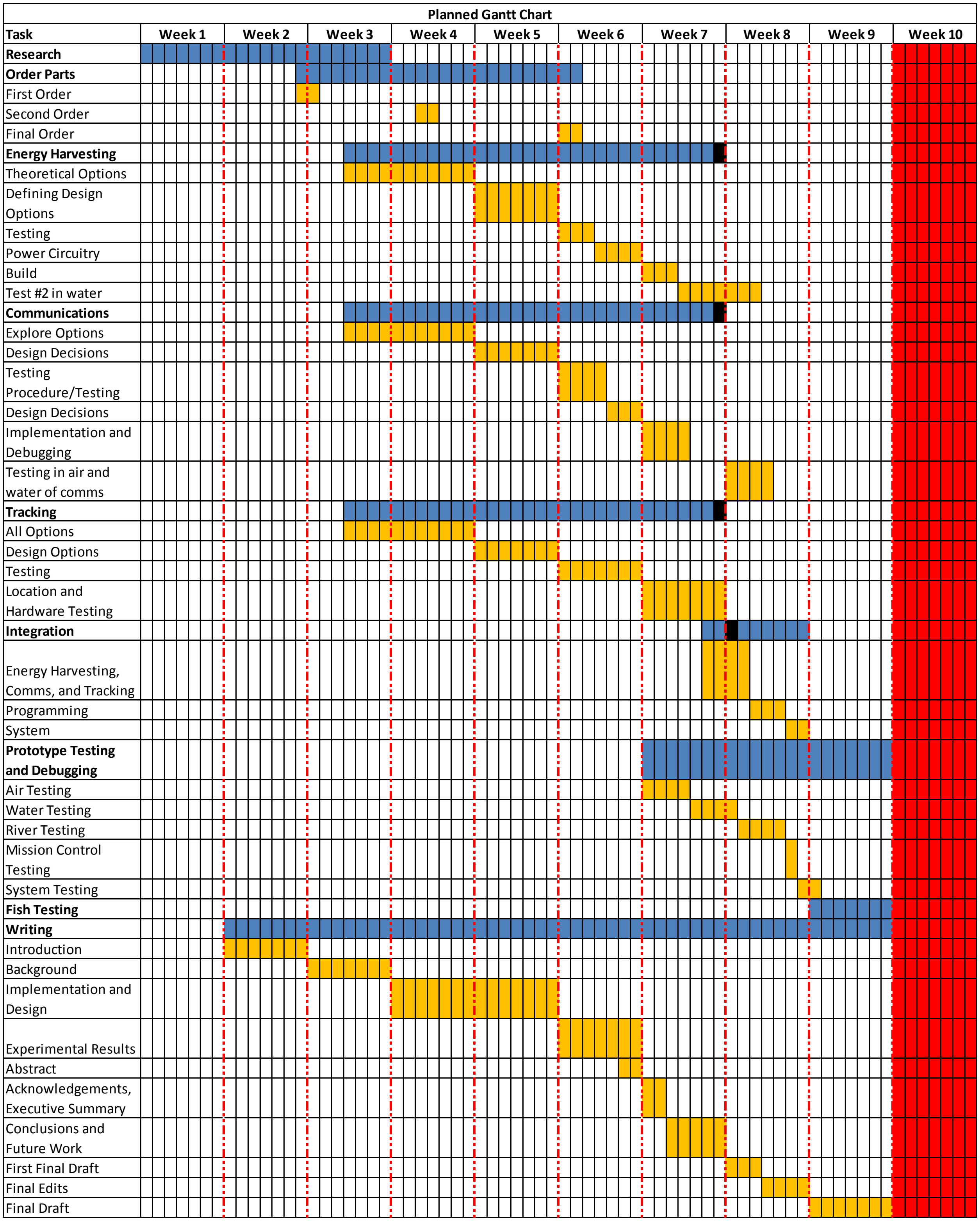
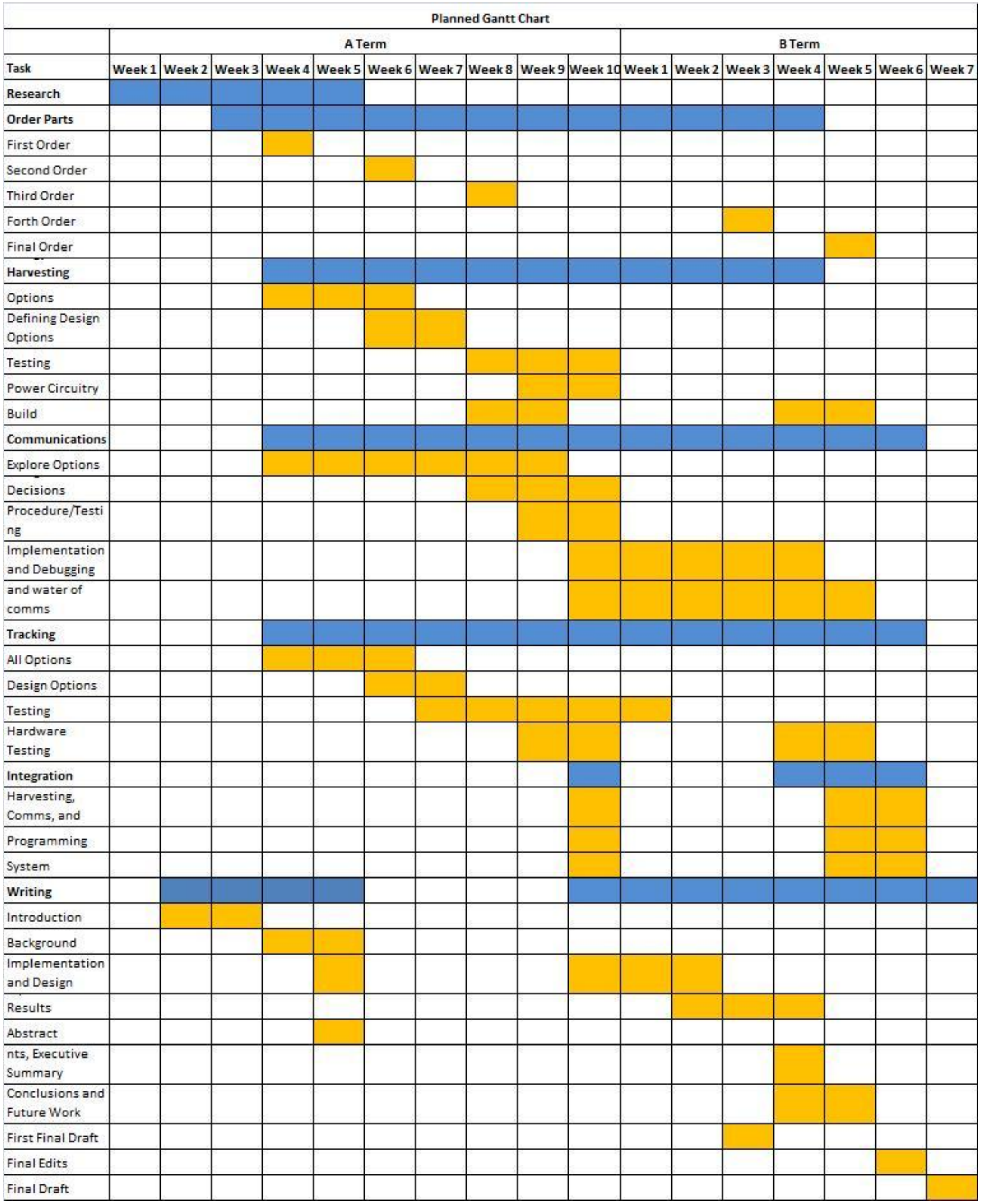


Figure 3.3-2 Planned Gantt Chart

Though the team worked to meet the goals of the chart above, the chart below indicates the actual schedule of the project.

Table 2 - Actual Gantt Chart



Planned Gantt Chart																	
	A Term										B Term						
Task	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**	**Week 7**	**Week 8**	**Week 9**	**Week 10**	**Week 1**	**Week 2**	**Week 3**	**Week 4**	**Week 5**	**Week 6**	**Week 7**
Research	🟦	🟦	🟦	🟦	🟦												
Order Parts			🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
First Order				🟨													
Second Order						🟨											
Third Order								🟨									
Forth Order													🟨				
Final Order															🟨		
Harvesting				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦			
Options				🟨	🟨	🟨											
Defining Design Options						🟨	🟨										
Testing								🟨	🟨	🟨							
Power Circuitry									🟨	🟨							
Build								🟨	🟨					🟨	🟨		
Communications				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	
Explore Options				🟨	🟨	🟨	🟨	🟨	🟨								
Decisions								🟨	🟨	🟨							
Procedure/Testing									🟨	🟨							
Implementation and Debugging										🟨	🟨	🟨	🟨	🟨			
and water of comms										🟨	🟨	🟨	🟨	🟨	🟨		
Tracking				🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦	
All Options				🟨	🟨	🟨											
Design Options						🟨	🟨										
Testing							🟨	🟨	🟨	🟨	🟨						
Hardware Testing									🟨	🟨				🟨	🟨		
Integration										🟦				🟦	🟦	🟦	
Harvesting, Comms, and										🟨					🟨	🟨	
Programming										🟨					🟨	🟨	
System										🟨					🟨	🟨	
Writing		🟦	🟦	🟦	🟦					🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
Introduction		🟨	🟨														
Background				🟨	🟨												
Implementation and Design					🟨					🟨	🟨	🟨					
Results												🟨	🟨	🟨			
Abstract					🟨												
nts, Executive Summary														🟨			
Conclusions and Future Work														🟨	🟨		
First Final Draft													🟨				
Final Edits																🟨	
Final Draft																	🟨

3.4. Design Decisions

This section provides a technical analysis of the overall design approach as well as specific analysis of the subsystems discussed earlier. The specifications for each subsystem were developed based on the system's requirements. The overall system is shown in Figure 3.4-1. The system is composed of four modules: energy harvesting, tracking, communication and the mission control center. The energy harvesting module provides power to the fish's transmitting device which is enclosed in the fish tag along with the power circuitry. The preceding device periodically sends the fish's ID number to listening stations along the river Shannon. The stations consist of hydrophones in deep sections of the river and RFID readers in shallow or narrow areas of the river. This data is wirelessly transmitted to a mission control center which continually processes the different signals received and outputs the fish location.

Figure 3.4-1 System Integration

3.4.1. Energy Harvesting

Based on the background research, several energy harvesting techniques were initially considered before selecting the appropriate one. These techniques consist of piezoelectricity, thermal energy, rotational energy, acoustic energy and solar energy. Solar energy was immediately eliminated due to the size restriction of the panels, the high cost, and non-functionality in deep or murky waters. Although thermal energy seemed feasible because fish are constantly moving in the water, trout are considered to be cold-blooded creatures which mean they adopt the environmental temperature. The metabolic heat gets lost through the trout's gills into the water. In an acoustic energy application, the sound vibrations coming from the flow of the river or the motion of the fish could be harvested using transducers. However, these transducers are only activated by certain frequencies, so it will be hard to consistently trigger the transducers underwater. The two potential options left for the energy harvesting system consisted of piezoelectricity and rotational energy. To determine which option would be more appropriate for our application, these two options were further tested.

To test the rotational energy, a DC motor was tested in a fountain at the University of Limerick. In order to observe the voltage generated, a propeller was attached to the motor's shaft and submerged into the fountain. The output of the motor was then connected in series with a resistor to measure the current. The maximum power calculated was 0.14 μW, which is too low to trigger a transmitting device.

The feasibility of using piezoelectricity was then examined. A PVDF piezoelectric film was tested. The piezoelectric film can be used to harvest power from the fish's external respiration and the vibrations of the water on the fish's skin. The oscilloscope was used to measure the output voltage as the film was stressed. To test the current output, the voltage drop of a known resistor is measured while compressing the film using a constant force. Different resistances values were tested to match the impedance of the film. The output voltage dropped from 10V pk-pk to 1 V pk-pk in the first five minutes of testing. Similarly, the current measured using a 100 ohm resistor dropped from 1 mA to ≈ 0A. The piezoelectric film operates as a capacitor. When the film is placed under stress it produces a proportional charge which produces an open circuit voltage but very low current since the charge flows away once unstressed. These results also showed that the film is very fragile and it loses sensitivity quickly when compressed.

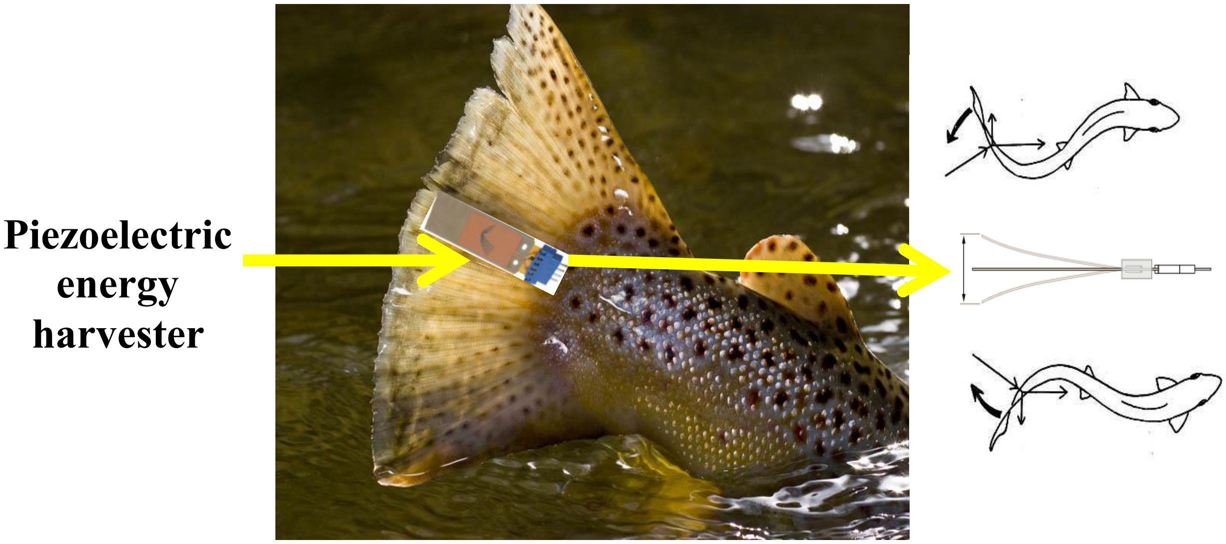


Figure 3.4-2 Piezoelectric energy harvester attached to the fish diagram. As the fish swims, the movement of the tail will cause a displacement in the piezoelectric harvester.

Next, the ability to harvest energy from the deflection of a bimorph was tested. The bimorph could be attached to the fish as shown in Figure 3.4-2. The bending motion of the fish was simulated by taping the bimorph to a ruler, as shown in Figure 3.4-3. The bending of the ruler generates an oscillation of the bimorph at different frequencies. Each natural frequency of the vibration corresponds to a displacement of the end of the ruler, for which the corresponding output voltage and current were measured.

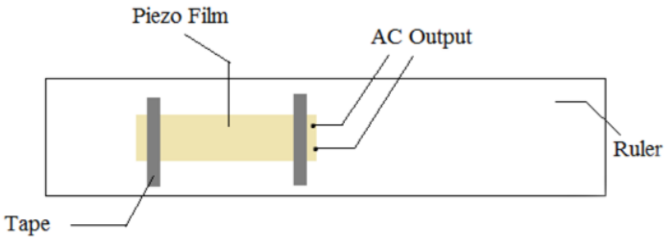


Figure 3.4-3 The piezo film is secured to the end of a ruler using tape, allowing room for the AC output to be accessed. The ruler allows for the simulation of a fish's movement.

The bimorph purchased from Farnell was rated for a 4V pk-pk with a displacement of 10 µm. However, when tested the material was not flexible enough to allow any bending. The team decided to purchase a more flexible and expensive piezoelectric bender that is rated for a power of 0.030 mW. The next chapter covers the implementation of the power management circuitry for the piezoelectric bender.

The table below summarizes the design decision options.

Table 3.4-1 Comparison of Underwater Energy Harvesting Techniques

Underwater Energy Harvesting			
Type	**Application**	**Advantages**	**Disadvantages**
Thermal	Metabolic Heat	Fish is always moving No moving parts	Trout is cold blooded Loss of heat through gills
Rotational	Water Flow	Currents in river	Attract other fish Large and heavy
Piezoelectricity	Fish Movement	Easily attached to fish Constant fish movement High voltage output	Low current output
Acoustic	Ambient Noise	Inexpensive	Unreliable Tuned to specific frequency Inefficient
Solar	Sun	No moving parts	Only operates when sun available Inefficient underwater Large form factor Expensive Difficult attachment to fish

3.4.2. Tracking

Tracking the position of fish, especially in rivers, has not yet been fully developed and presents many challenges. This project focuses on the tracking of the Gillaroo, which lives in a small portion of the River Shannon that contains both very shallow areas, as well as a few deeper areas and has both fast moving and slow moving currents. In order to better address the problem, the team divided the river into sections based on the type of topology, allowing each section to be assigned a tracking method.

Though there are many methods available to track animals and assets, not all of these methods work underwater. A common way to track the position of anything is to use GPS. However, commercially available GPS does not have the ability to work underwater because the signal becomes heavily attenuated when intercepted from a satellite. Another method of tracking is to use thermal imaging, which would be useful to warm blooded animals. Thermal imaging will not work on fish for two reasons. First, fish are coldblooded and maintain the same temperature as their surroundings. Second, a thermal imaging camera cannot penetrate water and will reflect off the surface. In addition, proximity sensors, both inductive and capacitive, can provide a useful way of tracking, but will not work well underwater. Inductive capacitors will produce a magnetic field, which has the potential to negatively affect the fish, while capacitive sensors have problems identifying the fish through water. Though RFID tagging cannot be used over wide ranges and cannot provide specific data, RFID tagging has the ability to be used in water in shorter ranges. Finally, acoustic tagging was identified as a potential solution because of its successful use in water. However, acoustic tagging must be used in conjunction with a listener to determine the location of the fish.

The first tracking decision revolved around what system to use in shallow narrow areas of the river, such as the entrances to small side streams. For these areas, the team looked at RFID readers and proximity sensors. Proximity sensors, whether inductive or capacitive, can record when an appropriate object passes nearby. Proximity sensors do have the advantage of requiring no power supply on the item being detected. However, the given range of these sensors is typically limited to less than 5 cm which will not be able to cover the entire depth of the river [80], [81]. RFID readers have a larger range, from 2 cm to several meters, but this range is dependent on the type of tag used. RFID systems have both active and passive tags. Passive tags have no onboard power source, and instead are powered by the reader, and only transmit within a short range. Active tags contain an onboard power supply which is used to boost the transmitting range [92]. RFID systems are the choice for this part of the tracking because of the greater range and, for passive tags, equal power requirements to inductive and capacitive proximity sensors.

The second tracking decision was how the Gillaroo should be tracked in the relatively open and deep sections of the River Shannon. The two systems considered for this portion of the tracking system were radio signals and acoustic signals. Radio signals are able to transmit large quantities of information at the speed of light. However, in water radio signals attenuate very rapidly, except at very low frequencies, which have a low bandwidth and require long antennas [104], [105]. Acoustic signals are slower than radio signals, and have a lower bandwidth on any given frequency. However, acoustic signals can propagate for longer distances underwater before attenuating, and do not require large antennas to transmit [29]. The team decided to use acoustic signals because they have a longer underwater range, and require a smaller transmitting antenna, which will have a smaller impact on the fish, than a radio system.

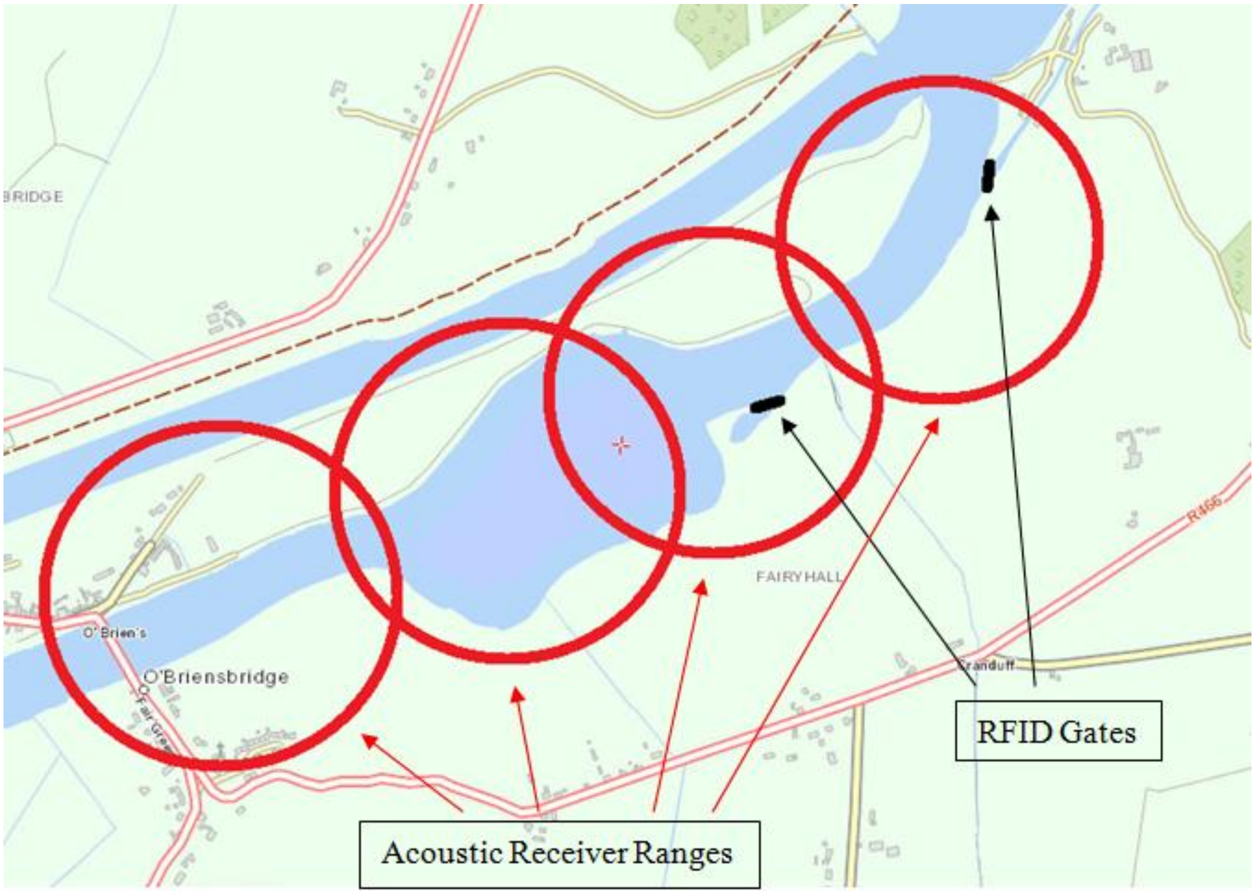


Figure 3.4-4 An example of the integration of the two tracking methods employed in this project. The RFID gates monitor narrow areas of the river and record whenever a fish passes through. The acoustic receivers monitor the more open sections of the river and record whenever they hear a fish within their range.

Based on the investigation into several different tracking methods and the sections of the river, the team chose two main forms of tracking to use: RFID and acoustic. The RFID tagging will be used in the narrow parts of the River Shannon where the fish are forced into relatively narrow passages. A passive RFID chip, one that requires no on board power, was chosen to save energy which will operate at 125 kHz. The communication between the receiver and tag will be done completely underwater because of the attenuation that the reflection causes when traveling between water and air. The RFID portion of the system will only give the position of the fish when it is passing through an antenna. The team will build an antenna to optimize the range of the passive RFID chip underwater. This antenna will be built around a wooden frame that is one meter tall and 2 meters long so that it can be placed at the entrance to small side rivers. The planed placement of the RFID systems is shown in Figure 3.4-4.

The acoustic system will be used for the deeper areas of the river, as shown in Figure 3.4-4, and is comprised of a tag which transmits a periodic signal and a series of listening devices which receive the signal transmitted by the tag. The three tags in the system will transmit at 20, 40, and 60 kHz. These frequencies were chosen based on Figure 3.4-5 which shows that from 20 to 70 kHz, the received voltage is at least 70% of the transmitted voltage. For frequencies above 120 kHz, the received voltage steadily drops off to nothing, and between 80 and 110 kHz the received signal strength varies greatly from 30% to over 100%, and if this area were used only the area between 100 and 110 kHz which would limit the bandwidth that could be used. 20 to 70 kHz provides the widest bandwidth with a high percentage of the original signal received.

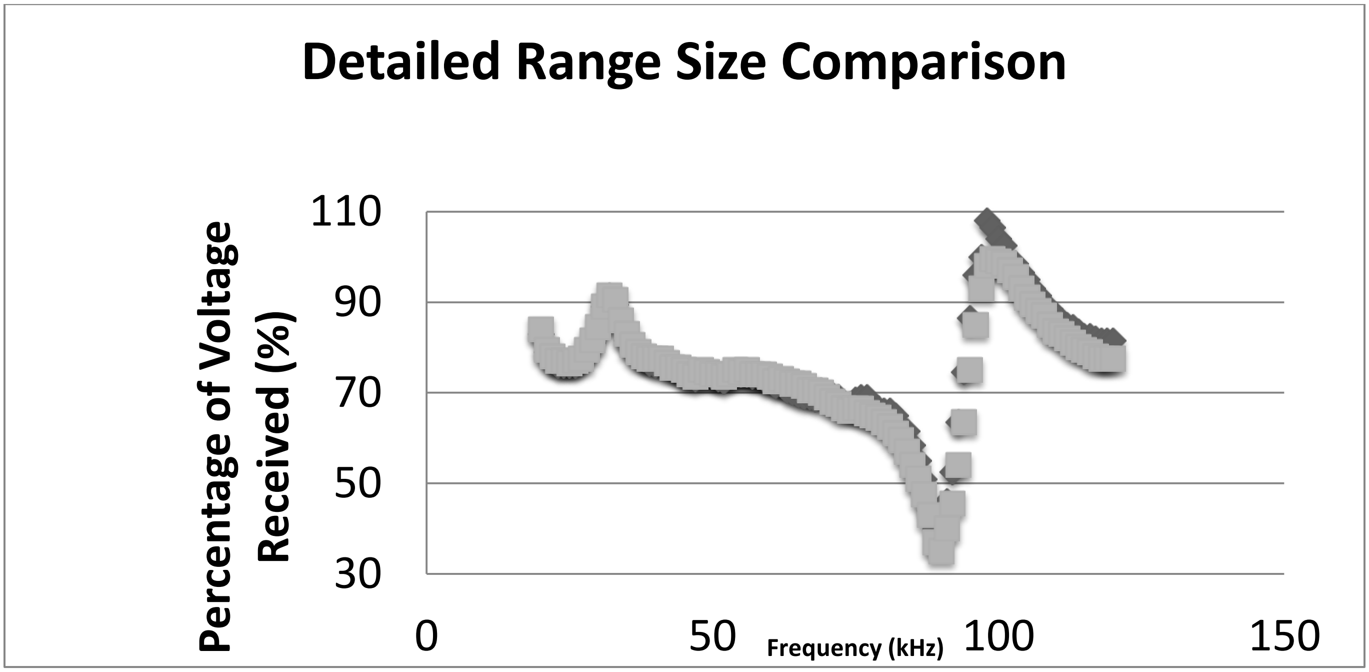


Figure 3.4-5 A graph showing the percentage of the transmitted voltage received at a range of approximately 30 cm in two different size buckets. The graph shows a relatively flat section from 20 to 70 kHz where 70 to 80% of the initial voltage is received.

The listening stations will be submerged along the side of the river spaced to overlap in range. Each listening station will be placed approximately 75 meters apart along the bank of the river to allow for 15 to 25 meters of dual coverage. By incorporating this overlap the reliability of the system increases because it will eliminate the possibility of areas between each listening circuit where the fish could be out of range of any station. These listeners will receive signals at different amplitudes based on the distance between the fish and the receiver. Though certain areas of the river may present problems for the acoustic system, such as large debris at the river floor, the overall location of the fish will be easily tracked. The information collected from the listeners can then be passed to the mission control center for processing. The mission control center will use the amplitude of the signals received from any number of listening stations to determine the location of the fish.

A summary of the design options are in the table below.

Table 3.4-2Comparison of Tracking Methods

Tracking Methods			
Type	**Application**	**Advantages**	**Disadvantages**
Multilateration	GPS	Highly accurate Infrastructure in place	Does not work underwater
Multilateration	Telephony	Highly accurate	Need access to provider base stations
Multilateration	Independently Manufactured	Control operation frequency	Complex calculations
Triangulation	Directional Antenna	Simple calculations	Reliance on signal strength Higher accuracy requires more antennas
Proximity	Capacitive	No advantages	Does not penetrate through water Limited range Differentiation between fish difficult
Proximity	Inductive	No advantages	Field produced might affect fish Differentiation between fish difficult Only detects metal
Thermal	Infrared Camera	No advantages	Expensive Reflects off of water Differentiation between fish difficult
RFID	Passive	No on board power required for tag Unique identification included	Limited range
RFID	Active	Longer range than passive Unique identification included	On board power required for tag
Sonar	Passive	Unique identification included	On board power required for tag Requires multiple listening stations
Sonar	Active	No on board power required for tag	No unique identifier for individual fish

3.4.3. Communication

In order to communicate the information about the location of a particular tagged fish to a user interface, a wireless network approach will be implemented. As discussed in section 3.4.2, a combination of an RFID array and several listening stations will be used to detect a fish tagged with both an RFID tag and an acoustic tag. To communicate this information wirelessly, several steps will be involved: encoding the digital tracking information into a form that is compatible with the wireless transmission components, transmitting the digital information by modulating it on a carrier wave, and decoding the information at the receiving end to discern the original data. Eventually, this data will be fed to the mission control center for further processing.

The encoding part of the project will act as a digital interface of the RFID array and the listening stations with a wireless transmission device. This digital interface will convert the tracking information of the fish which will be in the form of parallel binary logic levels into serial binary sequence that is compatible with a wireless transmission device. In order to encode the data, several approaches were considered before selecting the most feasible option. One of the design options could have employed the use of microcontroller for encoding data. A microcontroller can be reprogrammed to account for changes in design over time. However, the use of microcontroller design option would require the placement of microcontrollers at every RFID array and listening stations along the river. This design option would not have been cost effective as the development boards for microcontroller are expensive. Also, the encoding part of the project does not need to be reprogrammed overtime as the design would remain consistent throughout. Another design option that was considered for the encoder part requires the use of integrated circuits and digital logic implementation. Multiplexers will be used to convert the tracking information in parallel logic form into serial binary sequence. An 8-bit binary counter will be used in conjunction with different logic gates to operate the multiplexers at specific time intervals to output the serial binary sequence. This design option is comparatively simpler to implement, and the required components are readily available in the labs. This circuit design has additional benefit of having low power requirement of less than 100 mA. Although, this design option will be comparatively harder to make changes to but this will not be an issue because the encoder circuit design will remain consistent for the scale of the project. Therefore, based on cost effectiveness, design simplicity and the small timeline for the project completion, this design option will be used for the encoder part of the circuit.

In order to implement the wireless transmission and reception of the tracking information, several approaches were considered before selecting the most feasible option, considering the timeline and the scale of the project. One of the design options would have employed the use of cellular telephony for the wireless communication. Based on the background research, it was discovered that the architecture of cellular telephony such as GSM and UMTS require complicated programming and protocol implementation. The implementation of cellular telephony design would have required comparatively expensive components such as GSM dongle and considering that these would have to be placed at every listening station and RFID array along the river, it was not a cost effective option.

Another approach could have used acoustic communication for wireless transmission and reception of the data. However, wireless data transmission through acoustic means has limitations in the form of lower bandwidth and slower data transmission. The speed of sound in air is around 330 m/s which is inadequate for applications that require fast wireless data communication. For the accurate discerning of tracking information by the mission control, it is necessary that the wireless data transmission and reception of data takes place at a rapid rate. Another design option that was considered for wireless transmission and reception of the data uses radio communication. The principle behind the use of radio communication involves the conversion of the digital binary information obtained from the tracking sensors into an analog signal. This signal will then be transmitted in air with the use of a radio transmitter device such a FM transmitter chipset. The analog signal will then be demodulated back into digital form by a radio receiver device such as a FM receiver chipset. The FM chipsets are cheap and were readily available in our project lab. There needs to be a FM transmitter at every listening station and RFID array and therefore cost effectiveness is an important factor for the project. The specific chipsets that will be used have high data rate up to 50 Khz and these operate at 433mHz frequency. They have low power consumption of less than 100 mA. Radio waves travel at the speed of light and therefore the wireless data transmission through radio will be fast enough for the accurate discerning of tracking information by the mission control. The output from the FM receiver chipsets will be logic levels in a serial binary sequence that will be fed to the mission control for further processing.

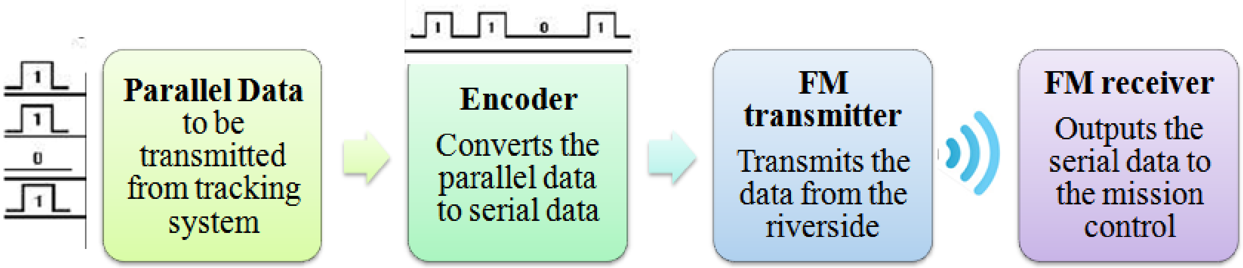


Figure 3.4-6 Block diagram of the communication setup.

Figure 3.4-6 shows the block diagram of the communication setup for the project. The parallel binary information from the tracking system will be fed to an encoder that will convert the parallel binary sequence into serial binary sequence. This serial data will then be fed to an FM transmitter for wireless transmission. The FM receiver will convert the wireless signal back into serial data that will be fed to the mission control for further processing.

The following chart summarizes the communications design decisions.

Communication methods			
Type	**Application**	**Advantages**	**Disadvantages**
Radio (Cellular telephony)	GSM	Divides B.W of RF ->Provides more radio channels	Lower data rate
Radio (Cellular telephony)	UMTS	Faster data rate Better quality of service	More power consumption
Radio (Analog)	AM	Simple circuitry	Limited bandwidth
Radio (Analog)	FM	Higher bandwidth	Complicated circuitry
Radio (Digital)	OOK	Simple to implement Less power consumption	Signal more prone to noise
Radio (Digital)	FSK	Signal less prone to noise	Complicated circuitry More power consumption
Acoustic		Less attenuated in water	Slow data rate Multipath effect Path loss

3.4.4. Mission Control Center

Mission control will integrate the information gathered from all sensors to enable an accurate and efficient method of tracking the fish. It will perform all calculations in determining position as well as a display to show the position of the fish to users. Several key parameters where considered when selecting a controller for the mission control. The controller needs to be capable of accepting different acoustic and RF signals that have been transmitted from the acoustic sensors underwater and the RFID reader. It also needs to be capable of outputting the fish number and constantly updating the fish’s last known closest station as the fish is swimming along the river. The location will be computed by comparing the different RSS from the acoustic sensors and by giving the priority to the RFID tracking to show the fish has passed through a particular area.

The main two options for a controller are a microcontroller or a Field Programmable Gate Array (FPGA). The microcontroller provides more freedom compared to an FPGA since it's easier to program and to change design functionality but provides lower performance. Also, the microcontroller is better at executing things in a sequential manner while the FPGA is better for performing things in parallel. Based on the preceding information, the microcontroller was initially considered as it is more suitable for performing mathematical calculations and communicating with other devices. However, the team decided to use an FPGA instead due to the group's familiarly with the FPGAs and available support for it. The UL lab had an evaluation board kit for the Spartan-3A FPGA which is shown in Figure 3.4-7. The FPGA will be programmed using VHDL.

Figure 3.4-7 Spartan 3A FPGA Starter Kit

3.5. Design Summary

The aforementioned deign has undergone several revisions to come to the current design approach. Several design options were considered and experimentally tested before drawing any conclusions. The final design consists of a transmitter powered by a piezoelectric actuator, which communicates with both RFID and acoustic listening stations, utilizing an FM transmitter to transmit all location information to a mission control center, which performs all data processing. The next chapter will detail the implementation of this design approach.

4.0 Prototype Implementation

This section of the report provides the technical design of the self-powering trout tracking system. It first presents the specifics of the independent modules that make up the system, which consist of a self-powered transmitter, acoustic and RFID tracking systems and a communication module to transmit the tracking data to a mission control. The integration of these modules into a unified prototype is then detailed. The modular approach allows the group to work synchronously to contribute independently to the design. It also simplifies the debugging and testing stages which will be discussed in the next chapter.

4.1. Energy Harvesting

From the previous chapter, it was concluded that piezoelectricity is the most suitable option for the energy harvesting module. By attaching a piezoelectric bender to the tail of the fish, the motion of the fish can be converted into electricity. Although rotational energy presented as a viable solution because there is current flow in the river and the fish is constantly swimming, the experiments conducted using a DC motor underwater were not successful. The motor outputted very low power that was not high enough for use, even when amplified.

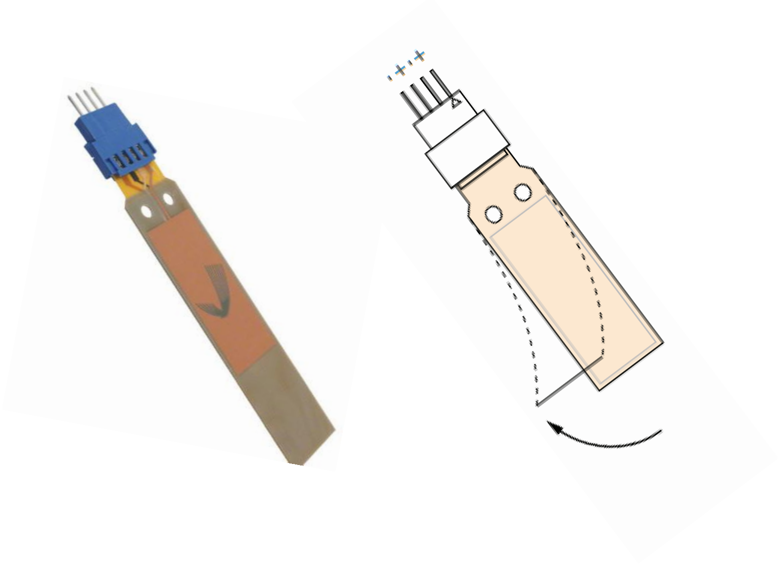


Figure 4.1-1 Volture piezoelectric bender. The bender is composed of two wafers than can be either connected in parallel or series for increased power. When deflected, each wafer produces a corresponding AC output than can be measured across two of the four pins.

The energy sensing subsystem converts the tail's deflections to electrical signals. To harvest the energy from the deflections, a Volture piezoelectric bender was bought from Digikey which is shown in Figure 4.1-1. The bender has a thickness of 0.031 inches, a width of 0.57 inches, a height of 3.56 inches, and contains two electrically isolated piezo wafers, which can be used independently or bridged together for increased power [136]. The raw output of the bender is an AC waveform as the bender deflects in both directions. As shown in Figure 4.1-2, when the wafers are connected in series, the open-circuit voltage is doubled while the current remains the same, and when the wafers are connected in parallel, the current output is doubled while the voltage remains the same. For our application, the parallel connection is more suitable since there is a need for higher current to drive the energy conversion and storage subsystem.

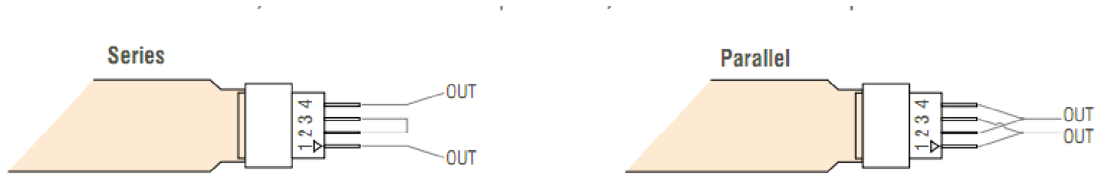


Figure 4.1-2 Series and Parallel configuration of the two wafers of the bender

4.1.2 Energy storage and conversion

The energy conversion and storage subsystem will consist of AC to DC rectification, energy storage and voltage regulation as shown in Figure 4.1-3. The AC to DC conversion is accomplished by rectifying and filtering the AC signal. The bridge rectifier uses both the positive and negative portions of the AC signal by directing the current in the same direction to the load, preventing back feeding the stored energy to the source. One of the problems of using a diode bridge is that it causes a voltage loss, therefore Schottky diodes are typically used since they require the least forward voltage among the other diodes. To increase the average DC output level, the output needs to be smoothed by using a capacitor across the output of the diode bridge. After filtering the output, the voltage needs to be regulated and amplified before stored in an energy storage device, which is attained using a DC to DC converter. There are many different types of DC-DC converters which vary on the power efficiency required. Since the output from the piezoelectric is relatively low, it needs to be stepped up using a boost converter or a pump charger. The boost converter stores the energy in the magnetic field of an inductor while the pump charger uses the electric charge in a capacitor. Finally, this energy is stored in either a capacitor or a battery. The battery can hold more charge for a longer period of time, while the capacitor uses less time to charge up to the desired voltage.

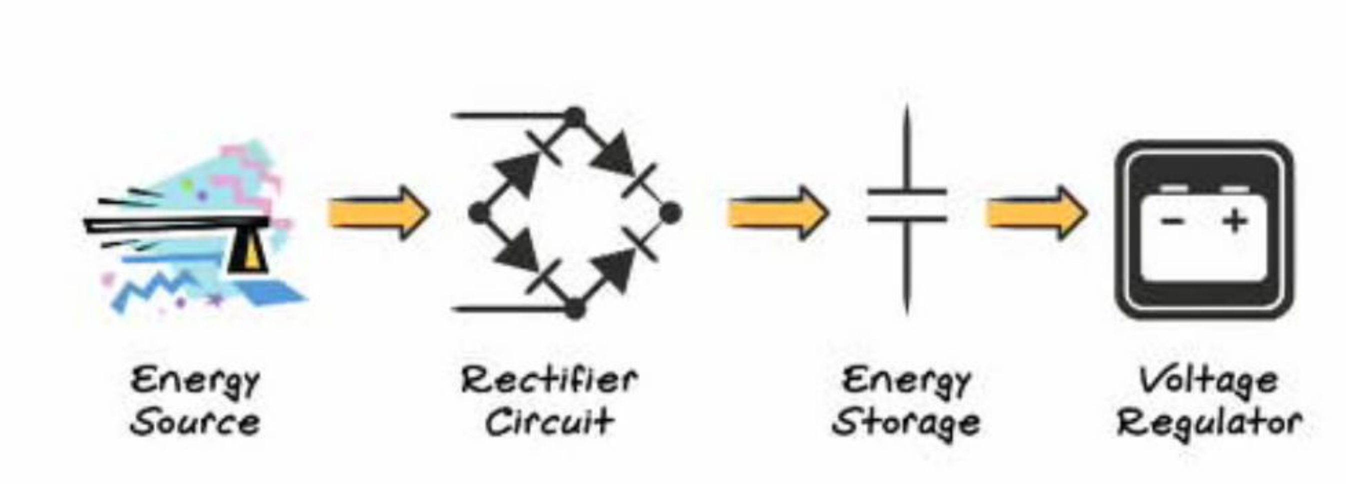


Figure 4.1-3 Energy Harvesting system. The output from the piezoelectric film gets rectified by a diode bridge, then filtered and regulated so it can be stored in a capacitor, which is going to trigger the transmitter device.

Instead of implementing the energy conversion and storage circuit using separate electronics for each block shown in Figure 4.1-3, an IC package was chosen from Linear Technology that incorporates all of the circuit requirements within one IC. The LTC-3588 presented a perfect choice for our system because it is compatible with the Volture piezoelectric bender since the chip is designed for high impedance elements such as piezoelectric materials. It is also recommended in the application information of the Volture datasheet and it encompasses all of the circuit capabilities discussed earlier that is needed for the circuitry. The block diagram for the IC is shown in Figure 4.1-4. Within the IC, there is a low voltage drop bridge rectifier that has a forward voltage drop of 400 mV and can support up to 50 mA and accepts a typical input current from the piezoelectric source of 10 µA. The output from the rectifier is fed to the input of the storage device, which gets transferred to the output energy storage device using a buck converter to efficiently charge the output energy storage device. The buck converter uses an inductor to charge the external capacitor as shown in Figure 4.1-4, allowing energy to get accumulated on the input capacitor when the energy must be harvested from low power sources. Since some applications may require more peak power than could be extracted from the piezoelectric source, this IC allows accumulation of energy over a long period of time to enable short high power bursts. When the voltage is being regulated, the chip enters a sleep state to minimize the input and output currents by turning on and off the buck converter as needed. The preceding switching of the buck converter is done using two internal PMOS and NMOS transistors that ramp the current though the inductor up using the PMOS switch, then down using the NMOS switch.

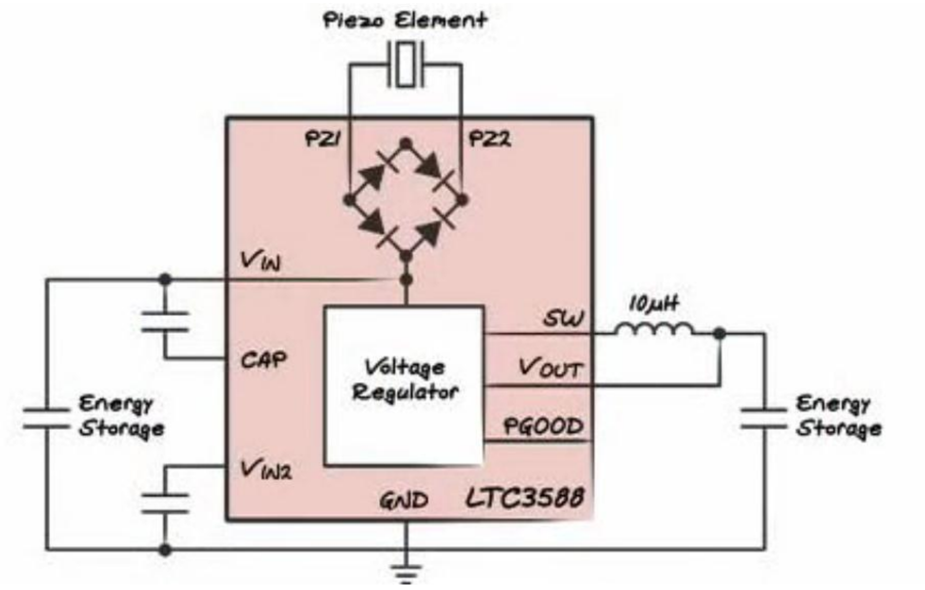


Figure 4.1-4 Block Diagram for LTC-3588

The LTC-3588 allows for four selectable output voltages (1.8 V, 2.5V, 3.3 V and 3.6V) with up to 100 mA of continuous output current. The output capacitance of the output energy storage was selected to output current burst using the following equation:

$$Tsleep = Cout * 24\frac{mV}{Iload}$$

Equation 19 Output current burst of the LTC-3588

where Tsleep represents the time between the bursts, Cout is the capacitance of the external output storage device and Iload is the output current. To select the output voltages, the inputs D0 and D1, shown in Figure 4.1-5, are modified by connecting them to GND (0) or Vin2 (1) as shown in Table 4.1-1 along with their corresponding output voltage.

Table 4.1-1 Output Voltage Selection

D1	D0	Vout (V)
0	0	1.8
0	1	2.5
1	0	3.3
1	1	3.6

Figure 4.1-5 shows the configuration of the LTC-3588 with a battery backup to supplement the system when the piezo source fails at providing power. When the battery is operating the system, the bridge is unused and the LTC-3588 serves a standalone buck converter which charges the external capacitor though the battery. The blocking diode prevents reverse current to flow to the battery if the piezo source is used. Using Equation 19 to select an output current of 100 mA, and a capacitance 47 µF, the time between the bursts will be 0.11 µs.

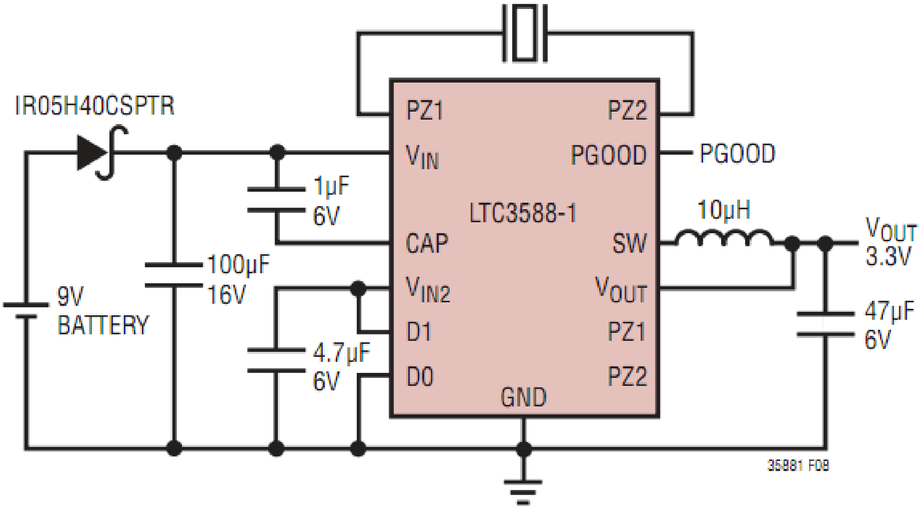


Figure 4.1-5 Piezo Energy Harvester with Battery Backup

The next chapter provides the results of implementing the energy harvesting module using the Volture piezoelectric bender and the LTC-3588 with the values shown in Figure 4.1-5. First, the piezo bender will be tested and its power is measured while varying the tip-to tip displacements to simulate the motion of the fish. Then, the IC will be tested with a battery alone to verify its functionality. Finally, both subsystems will be integrated to test the whole energy harvesting module and integrate it with the acoustic tag which is described in section 4.2.2.

4.2. Tracking

Based on the design decisions made in section3.4.2, the tracking portion of this project was implemented using two separate systems: an RFID system and an acoustic tagging system. The RFID system is used to cover the narrow parts of the river, such as the mouth of the Kilmastulla. The acoustic system is used to track the fish when it is in open water in river Shannon.

4.2.1. RFID System

The RFID system consists of three main parts: a passive tag, a reader, an antenna for the reader. These parts were ordered COTS (Commercial off the Shelf) from RF Solutions a product by Eureka. The kit contained two passive read only tags and one read/write tag along with a reader and a loop antenna which all operate at 125 kHz. The kit was chosen because it contained all of the required equipment to create an RFID system and was easy to implement, in addition to being a low cost option

Though the kit contained three different tags, the passive read only tag was chosen for two reasons, first to save on the use of energy and second, there is no need to program a new ID number, the one available is usable. The tag is attached to the adipose fin of the Gillaroo with glue that is recommended and used by biologists of the River Shannon. The orientation of the tag contributes to a successful read and therefore, the tag is positioned so that when the fish passes through the RFID reader antenna, the coils in the tag are parallel to the coils in the antenna.

The reader is used as it designed and has the option to connect to a PC to download the information. The reader outputs a 100 kHz, 8.6 V pk-pk square wave. The square wave peak values are -2.6 V and 5.8 V. In addition, there is a period of 10 us and a 50% duty cycle. Across the antenna, the reader outputs 119 kHz, in a triangle wave with peak voltages at -35.2V and 37.6 V. The reader is located out of water on the side of the river but is still enclosed in a waterproof enclosure for safety purposes. A 12 V battery powers the reader and the antenna. The reader collects the ID information from the tagged fish, then the information is transmitted later to the mission control center for additional analysis.

The last part for the RFID system is an antenna. Though the kit bought came with a loop antenna, the range was only 2 cm in air. For this reason, a loop antenna was created out of small gauged insulated wire. The new antenna was first successfully tested using a small plastic container filled with water, the range covering the entire container. The team then decided to build a new loop antenna, using the same wire was created by wrapping the wire around a 2 liter glass tank, much larger than the previous. The antenna successfully had a range that covered the entire tank containing 44 coils, which is 138 ft. Next, another loop antenna was created, again with the same wire, by wrapping a 120 liter plastic bin with wire. The optimized range, as shown in Table 4.2-1 was 19 coils, which is about 126 ft, but did have enough range to cover the entire container.

Table 4.2-1 Small Gauge Wire Range Test

Small Gauge Wire Range Test		
Turns	**Length(ft)**	**Success?**
50	350	No
40	266.7	No
30	200	No
27	180	No
26	173.3	Yes, no range
24	160	Yes, no range
20	133	Yes, 4 in
19	126.7	Yes, 8 in
18	120	Yes, Worse than 19

The final test used a much larger gauged wire around the same container. The optimized number of coils of this wire was 28, which is about 187 ft. This resulted in a range of 7 inches from above and below the water and complete coverage of the area, as seen in Table 4.2-2. With this test, the team discovered that the range of the RFID reader was associated with the resistance of the wire.

Table 4.2-2 Large Gauge Wire Range Test

Large Gauge Wire Range Test		
Turns	**Length (ft)**	**Success?**
34	226.66667	Yes, 1 in
33	220	Yes, 6 in
32	213.33333	Yes, full rang and 3in past bottom of coil
30	200	Yes, full range and 5 in past bottom of coil
29	193.33333	Yes, 5 in above water, which Is 6 in above coil, 6 in past bottom of coil, 5 in above water
28	186.66667	Yes, 7 above and below coil, 6 in above water
27	180	Yes, 2 in above the water, 0 below the coil

4.2.2. Acoustic Tag

In addition to the RFID tag described in section 4.2.1, each fish carries an acoustic tag. The acoustic tag transmits at an ultrasonic frequency, which is outside the hearing range of humans, the Gillaroo, and predators of the Gillaroo. This signal will be received by listening stations along the River Shannon and used to identify the position of the fish. The team decided that each fish tag would output a unique frequency which can be translated to a unique identification number. The signal generator was initially chosen to be a 555 timer circuit, designed to output a square wave between 20 and 70 kHz for short time intervals. The tag created for the projects prototype generates a 20 kHz square wave every 152 seconds which lasts for 10 seconds, implemented using the circuit show in Figure 4.2-1 below.

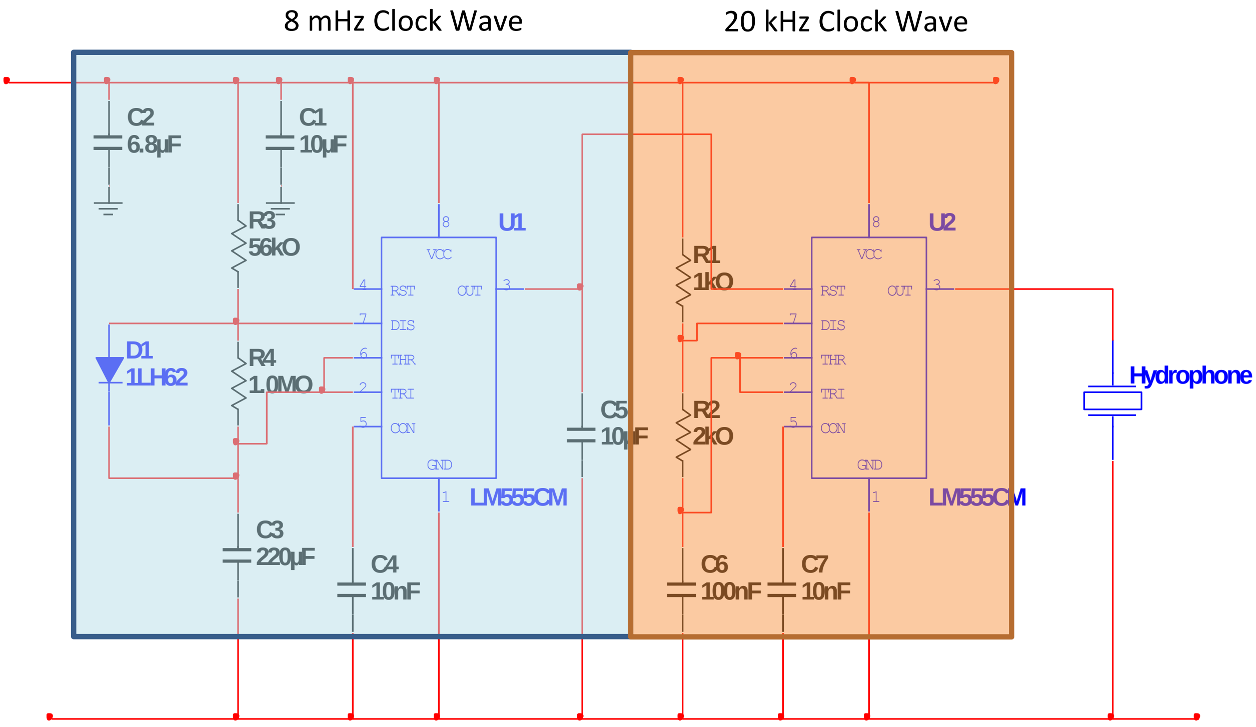
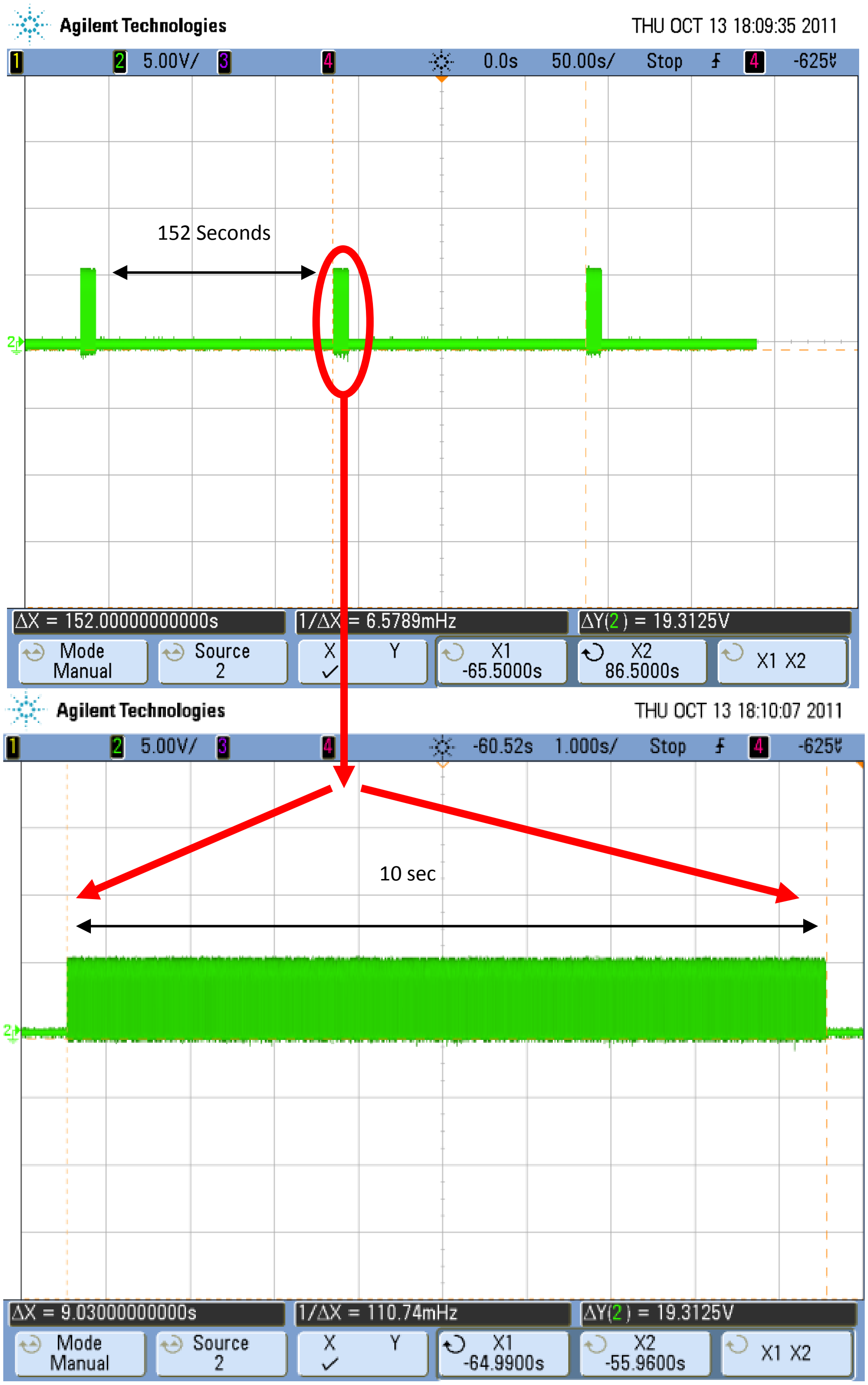


Figure 4.2-1 Version one of the acoustic tag circuit. This circuit, when powered by the energy storage device, will output a 20, 40, or 60 kHz square wave for 10 seconds every three minutes.

The first 555 timer is configured to output a 10 second pulse every three minutes which drives the enable of the second 555 timer in the initial design. The second 555timer is configured to output a 20, 40, or 60 kHz square wave when enabled. This circuit functions as expected and the results can be seen in Figure 4.2-2.



ΔX = 152.00000000000s
1/ΔX = 6.5789mHz
ΔY(2) = 19.3125V
Mode Manual
Source 2
X ✓ Y
X1 -65.5000s
X2 86.5000s
X1 X2

ΔX = 9.03000000000s
1/ΔX = 110.74mHz
ΔY(2) = 19.3125V
Mode Manual
Source 2
X ✓ Y
X1 -64.9900s
X2 -55.9600s
X1 X2

Figure 4.2-2 Pulse wave for first 555 timer. Waveform on left shows the pulse every 3 minutes. The waveform on the right shows the duration of the pulse as 10 seconds.

However, one problem with the initial configuration is that the circuit draws a constant five volts and 17mA. A 9V battery is capable of supplying enough power to run this circuit, but the energy harvesting circuit is unable to supply that much current.

The output of the circuit is connected to a piezoelectric disc known as a hydrophone, with a resonant frequency of 1.65 MHz. This piezoelectric buzzer is in direct physical contact with the water around the fish to allow the maximum amount of energy to be transferred from the piezoelectric buzzer to the water. The transmission occurs every 152 seconds based on the first 555 timer, to allow the energy storage device to recharge between each signal pulse, while still allowing the position of the fish to be identified at any time within 100 meters of a listening station.

4.2.3. Acoustic Receiver System

To receive the signal being transmitted by the acoustic tag, stations would be placed along the River Shannon at 75 m intervals. Each listening station contains four main parts: a power supply, a hydrophone, a signal processing circuit, and a sequence generator. The overall circuit schematic is as shown in Figure 4.2-3.

To power the listening stations, a battery capable of supplying 12 volts and 100mA would be needed at each station, and should be able to power each station for a minimum of 90 days. Alternatively, each station could be powered by a solar panel placed on shore to eliminate the need for replacement batteries. However, the implementation of solar panels fell beyond the scope of this project, and therefore the team did not include them in the design.

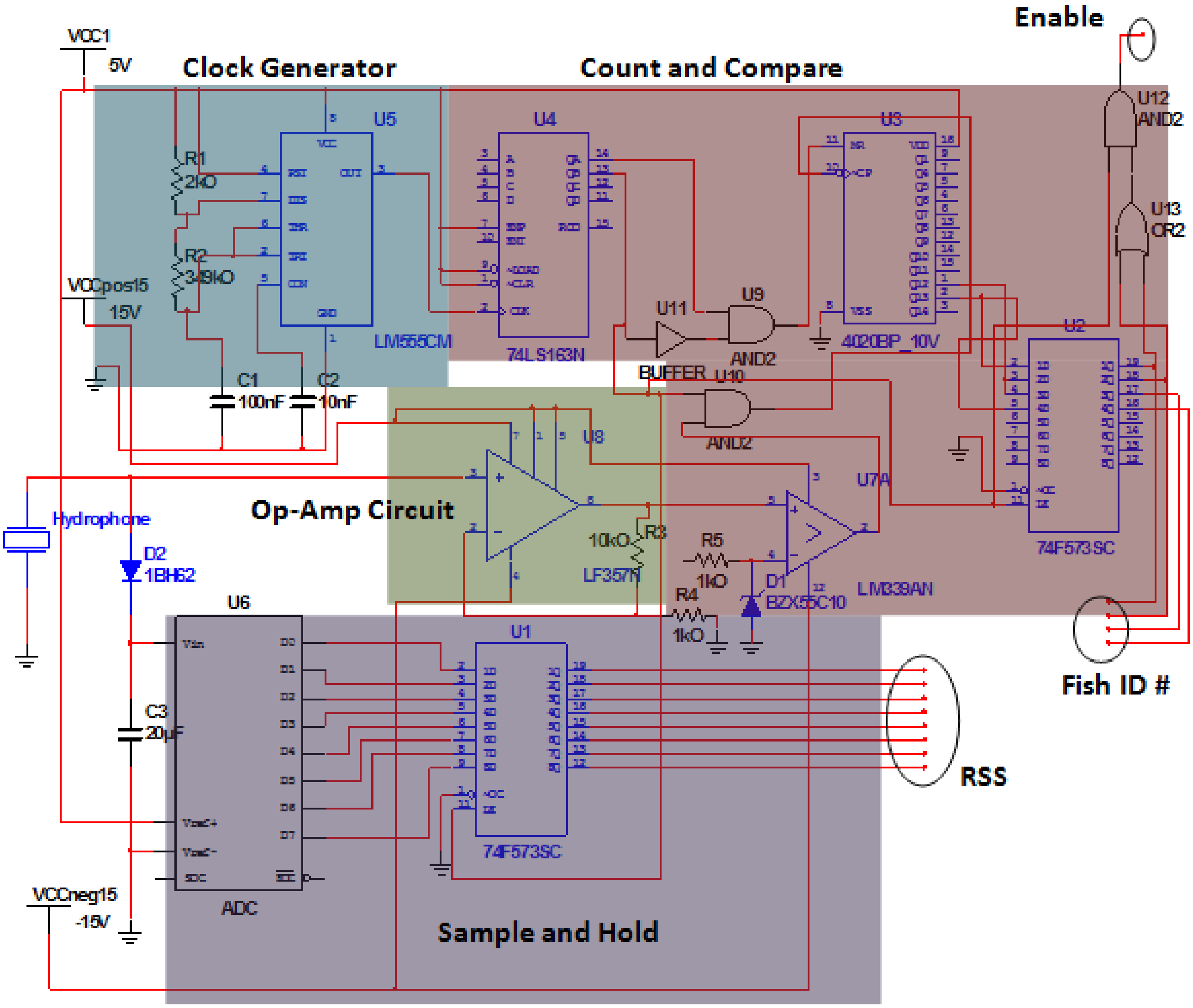


Figure 4.2-3 Overall Circuit Schematic for each listening station

The hydrophones used in the project to receive the acoustic signal transmitted by the fish are Pro-wave M165D25 Ultrasonic Atomizing Transducers, differing from other transducers, they are a type of piezoelectric transducer with a resonant frequency of 1.65 MHz, and receive the acoustic signal emitted by the fish tag. The signal is then amplified by a factor of 10 using the circuit shown in Figure 4.2-4.

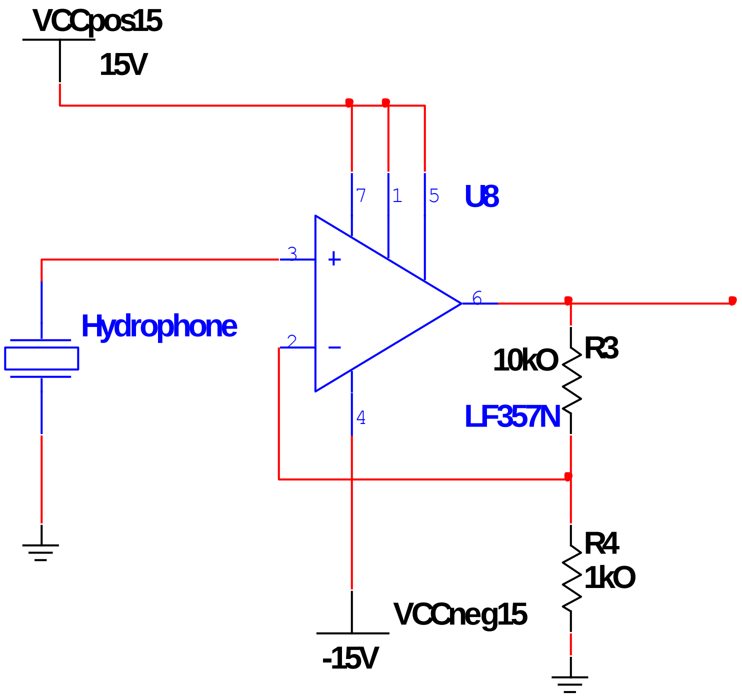


Figure 4.2-4 Op-Amp Circuit schematic. This circuit is designed to amplify the signal received by the hydrophone, by a factor of 10. The input will be a signal s received by the hydrophone, and the output will be equal to A*s.

The amplified signal is then sent to a comparator which converts the sinusoid into a digital square wave which is used to drive the clock signal of a 14 bit counter for a period of .1 seconds. To identify the transmitting fish, the portion of the circuit shown in Figure 4.2-5 is used to count the number of peaks in the signal thereby determining the frequency of the fish. The number stored in the counter after one tenth of a second is equal to one tenth of the frequency that the fish is transmitting at, and corresponds to a fish's identification number which is stored in binary form to later be sent to the transmitter.

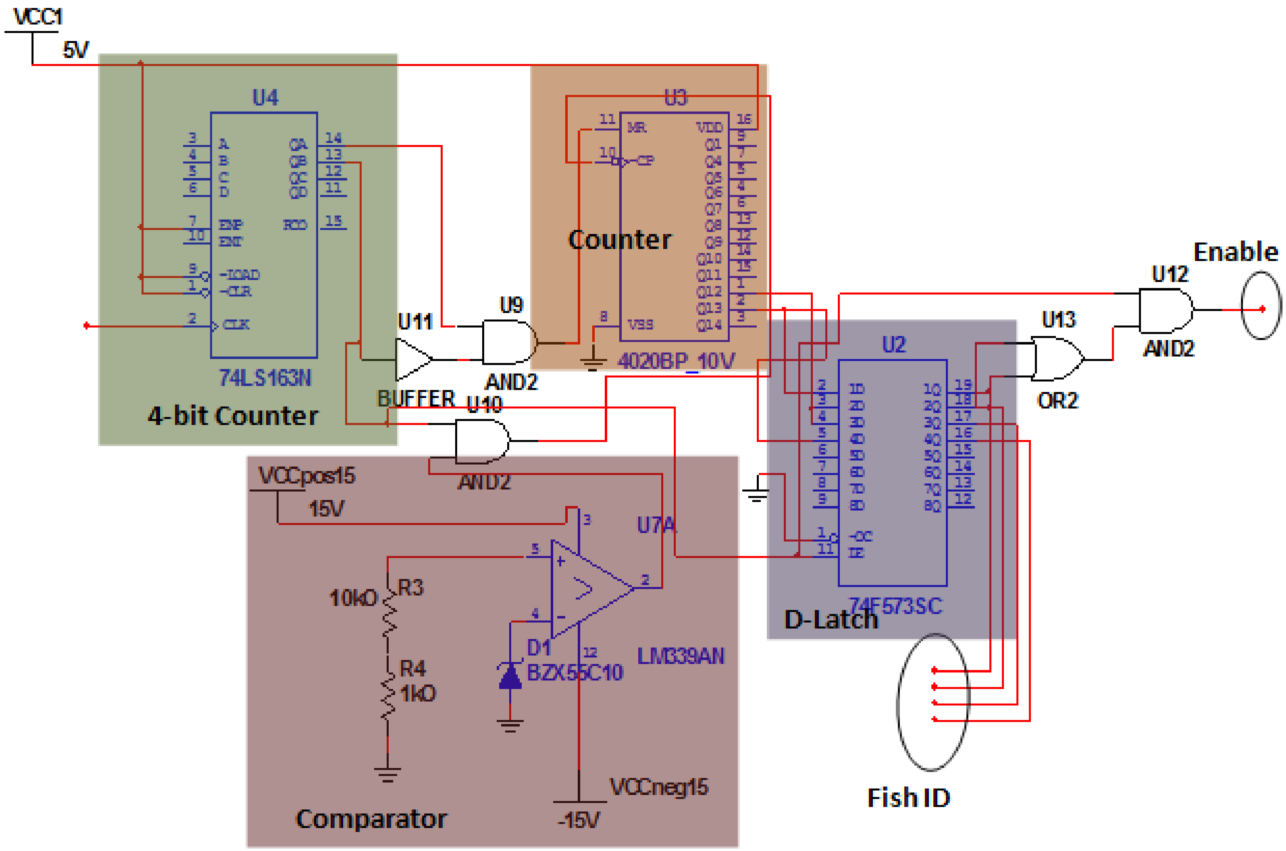


Figure 4.2-5 The circuit schematic of the comparator and counters, used to determine the frequency of the received signal. The amplified signal Vin is sent to the comparator, which transforms the sinusoid into a digital clock signal. That signal is used to drive the clock of a counter for one second. The number stored on the counter at the end of one second is the frequency of the signal, which corresponds to the frequency that the fish is transmitting.

In addition, if multiple stations receive the same signal, the peak amplitude of the signal needs to be recorded as a way to compare the signal strength. The portion of the circuit shown in Figure 4.2-6 is used to measure the maximum amplitude of the signal. The output from the amplifier is sent to an analog to digital converter, and the amplitude is recorded and sent along with the identification number of the fish to the transmission circuitry. A capacitor charges to the peak value of the input signal, and prevents the signal voltage from changing rapidly, allowing the Analog to Digital Converter (ADC) to convert the amplitude into an 8 bit binary value.

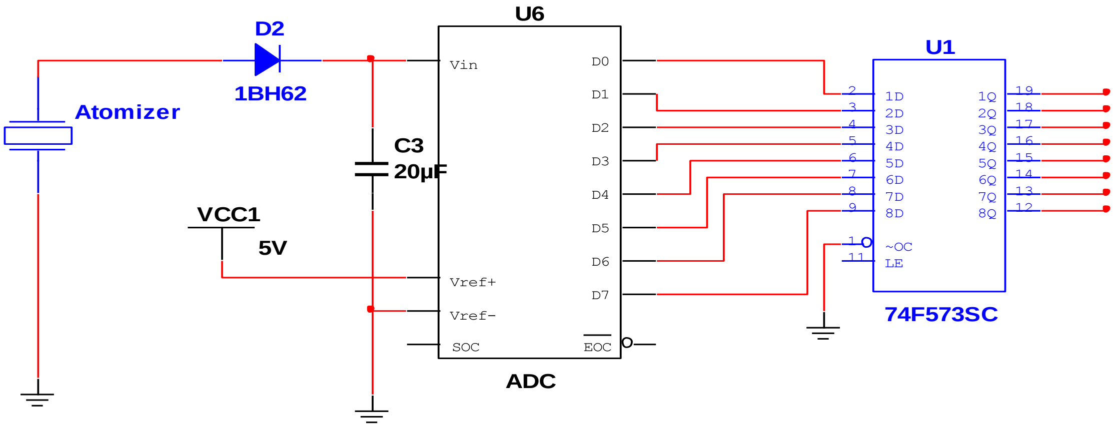


Figure 4.2-6 The circuit schematic of a sample and hold circuit and an analog to digital converter (ADC). This circuit takes the amplified signal from the hydrophone, and holds its peak value. That peak value is then converted to an 8 bit digital logic value which can then be transmitted to the mission control center.

The final piece of information sent to the transmission circuit is the identification number of the listening station. Since the identification number is unchanging, each listening station has its identification number hard wired, and every transmission sent by a station contains that station's unique identification number.

4.3. Communication

The communication part of the project is comprised of two subsystems: the encoding and the wireless transmission of the tracking information of the fish. Based on the design decisions, the team decided that the usage of integrated chips for digital logic design implementation would be the most suitable option for the encoding part of the communication. The team also decided, based on the design decisions, to use FM transmitter and receiver chipsets for the wireless transmission and reception of the tracking information. The encoder circuitry and the FM transmitter are being used at the transmit end of the wireless communication of the data obtained from the RFID reader and the listening stations. An FM receiver chipset is being used at the receive end of wireless communication and converts the wireless data back into the digital logic sequence that is fed to the mission control.

The tracking information obtained from the RFID reader or a listening station will consist of 17 binary logic bits in parallel sequence. The 17 bits obtained from a listening station consists of 8 bits for received signal strength (RSS), 5 bits for the station number and 4 bits for the fish number. Even though the mission control gives priority to the RF signal emanating from the RFID reader, 8 unique bits “11111111” are still provided to represent RSS of the RF signal to maintain consistency of the data fed to the mission control. The 17 bits are preceded by 9 bits which are “100110010” and contain the header information and succeeded by 9 bits which are “100110010” and contain the tail information. The header and tail bits are used to synchronize the transmission timing between two or more systems in wireless communication and therefore the mission control needs the header and tail information in order to accept and discern a data sequence. Thus, the output from the encoder circuitry is a serial binary sequence of 35 bits.

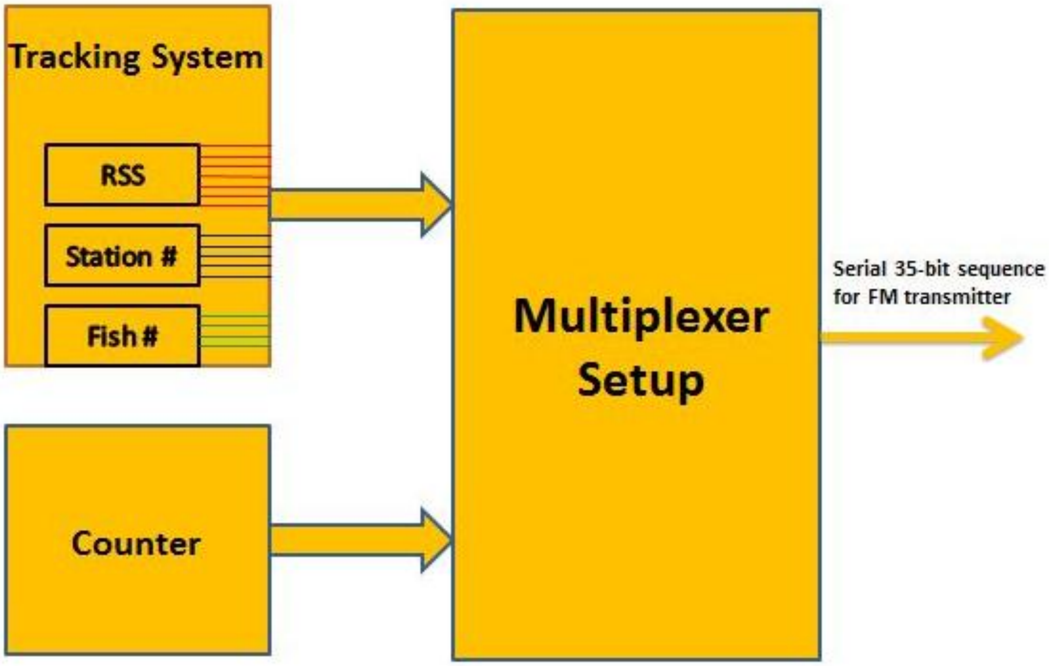


Figure 4.3-1 The block diagram of the encoder. The tracking system provides 17 logic bits in parallel form to the multiplexer setup. As shown in the figure, the number of lines originating from the individual components of the tracking system represents the 17bits. The multiplexer setup converts this parallel data into a serial binary sequence. The counter is used to operate the multiplexers in a selective order to generate the 35bit serial binary sequence.

The encoder is comprised of two subsystems which are the counter and the multiplexer circuitry. In Figure 4.3-1, the block diagram shows a basic overview of how the tracking system is used in conjunction with the encoder. The tracking system provides 17 bits to the multiplexer setup when it tracks the position of the fish. The output from the counter controls the input select pins of the multiplexers and based on the output logic levels of the counter, a serial sequence of 35-bits is generated by the multiplexer setup.

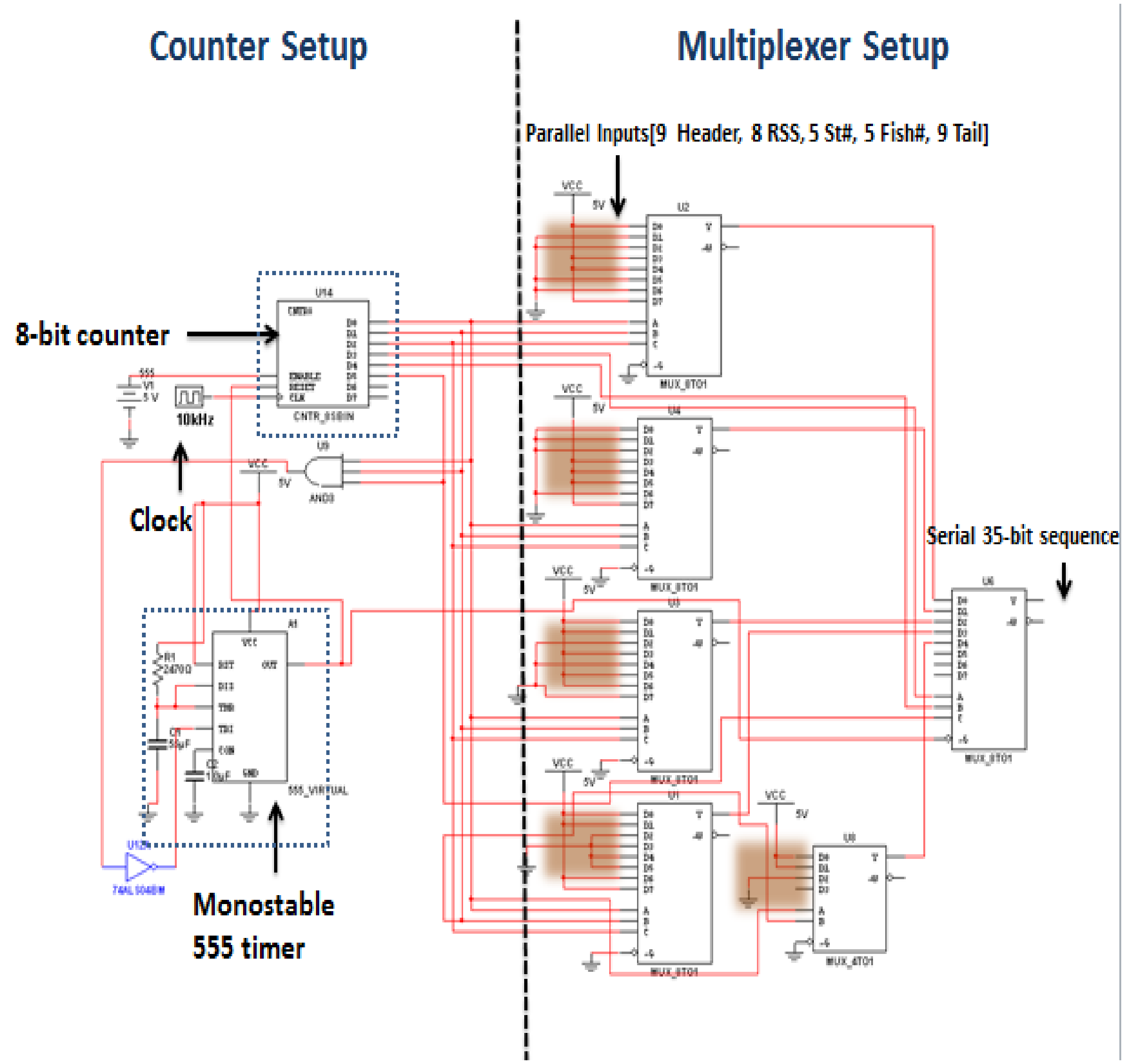


Figure 4.3-2 The schematic of the encoder circuit. An 8-bit binary counter is used for the counter. A monostable mode of the 555 timer is used to reset the counter for a specific time after the 35th bit of the sequence is generated by the multiplexer setup. The arbitrary logics values at the input of the multiplexers represent the information fed by the tracking system

Figure 4.3-2 shows the schematic for the encoder circuit. The binary counter chosen consumes 80uA of current and requires a typical value of 5V to operate. The data from the specific output pins of the counter is fed to the input select pins of the multiplexers and based on the circuit design in Figure 4.4-2, a 35 bit binary sequence is generated. The clock to the counter is being provided by a 555 timer which is configured in astable mode and the frequency of the clock is configured to 9 kHz. Each bit that is generated by the multiplexer setup has the same frequency as the clock. A 555 timer, configured for monostable mode, resets the counter when the 35th bit of tracking information is generated by the encoder circuit and it will keep the encoder circuit in the reset state until the enable provided by the tracking system turns off. The enable time provided by the listening station is for 0.1 seconds and the enable time provided by the RFID reader is for Xms. Therefore, clock frequency of 9 kHz was chosen in order to transmit the 35-bit data in 3.9ms which is within the enable times. When the 35th data bit is generated by the multiplexer setup, the monostable configured 555 timer gets activated and resets the counter and keeps it in reset mode for a particular time. This particular time duration was determined from Equation 20where T refers to time, R refers to resistor and C refers to capacitor,

$$T = 1.1 * R * C$$

Equation 20 Time period determination of output pulse from a monostable 555 timer

The resistor value of 2.47kΩ and a capacitor value of 55nF were chosen to select the time duration of 0.149 seconds. This time duration of 0.149 seconds ensures that the encoder circuit goes into reset mode as soon as the 35th bit of the sequence is generated by the multiplexer setup and remains in the reset mode until the original enable times from the tracking system turns off. Without the monostable circuitry in the design, the multiplexer setup will generate the same binary sequence a number of times that will result in the wireless transmission of the same tracking information until the enables from the tracking system turn off.

The multiplexer setup is comprised of four multiplexers of 8-to-1 composition and one 4-to-1 multiplexer which are fed with the 35 bit data. Each of these multiplexers converts the parallel binary logic values obtained from the tracking system into serial binary sequence which is then fed to an 8-to-1 multiplexer. This multiplexer selects the serial binary sequence from each of the previous multiplexers in a specific order that is determined by the logic values of the outputs from the counter.

Table 4.3-1 Counter Output Logic vs. Multiplexer Selected

Counter Output Logic vs. Multiplexer Selected		
Hex Values	**Counter Output Logic**	**Multiplexer selected**
	D5 D4 D3 D2 D1 D0	
0	0 0 0 0 0 0	MUX1
7	0 0 0 1 1 1	MUX1
8	0 0 1 0 0 0	MUX2
15	0 0 1 1 1 1	MUX2
16	0 1 0 0 0 0	MUX3
23	0 1 0 1 1 1	MUX3
24	0 1 1 0 0 0	MUX4
31	0 1 1 1 1 1	MUX4
32	1 0 0 0 0 0	MUX5
35	1 0 0 0 1 1	MUX5
36	0 0 0 0 0 0	Clock Reset

Table 4.3-1 shows the order in which the outputs from the 5 multiplexers is selected by the last 8-to-1 multiplexer based on the counter logic values. The 35th bit of the sequence is

generated when counter reaches a count where the logic levels become high only at its output pins D5, D1 and D0. As discussed earlier in this section, a 9 kHz clock was chosen for the counter which led to the total duration of the 35-bit sequence to be 3.9ms. Each data bit therefore has time duration of 110us. It can be seen from the graph that when the 35th bit is processed, the monostable 555 timer gets activated and it resets the counter.

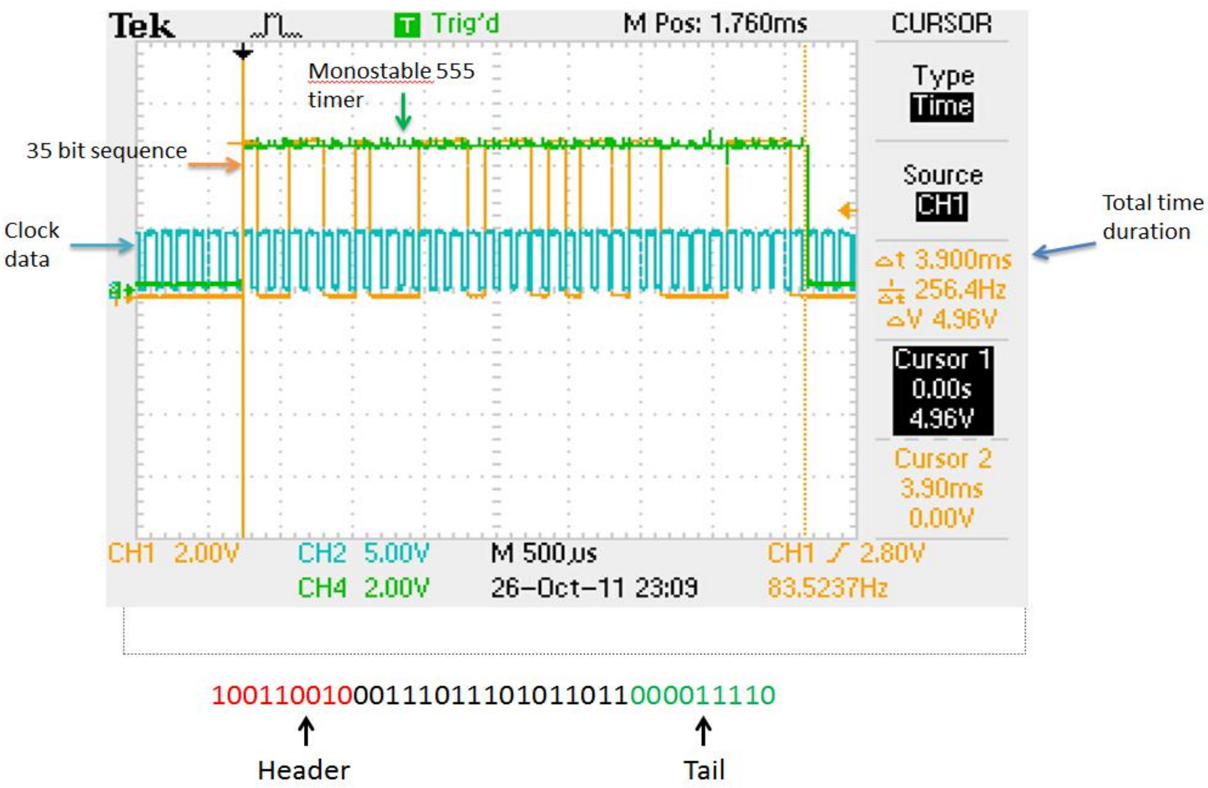


Figure 4.3-3 The data signals of the encoder circuit. The channel 1 of the oscilloscope is connected to the output of the multiplexer setup. Channel 2of the oscilloscope is connected to the clock output and channel 4 of the oscilloscope is connected to the inverted logic of monostable 555 timer.

Figure 4.3-3 shows the results from the encoder which outputs a 35-bit binary sequence “10011001000111011101011011000011110” as shown in the figure above. The total time period of the sequence has the expected value of 3.9ms.The clock of 9 kHz is being used for the counter and the width of each generated is equal to the clock period. Channel 4 of the oscilloscope is connected to the output pin of an inverter that is connected to the output of monostable configured 555 timer. The particular counter that is being used for the project is configured in such a way that its reset turns on when it is supplied with logic 0 at the reset pin. Therefore, the output logic of the monostable 555 timer had to be inverted in order to connect to the reset pin of the particular binary counter chip to reset the counter when the 35th bit is generated by the multiplexer system.

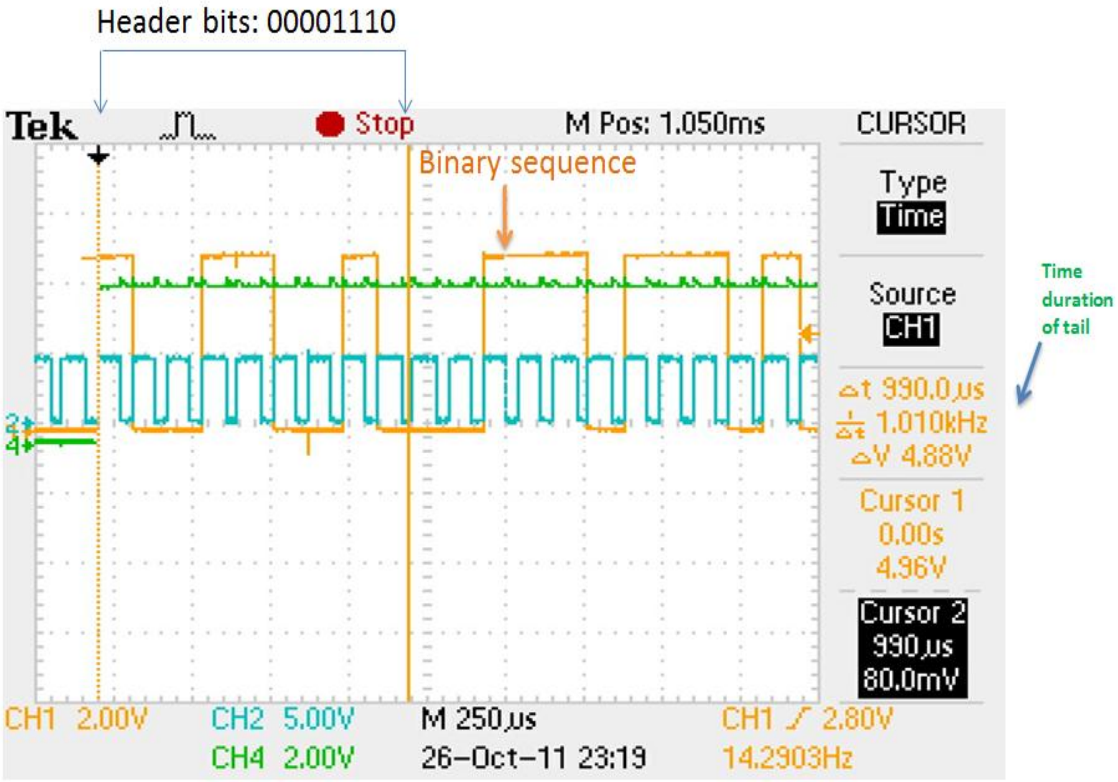


Figure 4.3-4 The header waveform bits

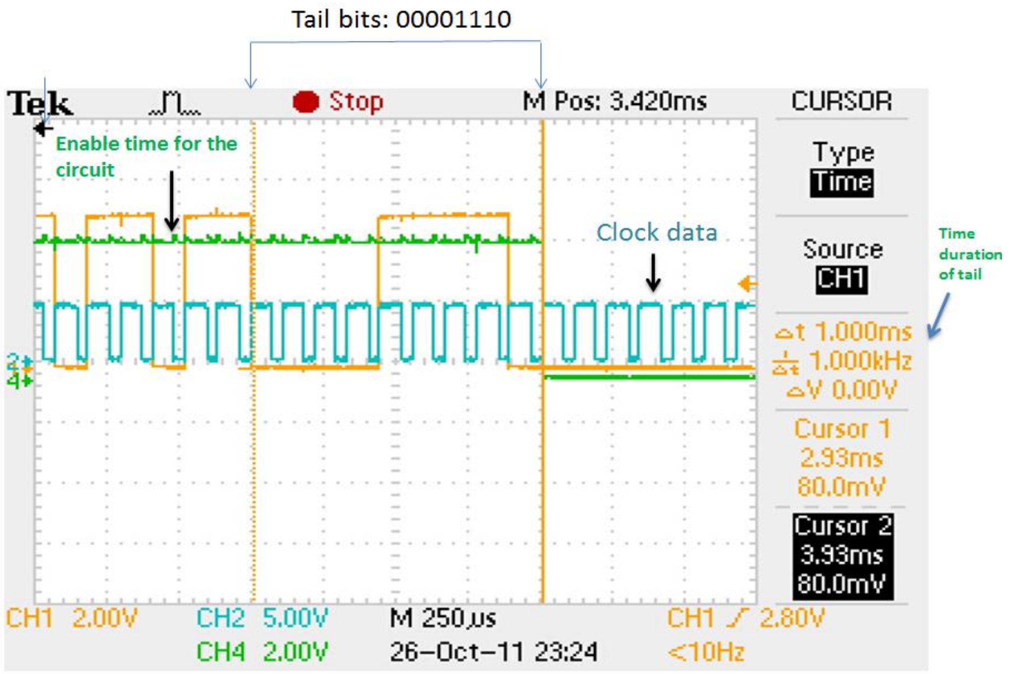


Figure 4.3-5 The tail waveform bits.

Figure 4.3-4 and Figure 4.3-5 shows information of the header bits which are “100110010” and the tail bits which are “000011110”. The 35-bit binary sequence from the multiplexer setup is fed to an FM transmitter for wireless transmission. The FM transmitter chipset being used for the project has a frequency of 433 MHz and it modulates the serial binary sequence onto the carrier wave which is then transmitted wirelessly in air. The FM transmitter has an ability to transmit data for 75m within a building and 250m in open air. It typically requires 5V to operate and consumes 1mA of current. A 17.3cm long wire was used as the antenna for the FM transmitter and this value was determined from the datasheet of the FM transmitter. This analog signal is received by an FM receiver chipset that can be positioned a certain distance away but within the transmission range of the transmitter. The FM receiver chipset being used for the project operates at 433 MHz and requires voltage of 5V and typically consumes 1mA of current. The circuitry inside the FM receiver chipset converts the analog signal back into the digital signal which consists of the serial 35-bit binary sequence. Each of these bits has the same time period as that of the originating bit. The serial binary sequence output from the FM receiver chipset is then fed to mission control for further processing of the data.

4.4. Mission Control

The mission control represents the user interface of the system. It handles all the data processing at a remote location, and constantly displays the current location of the fish to the user. As discussed in section 3.4.4, a Spartan 3A FPGA Starter Kit board is used and programmed using VHDL. The FPGA has 232 user-I/O pin, a 50 MHz clock oscillator and eight discrete LEDs. The first step in implementing the mission control module is to develop the algorithm. For a proof of concept, the system is implemented using three listening stations and one RFID reader. Therefore, the FPGA will take these four parallel inputs, each attached to an I/O pin and the binary representation of the fish number and station number outputs will be displayed on the LEDs.

As shown in Figure 4.4-1, the mission control algorithm is implemented using state machines, where the inputs are composed of three acoustic signals and an RF signal. Each acoustic signal is comprised of 5 sequences of numbers: the header, an RSS that corresponds to the amplitude of the listening station, the fish identification number, the listening station identification number and finally a tail. Similarly, the RF signal is made up of the same structure. Although the RSS is not necessary for the RF signal because the priority is always given to the RF signal, the RSS is still provided for constancy. Each signal passes to a process which looks for the 35 bit sequence and extracts the necessary information from it, which is used by a different process that analyzes the information and selects the closest station. This module also takes a clock signal from the communication module, so that the processes transitions can occur synchronously with the serial bits arriving from the receiver. Although the FPGA has on board 50 MHz oscillator that can be used to generate slower clock frequencies, the clock from the receiver unit is used to synchronize both modules.

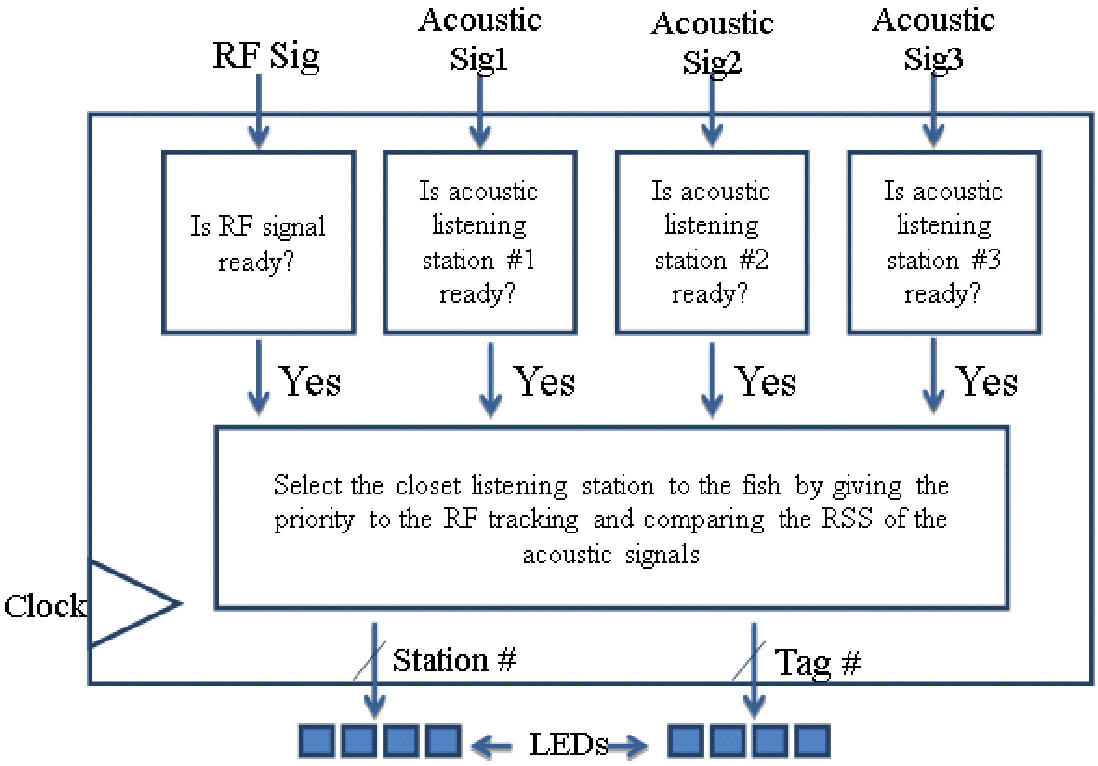


Figure 4.4-1 Mission Control Algorithm Flowchart

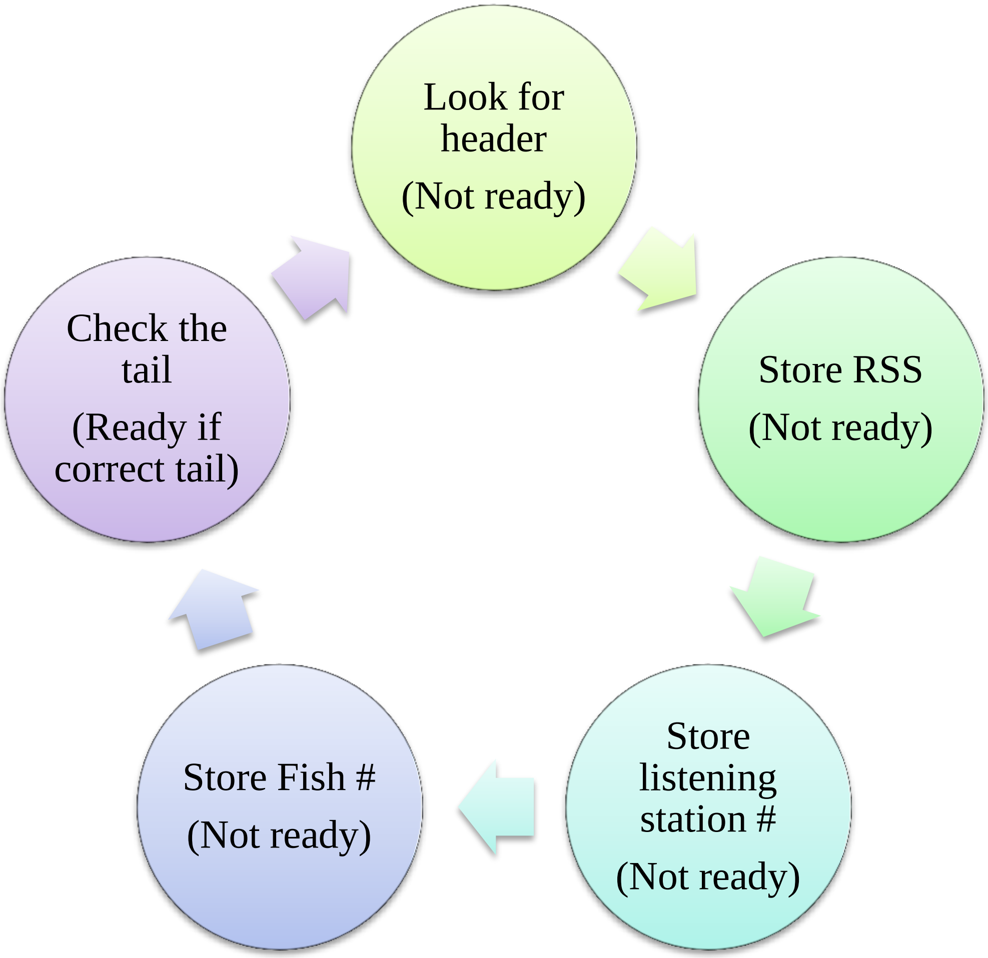


Figure 4.4-2 State Diagram for capturing the 35 bit sequence from the receiver

The mission control algorithm used to process the input signals, and identify the station closest to the fish, consists of two stages. The first stage contains four parallel processes that are constantly looking for the correct sequence from the receiver and then output a ready signal when all the information that is going to be used by the next stage has been stored. Each process contains 35 states since each received signal carries 35 bits. As shown in Figure 4.4-2, the first set of states look for the header which is a series of the following bits: "100110010". Once detected, the next states are used to store an array of 8 bits for the RSS, 5 bits for the listening station number and 4 bits for the fish number. The last 9 states of the process check the following sequence of the tail, "000011110" and output a ready signal if the last 9 bits of the signal match the previous tail sequence. The state returns to the header states and waits for the next correct sequence of the header while the ready signal gets deactivated. The 4 input signals and the clock are mapped to 5 pins on a 100-pin edge connector that has 43 associated FPGA user-I/O pins. Since the I/O bank accepts a logic level of 3.3 V, a 3.3 Zener diode is used to bring down the 5 V voltage logic level coming from the receiver.

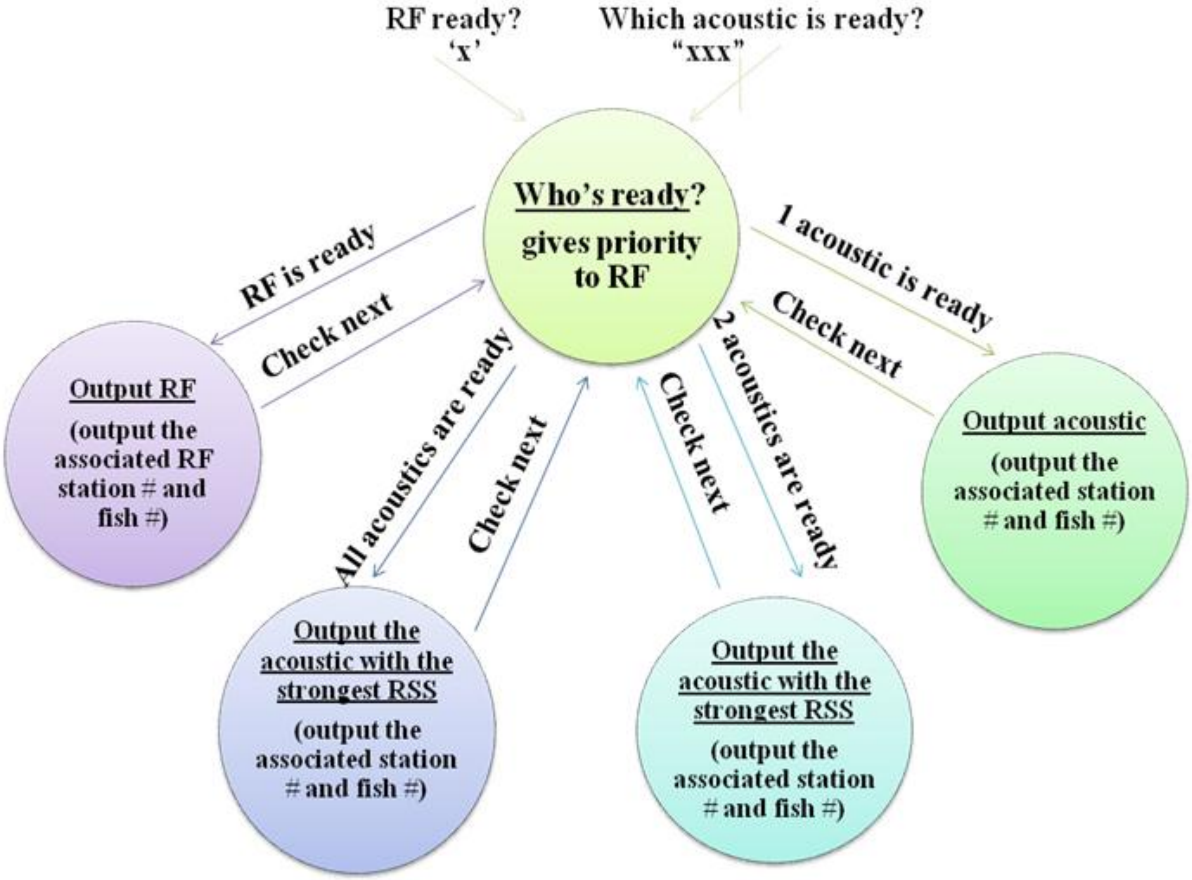


Figure 4.4-3 State Diagram for selecting the output station and fish numbers

4.5. Summary

This chapter details the implementation and integration of the project's subsystems into a cohesive system. The project is divided into four categories: an energy harvesting system to power the acoustic transmitter, two tracking systems, a communication module to transfer the data to a base station and a mission control module that synthesizes and displays the information. The energy harvesting device is implemented using a piezoelectric film that harvests power from the movement of the fish. The two tracking systems consist of an acoustic system in the deep sections of the river and an RFID in the narrow sections. Next, the data from the tracking system is converted into serial binary sequence using an encoder and communicated wirelessly to the mission control using a FM transmitter and receiver chip set. Finally, the mission control center processes the data and outputs both the fish ID number and the station ID number closest to the fish. The next chapter discusses the results of system integration.

5.0 Field Trials and Experimental Results

5.1. Piezoelectric Energy Harvester

The testing for the piezoelectric energy harvester system consisted of several different tests. Before implementing the energy harvesting module using both the Volture piezoelectric bender and the LTC-3588, the piezo bender was first tested separately to measure power while varying the tip-to tip displacements. Next, the energy harvesting module circuit was built using the LTC-3588, as shown in Figure 5.1-1. In order to test the piezoelectric energy harvester module discussed in section 4.1, a rod was attached to the shaft of a DC motor, as shown in Figure 5.1-1, to oscillate the piezo bender with a frequency that corresponds to the RPM of the motor. When the rod hits the piezo bender, it causes a tip-to tip displacement which simulates the motion of the fish, generating an output voltage of 3.6 V.

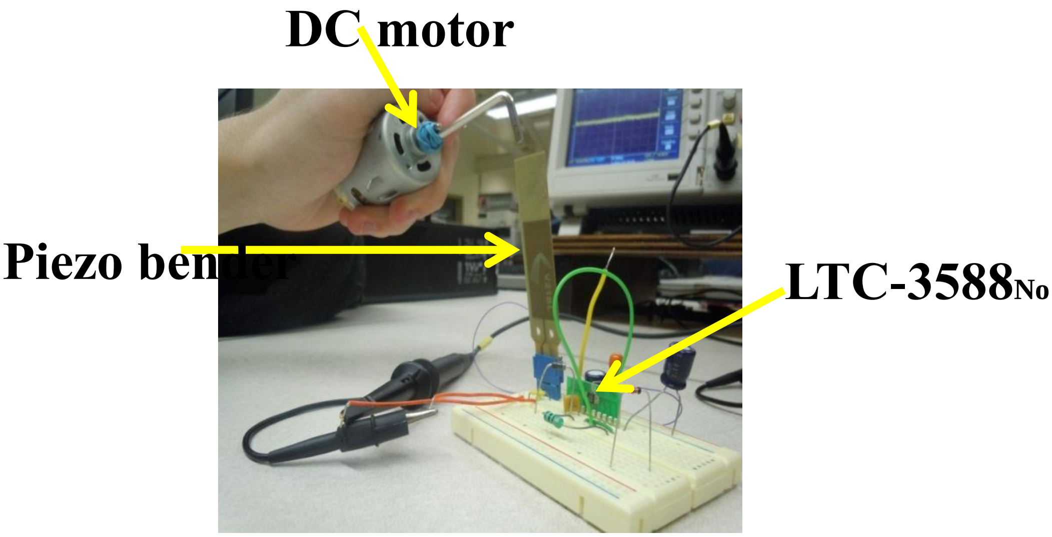


Figure 5.1-1 Energy harvesting module test setup. The speed of the motor is controlled by the power inputted to it. The rod hits the piezo bender causing it to get displaced and oscillate at different frequencies.

To measure the frequency at which the motor was turning, the inputted voltage and current from the power supply were used to calculate the motor's power. The graph from the datasheet of the motor, which relates RPM to the power being dissipated or generated, is shown in Figure 5.1-2.

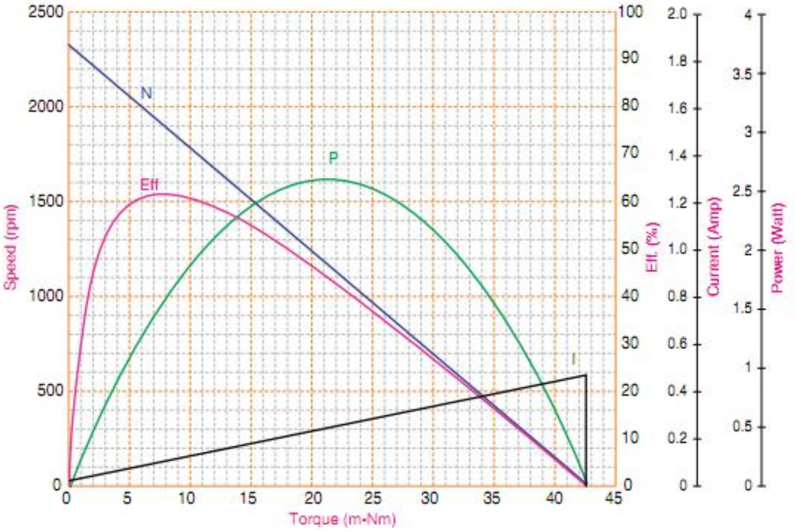


Figure 5.1-2 Motor RPM versus power. The RPM is used to calculate the frequency at which the piezo bender is being triggered at.

After the power was calculated and its corresponding RPM was mapped using the chart in Figure 5.1-2. The frequency of the speed of the motor was calculated to allow the comparison of the natural frequency of the vibration of the piezo bender, and its output power. Table 5.1-1 summarizes the motor measurements.

Table 5.1-1 DC Motor Frequency measurements

Motor Specifications				
Voltage(V)	**Current(A)**	**Power(W)**	**RPM**	**Frequency(Hz)**
1	0.2	0.2	150	2.5
1.5	0.2	0.3	200	3.33
2	0.2	0.4	250	4.17
2.5	0.23	0.575	300	5.00
3	0.23	0.69	450	7.50
3.5	0.24	0.84	550	9.17
4	0.26	1.04	625	10.42
4.5	0.26	1.17	650	10.83
5	0.32	1.6	1100	18.33
5.5	0.32	1.76	1100	18.33
6	0.32	1.92	1200	20.00
6.5	0.32	2.08	1250	20.83
7	0.35	2.45	1500	25.00
7.5	0.34	2.55	1550	25.83

The piezo bender was tuned at different frequencies that were calculated in Table 5.1-1, for which the corresponding output voltage and current were measured. The oscilloscope was used to measure the open circuit output voltage as the piezo bender was oscillating. To test the current output, the voltage drop across a 100 Ω resistor was measured. Figure 5.1-3 shows the open circuit voltage output when the bender was oscillating at 10 Hz. The output is an AC wave that has a peak to peak voltage of 22 V.

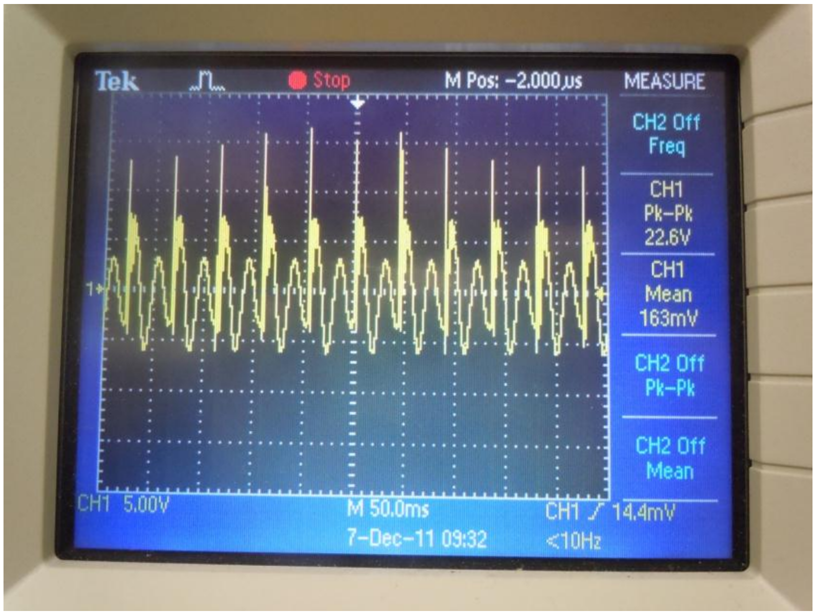


Figure 5.1-3 Open circuit output voltage when the piezo bender was tuned at 10 Hz

The power generated from the piezo bender was calculated using the open circuit output voltage and the current obtained from the voltage drop output across the 100 Ω resistor. Table 5.1-2 shows the power results over a range of frequencies between 2.5 Hz and 18 Hz. No measurements were taken using anything above 18 Hz to reduce the risk of damaging equipment.. As shown in Table 5.1-2 , the power increased up to 250 mV from 0.14 mW as the oscillation speed was increased.

Table 5.1-2 Piezo bender output power versus frequency of the vibration

Piezoelectric Energy Harvester				
Frequency(Hz)	**OC pk-pk(V)**	**pk-pk(V) w/100 ohm**	**current(A)**	**power(mW)**
2.5	5	0.12	0.0012	0.144
3.33	11	0.32	0.0032	1.024
4.17	18	0.7	0.007	4.9
5.00	19	1.2	0.012	14.4
7.50	27	2	0.02	40
9.17	20	2.4	0.024	57.6
10.42	22	3	0.03	90
10.83	37	4.5	0.045	202.5
18.33	41	5	0.05	250

Next, the response time of the bender to generate an output voltage of 3.6 V was measured using a stopwatch while varying the frequency of the vibration of the bender. The time was recorded each time the output capacitor that holds the charge accumulated was discharged. Table 2.2-1 below shows the time results, with a frequency of 2.5 Hz, the piezo bender was unable to reach the 3.6 V output. As the frequency was increased from 3 Hz to 18 Hz, the time went from 24 s to 1 s.

Table 5.1-3 Time it takes the piezoelectric bender to reach an output voltage of 3.6 V

Piezoelectric Energy Harvester	
Frequency(Hz)	**Time to reach 3.6V(s)**
2.50	∞
3.33	24
4.17	12
5.00	10
7.50	5
9.17	4.76
10.42	4
10.83	3.65
16.67	3.5
18.33	3.4
20.00	2.16
20.83	1.56
25.00	1.5
25.83	1

The results from the piezo bender show potential for the use of piezoelectricity as a viable source of energy. The bender is able to deliver enough power in a short time as the frequency of the oscillation increases. The integration section shows the testing results of using the energy harvesting module to power the acoustic transmitter attached to the fish.

5.2. Tracking

In addition to testing the overall functionality of the circuits for the tracking portion of the project, several tests of the range of both the RFID and acoustic tracking technologies had to be done. The results obtained from the range testing allowed the team to improve upon the design of the various components, and make informed decisions regarding the final implementation of the system.

5.2.1. RFID

As discussed in section 4.2.1, the RFID module was an off the shelf model from Eureka, designed to work with passive tags. The RFID reader is shown below in Figure 5.2-1. Using the antenna that came with the RFID reader gave an effective range of 2 cm. While this would be insufficient to track fish on the River Shannon, it provided the team with a standard to test the RFID system with.

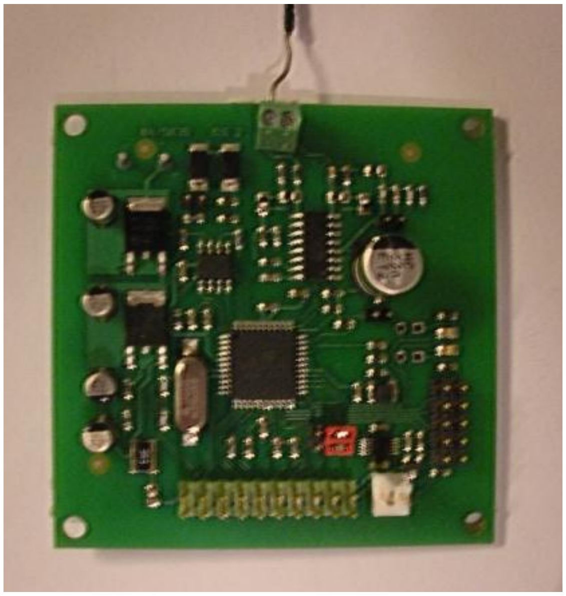


Figure 5.2-1: RFID Reader Circuit. This circuit transmits a signal out on the antenna, and looks for a response from a tag if it is within range

When reading a tag the RFID reader is capable of writing a new signal approximately every 175ms, as shown in Figure 5.2-2.

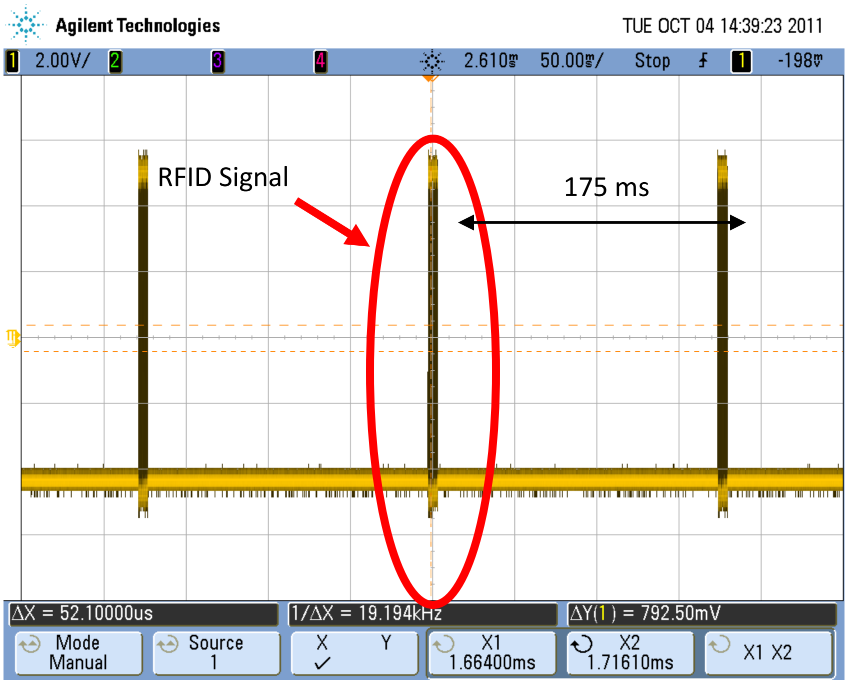


Figure 5.2-2: RFID reader output, showing the maximum frequency at which the RFID reader can detect a new tag to be 6 Hz.

For security in a commercial use, each tag is encoded with 109 bits corresponding to a 10 character ASCII code, as shown in Figure 5.2-3. The total sequence last for just 5.7 ms.

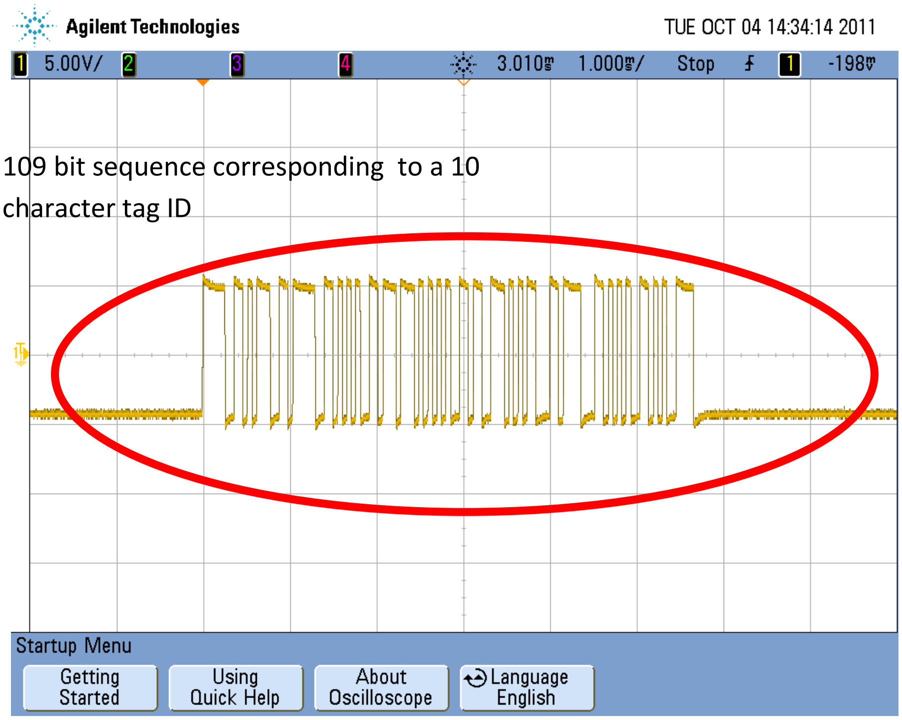
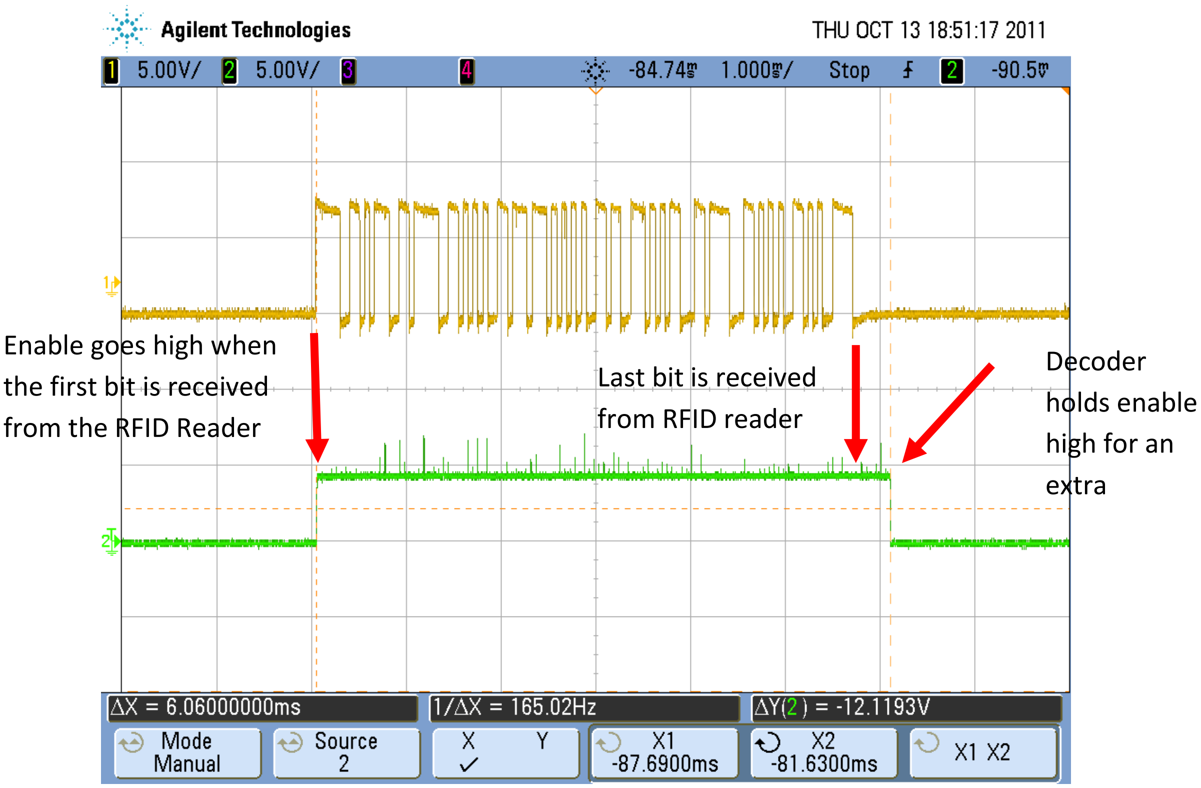


Figure 5.2-3: The image shows the full 109 bit ASCII code for one tag. Each bit has a period of approximately 52us and therefore is operating at approximately 20 kHz.

Since the team's system does not require the security of a 109 bit signal, the tag's identification number is decoded and replaced by a simpler four bit binary number. Figure 5.2-4 shows how once the data is fed into the decoder circuit, the decoder identifies that data is being transferred and the decoder outputs an enable signal to the communication circuit. This output signal indicates that a fish has passed through the RFID antenna and that information needs to be sent to mission control.



Enable goes high when the first bit is received from the RFID Reader

Last bit is received from RFID reader

Decoder holds enable high for an extra

Figure 5.2-4: The output of the RFID Reader compared to the enable output of the decoding circuit. Whenever the decoder detects any data from the RFID reader, it goes high for 6ms, telling the communication circuit to transmit that a fish has passed by.

As Figure 5.2-5 clearly shows, the decoder circuit reliably triggers every time that the RFID circuit outputs any data. The decoder outputs an enable signal to the communication circuit and preset data values are sent to the mission control for processing.

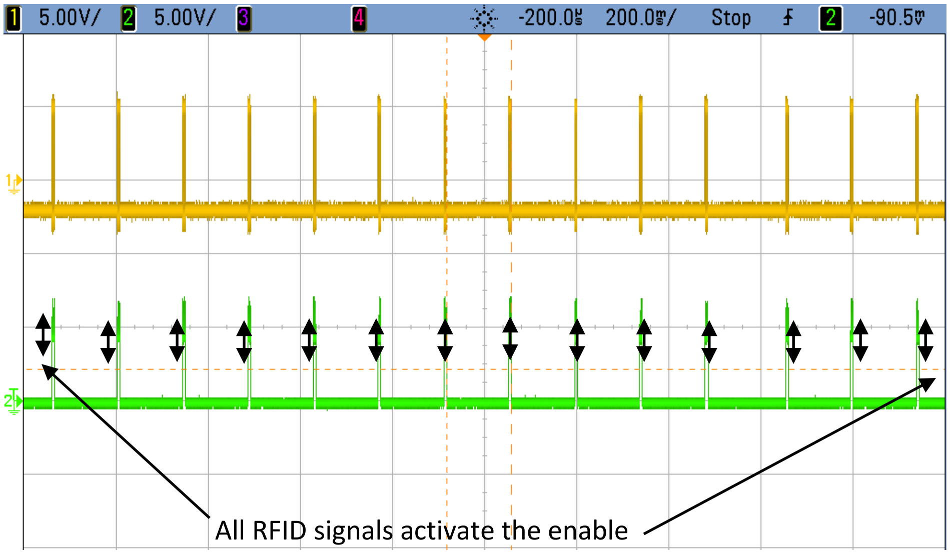


Figure 5.2-5: A scaled out view of the decoder output enable, showing that every time the RFID reader outputs a signal, shown in yellow, the decoder circuti successfully sets the enable high, shown in green.

The antenna provided with the RFID reader was only capable of reading tags less than a few centimeters away. To prove that an RFID system could work on a larger scale without requiring dozens of expensive RFID readers, the range needed to be improved. The first antenna built, shown in Figure 5.2-6, was formed by wrapping wire around a small fish tank, and recording the range at which the tag could be read for a various number of turns.

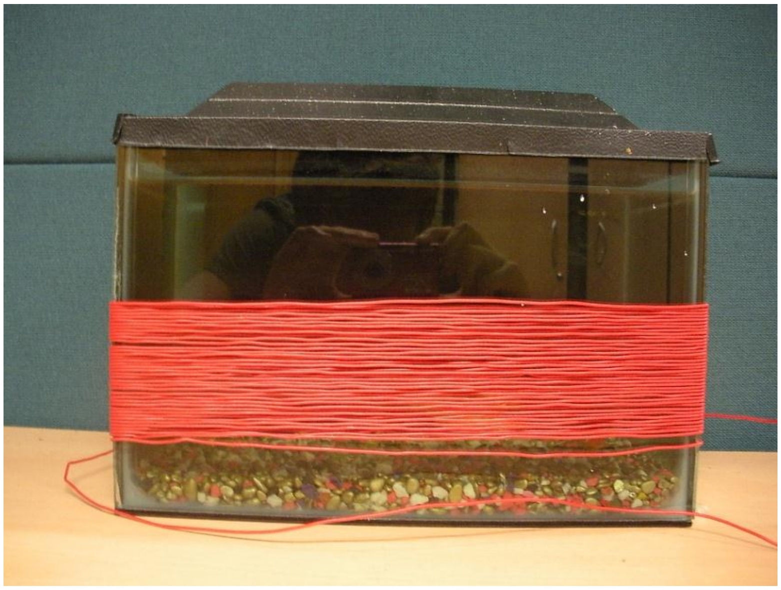


Figure 5.2-6: The initial scaled up version of the RFID antenna, demonstrating that the RFID can work in water.

Testing the read range with this antenna yielded the following results.

Table 5.2-1: Read Range of Fish Tank Antenna

Fish Tank Antenna			
length (ft)	# of turns	read range at center of tank	resistance(Ω)
455	65	top of the water	3 ohms
448	64	.5cm above water	3 ohms
441	63	2cm above water	3 ohms
434	62	.5cm above water	2.9 ohms
427	61	1.5cm above water	2.9 ohms
420	60	2.5cm above water	2.9 ohms
413	59	3cm above water	2.8 ohms
406	58	4.5cm above water	2.8 ohms
399	57	5.5cm above water	2.8 ohms
392	56	5.5cm above water	2.7 ohms
385	55	6.5cm above water	2.7 ohms
378	54	6.5cm above water	2.7 ohms
371	53	8.5cm above water	2.6 ohms
364	52	9.5cm above water	2.6 ohms
357	51	8cm above water	2.6 ohms
350	50	12.5cm above water	2.5 ohms
343	49	11.5cm above water	2.5 ohms
336	48	14cm above water	2.4 ohms
329	47	14cm above water	2.4 ohms
322	46	14cm above water	2.4 ohms
315	45	14.5cm above water	2.3 ohms
308	44	10.5cm above water	2.2 ohms
301	43	10.5cm above water	2.2 ohms
294	42	6.5cm above water	2.1 ohms
287	41	5.5cm above water	2.1 ohms
280	40	4.5cm above water	2.0 ohms

As Table 5.2-1 shows, the best range of the RFID reader occurred between 45 and 48 turns, the reader recorded any tag that passed within 14cm of the plane of the antenna. Any fish swimming near, or through the antenna would be recorded, however the fish tank antenna is only 15cm wide x 30cm long, and if it were to be used, fish would have to be funneled into it for it to have a reliable effect. With the goal of an antenna that would be able to cover an entrance to a small side stream, a larger antenna was built, and is shown in Figure 5.2-7. This image also shows the RFID reader and RFID decoder circuits attached to the antenna, and activating while the tag floats in the middle of the bucket.

Figure 5.2-7: This shows the next step up in the RFID system's capabilities, showing that increased size does not prevent the antenna from functioning. However, it does change how the antenna is constructed.

Testing the read range with this antenna yielded the following results.

Table 5.2-2: Read Range of Bucket Antenna

Large Gauge Wire Range Test		
Turns	**Length (ft)**	**Success?**
34	226.66667	Yes, 1 in
33	220	Yes, 6 in
32	213.33333	Yes, full range and 3in past bottom of coil
30	200	Yes, full range and 5 in past bottom of coil
29	193.33333	Yes, 5 in above water, which Is 6 in above coil, 6 in past bottom of coil, 5 in above water
28	186.66667	Yes, 7 above and below coil, 6 in above water
27	180	Yes, 2 in above the water, 0 below the coil

As Table 5.2-2 shows, the best range of the bucket antenna occurs between 28 and 30 turns, and the reader was capable of detecting any tag that came within 10 cm of the plane. At this point only two or three of these size antennas would be necessary to cover small side streams that branch off of the River Shannon. However, the team felt that a single antenna capable of covering the entire entrance to a side stream. A 1 meter x 2 meter frame was constructed and an antenna was structured around it. This antenna was 468ft long, consisted of 26 turns.

5.2.2. Acoustic

The acoustic tracking system is composed of an acoustic tag and a series of listening stations positioned along the banks of the river. Initial testing was conducted using a function generator to allow the attenuation of the transmitted signal to be tested over a wide range of frequencies. Initial tests were conducted in a small bucket, and the test was set up by connecting matching hydrophones to a function generator and an oscilloscope. The function generator was swept from 20 kHz to 1000 kHz in intervals of 10 kHz and the received signal strength was measured on the oscilloscope. The results were collected in a table and can be seen in appendix B, as well as in Figure 5.2-8.

Once this information was collected, a more detailed test was conducted focusing on the frequencies that provided the strongest received signal. For this test the frequency was stepped from 20 kHz to 70 kHz by intervals of 1 kHz. Again the tabulated results can be found in Appendix B, and a graphical representation can be seen in Figure 5.2-9.

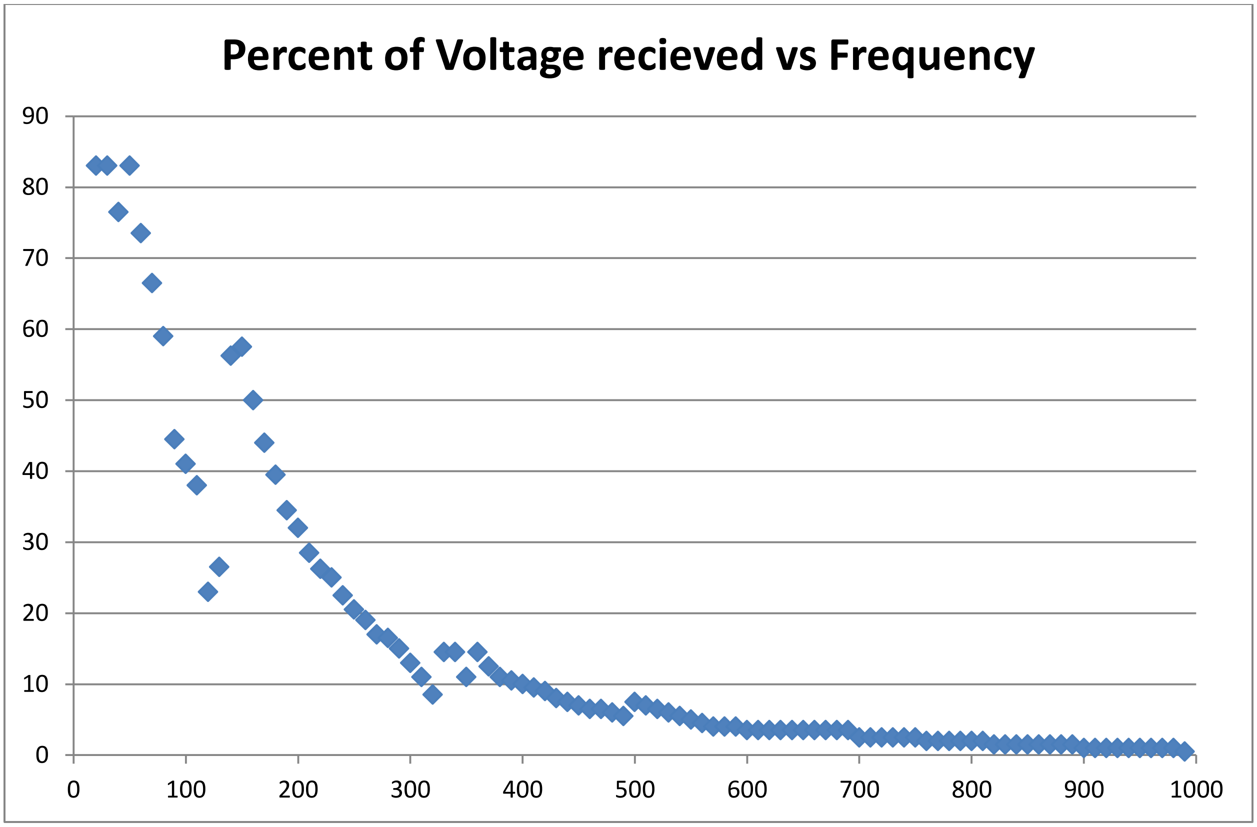


Figure 5.2-8 A graph showing the results of the frequency vs. attenuation test.

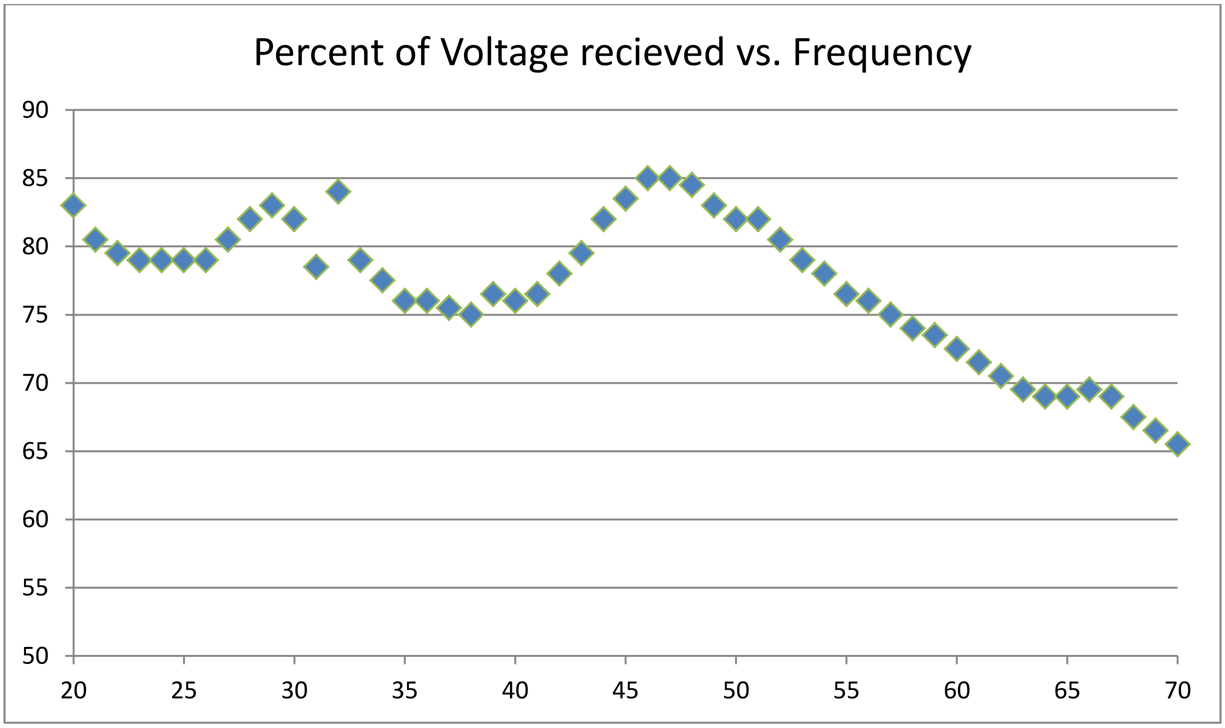
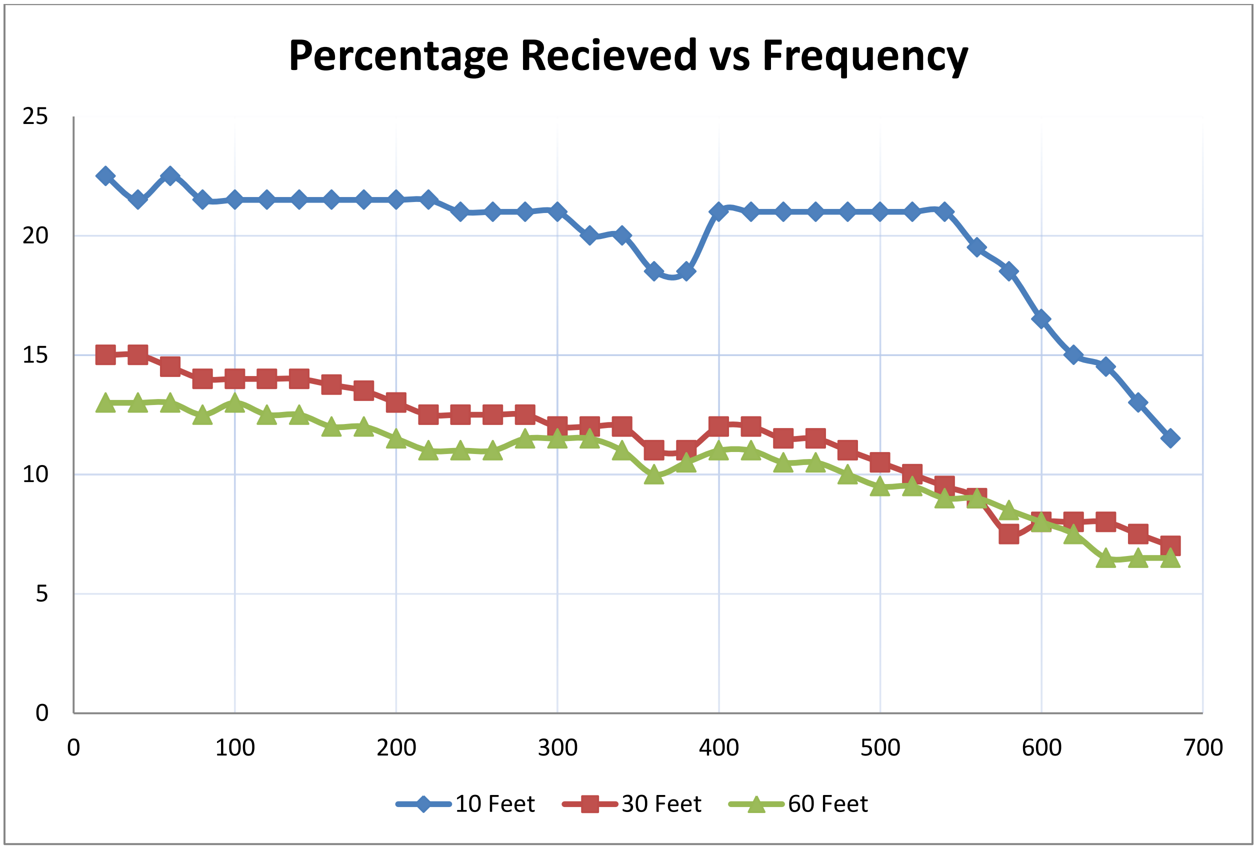


Figure 5.2-9: A graph showing the results of the second frequency vs. attenuation test, focusing on the least attenuated frequencies.

The results of this information show that for frequencies ranging from 20 to 65 kHz, between 60% and 85% of a transmitted signal is received by the hydrophone. The next step is adjusting the distance from the transmitter to the receiver in order to project at what range enough of the signal will be received so that the listening station will accurately detect the tag. To determine

the range of the acoustic tags, testing was performed at the WPI pool, and a range of frequencies was tested at distances of 5 to 55 feet. The results are shown inFigure 5.2-8.



5.2-10 A graph showing the percentage of the initial signal received at a hydrophone 10, 30, and 60 meters away.

From this graph and the knowledge that the listening station must receive a minimum of 10% of the transmitted signal, the expected range of the acoustic tag is 100 meters.

The next portion of the acoustic system is the listening circuit. This circuit was first tested using a function generator to simulate the three fish tags operating at 20, 40, and 60 kHz. The function generator is connected to a hydrophone, which is placed in the water. The other hydrophone is connected to the listening circuit as described in section 4.2.3, and placed in the water as shown in Figure 5.2-11.

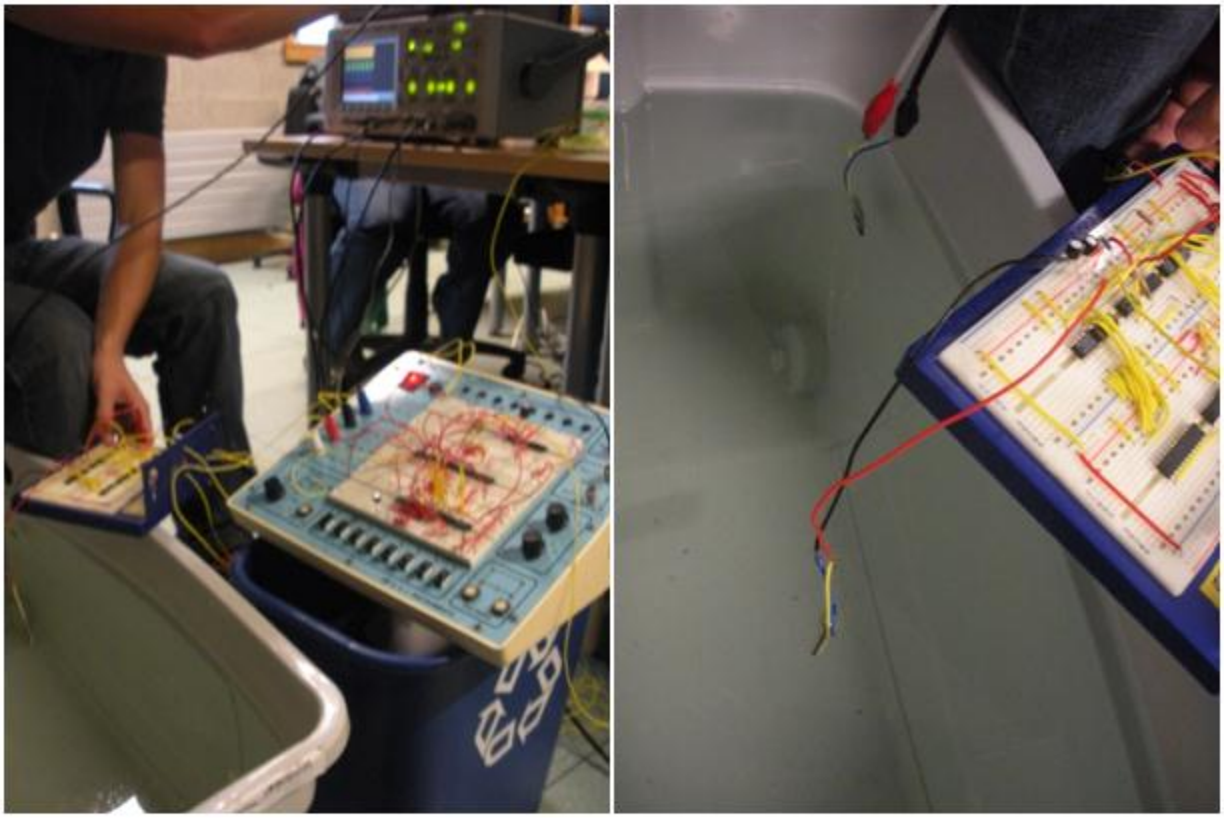


Figure 5.2-11: The image on the right shows the acoustic system set up for testing purposes. The tag is being simulated by a function generator so that various frequencies can be tested in a short period of time. On the left is a closer view showing that the two hydrophones in the water are transmitting the signal from the function generator to the listening circuit.

The oscilloscope is connected to monitor the input signal received at the hydrophone, the intermediate values of the frequency detector, and the two least significant bits of the fish identification number are all monitored. Figure 5.2-12, Figure 5.2-13, and Figure 5.2-14 show the results for the 20 kHz, 40 kHz, and 60 kHz respectively.

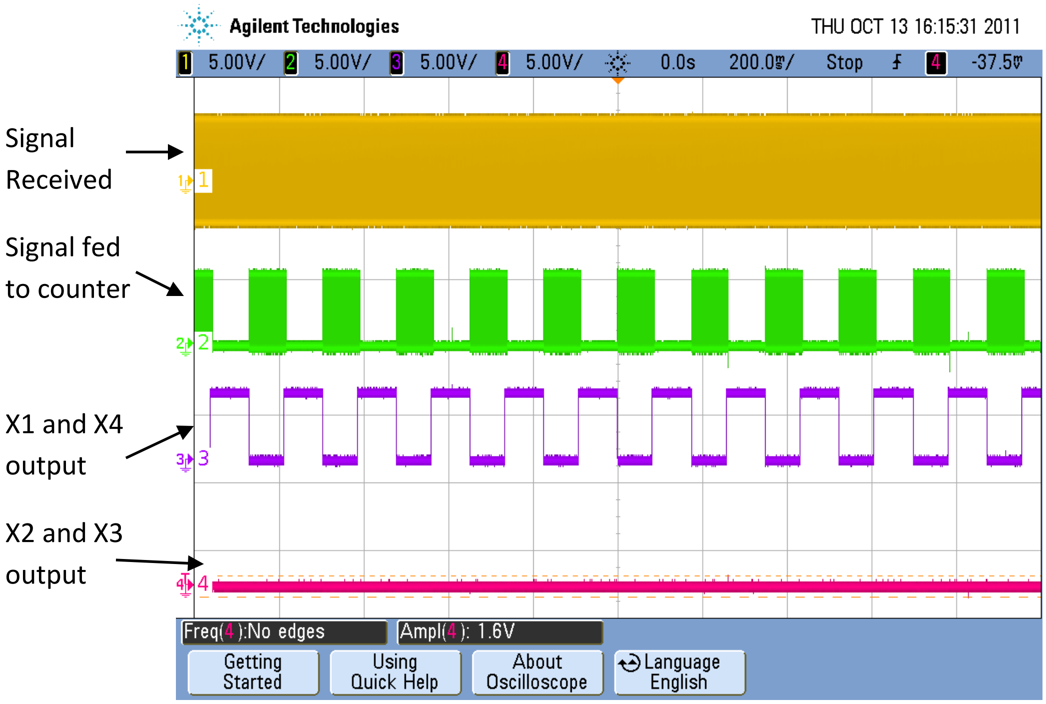


Figure 5.2-12: Oscilloscope image of the input and output of the listening circuit for a 20 kHz signal. The yellow trace is the input square wave, the green shows the input to each counter, and when the counter deactivates, the tag number is displayed at the output of the latch shown by the purple and pink traces, with purple being the least significant bit. For 20 kHz the output is “01” which is used to create fish id number “1001”

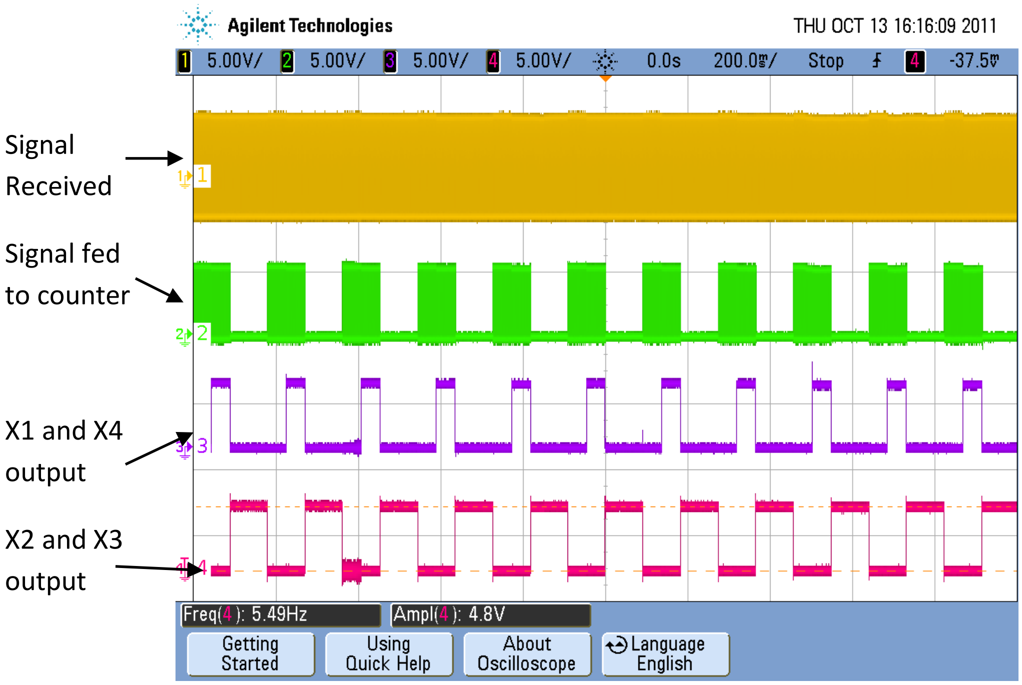


Figure 5.2-13: Oscilloscope image of the input and output of the listening circuit for a 40 kHz signal. The yellow trace is the input square wave, the green shows the input to each counter, and when the counter deactivates, the tag number is displayed at the output of the latch shown by the purple and pink traces, with purple being the least significant bit. For 40 kHz the output is “10” which is used to create fish id number “0110”

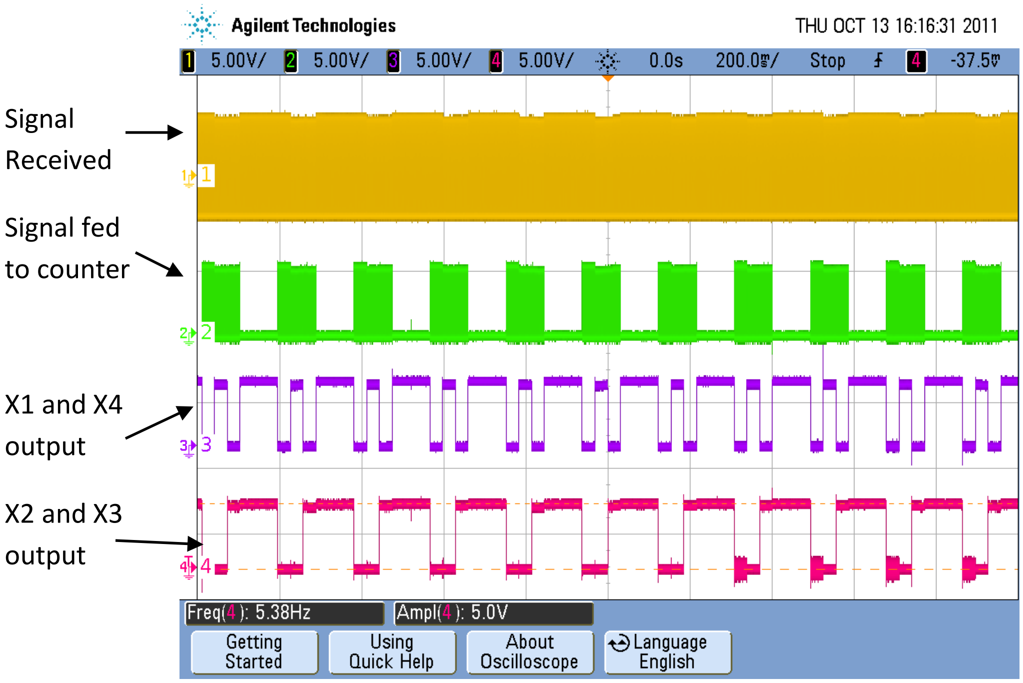


Figure 5.2-14: Oscilloscope image of the input and output of the listening circuit for a 60 kHz signal. The yellow trace is the input square wave, the green shows the input to each counter, and when the counter deactivates, the tag number is displayed at the output of the latch shown by the purple and pink traces, with purple being the least significant bit. For 60 kHz the output is "11" which is used to create fish id number "1111"

The three oscilloscope images clearly show that the listening circuit can succesfuly detect the three different tags and latch those valus long enough for the communication circuit to transmit all the data to mission control.

However, the aforementioned results are for simulated waveforms. In the actual system a small tag needs to be capable of transmitting a signal that can be recognized by the listening station as a valid result.The following figures show the waveforms produced by the acoustic tag.

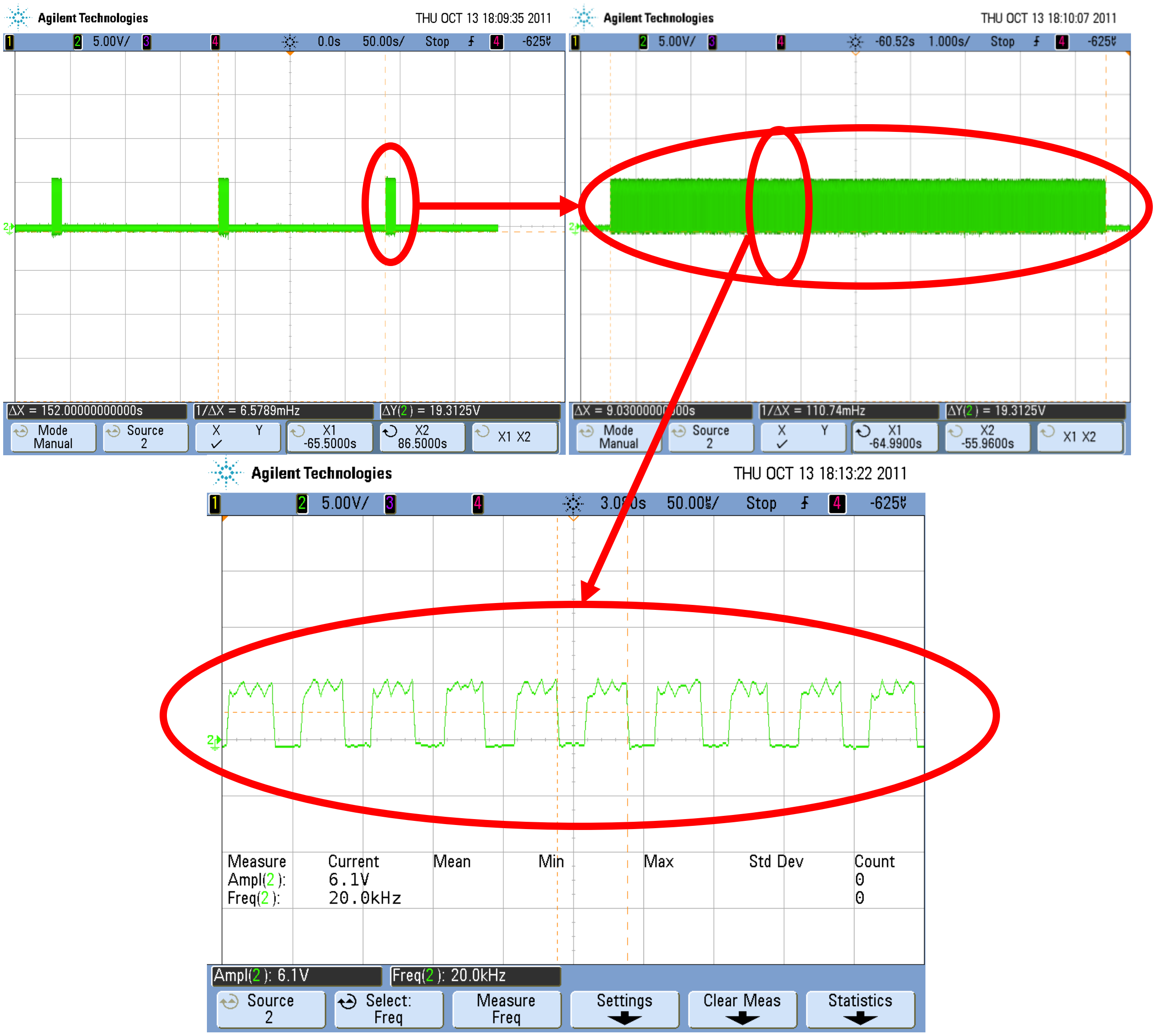


Figure 5.2-15: This shows the output of the tag transmitting a 20 kHz square wave for 9 seconds, every 152 seconds. The jagged top of the square wave shown in the last figure is not ideal, however it is compensated for at the listening station by amplifying the signal enough so that the bottom of those peaks fall above the threshold of the comparator.

The tag produces a 20 kHz square wave that lasts for nine seconds, and occurs every 152 seconds. When the output of the tag is connected to a hydrophone, and both the tag and listening station hydrophones are underwater, then the listening station can accurately detect that fish “1001” is within range, and transmits the correct information to the communications circuit.

5.3. Communication

The wireless radio communication system was chosen to be the means of the communication for the project. There were several tests that were conducted to check the feasibility of radio communication from water to air mediums. The results were then compared with similar test setup but with just air as the medium of the wireless communication. Another set of testing was conducted to check the efficiency of the FM transmitter and receiver chipsets for the radio communication of the tracking information of the fish.

5.3.1. Water to Air Radio Communication

From the background research, it was found that the radio waves get attenuated more in water than in air. In addition, the attenuation in water is related to the frequency values; the higher the frequency, the higher the attenuation. It was also determined that in the past, lower frequencies have been used for short range underwater radio communication. The team conducted several tests to check the feasibility of radio communication in water.

Two antennas were built out of two ferrite cores and 30 awg copper wire for the transmission and reception of radio signals. The inductor value of the antenna was determined from Equation 21, where N is the number of turns, x is the length of the windings on the core, r is the radius of the core, uo is the permittivity of the ferrite core.

$$L = \frac{0.5 * pi * uo * x * N^2 * \left(1 - \frac{x}{2y}\right)}{\ln\left(\frac{y}{r} - 1\right)}$$

Equation 21 Inductor value calculation

150 turns of copper wire were wound on a ferrite core of length 12.7cm, radius 5mm and permittivity 4*pi*10^-7. The x and y were chosen to be 0.07m and 0.12m respectively. This led to inductor value of the antenna to be 1.2 mH.

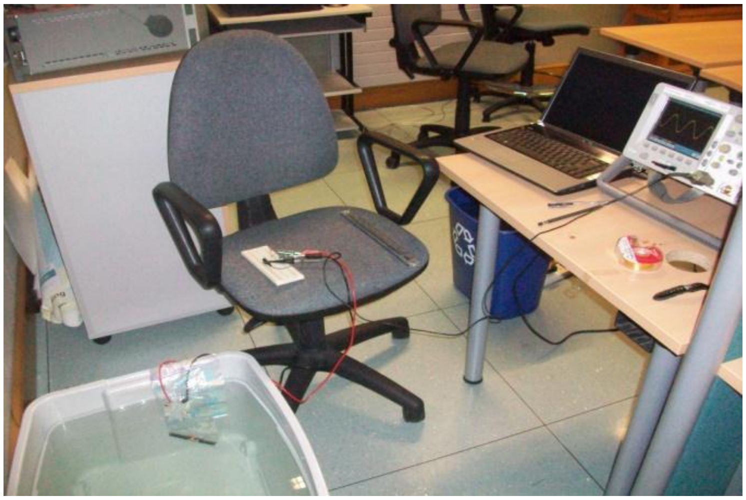


Figure 5.3-1 Test setup in the Lab. It can be seen from the picture that the transmit antenna is position in water and the receive antenna is placed outside of the water. The transmit antenna is used in a parallel combination with different tuning capacitors.

The transmitter antenna was connected to a function generator and the receiver antenna was connected to an oscilloscope as shown in Figure 5.3-1. The transmitter and receiver antennas were positioned 1 m apart from each other with transmitter antenna placed 25 cm under the surface of the water and the receiver antenna placed 75 cm above the surface of the water. To show differences in the mediums of communication, the same test was also repeated for air to air communication with the same separation distance of 1 m.

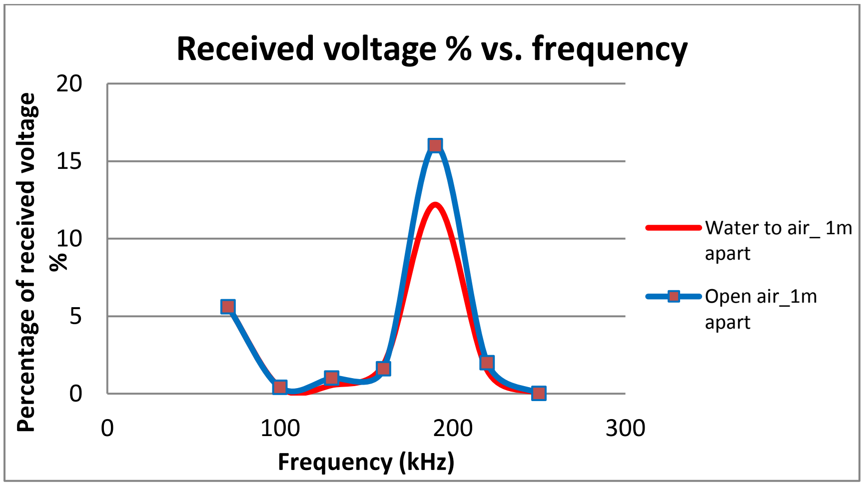


Figure 5.3-2 Comparison between air to air and water to air in radio communication.

The 1.2 mH antennas were tuned for a range of frequencies from 100 kHz to 250 kHz by changing the capacitor values attached in parallel to the antenna. As shown from Figure 5.3-2, 200 kHz seemed to be the antenna's best operating frequency.

5.3.2. Wireless communication results

To check the efficiency of the wireless communication system, a test was conducted by placing the FM transmitter and receiver 10 m apart from each other. The clock of the encoder was set to 4 kHz, making the time duration of each bit 240 us. A 900 MHz FM transmitter was used to wirelessly transmit the 35 bit data signal and a 433 MHz FM transmitter was chosen to wirelessly transmit the clock signal. To check the functionality of the communication system alone, the enable of the encoder was set to logic high by connecting it to Vcc. When the communication system is integrated with the tracking system for full system integration, the enable will be provided by the tracking system. Figure 5.3-3 displays the waveform of the data and clock signal at the transmit end of the wireless communication.

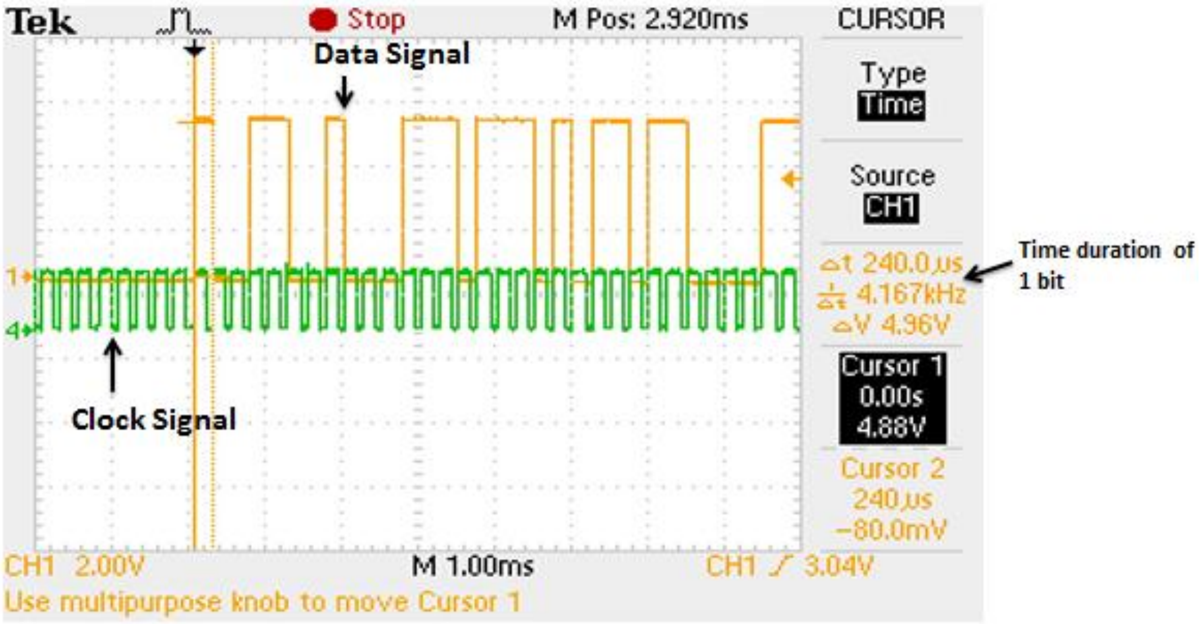


Figure 5.3-3 Transmitted signals waveform. Channel 1 represents the 35 bit data signal. Channel 4 represents the clock signal. The start of the each binary bit of the data is in synchronous with the rising edge of clock.

Both wireless signals were received by the FM receiver chipsets of same frequency configurations as the FM transmitter chipsets. The 900 MHz receiver demodulated the data signal to generate the 35 bit binary sequence and the 433 MHz receiver demodulated the clock signal. The periods of the received clock and the data signal were the same as the periods of the transmitted signals.

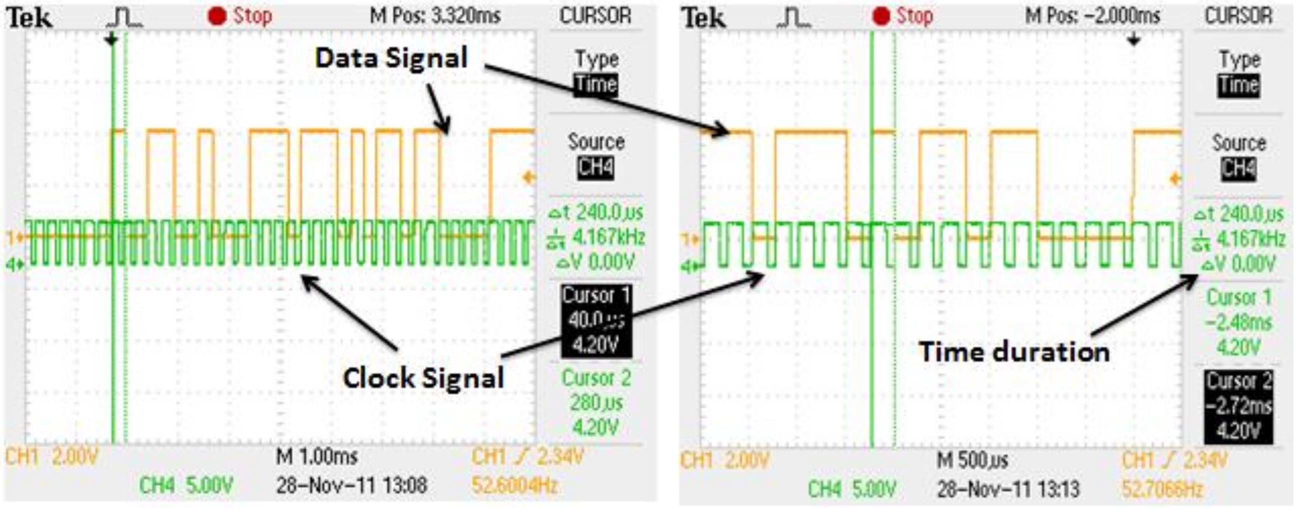


Figure 5.3-4 Received signal waveforms. The right picture is the high resolution version of the left picture.

As shown in Figure 5.3-4, the received data and clock signals are similar to the transmitted signals. The time periods of the data bits and the clock have the same values. However, there is a slight delay due to the processing of the two signals by the FM receiver chipsets and therefore the rising edge of clock and the data signal are not in perfect synchronous with each other.

5.4. Mission Control

The mission control is where all the received signals from the RFID reader and the acoustic listening station get processed. The mission control was implemented using an NEXYS2 FPGA and its program was written in VHDL. In order to verify the mission control program described in section 4.4, another process was added to the program. This program is used to simulate the inputs that would be given to the mission control, which consist of three acoustic signals and an RFID signal. Although the clock signal is also received from the communication module to allow synchronization with the data received, the internal clock signal was used for simulation. The simulation process is operated by shifting four different sequences to the inputs, while monitoring the LEDs' outputs to make sure the correct station and fish numbers are displayed. To cover all the possible inputs to the mission control, the following different combinations were inputted to the sequences: receiving the signals at different times, receiving all the signals at the same time, and disabling the RF signal to only receive the acoustic signals at the same time. These sequences were used to verify that the priority is first given to the RFID signal, then to the acoustic signal with the highest RSS and finally to check if the output updates when receiving the signals at different times. In order to complete the testing, the outputs were mapped to different I/O pins and connected to the inputs as shown in Figure 5.4-1.

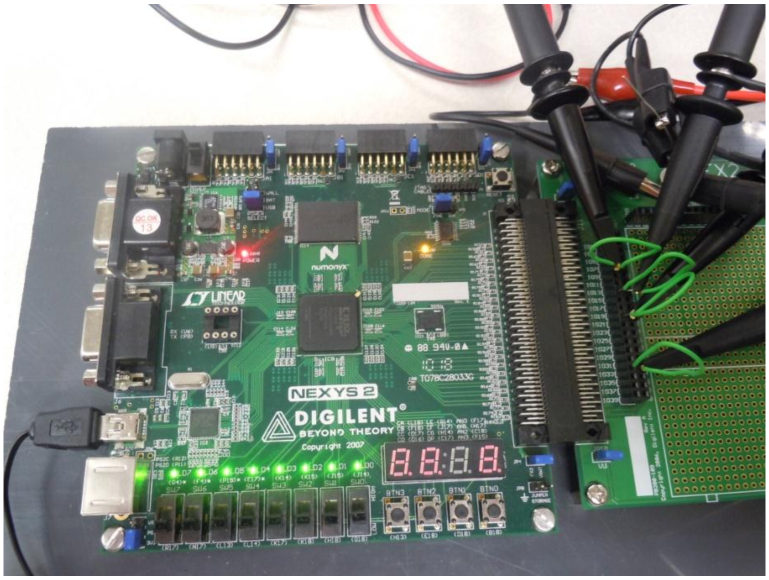


Figure 5.4-1 Mission control program simulation. Four sequences were outputted to the Acoustic and RF signals using the I/O pins the on the NEXYS2 Xilinx FPGA while monitoring the LEDs outputs for verification.

When the signals arrived at different times, the LED outputs looped between the information extracted from these signals as shown in Figure 5.4-2. After each correct sequence was detected, the FPGA outputted the associated station and fish numbers regardless of the RSS. As expected, the LEDs did not light up with the proper information until the right tail had been received. The LEDs first outputted a “11111” for the station number and a “111” for the tail number. As discussed earlier in section 4.5, due to the limited number of LEDs on the FPGA board used, only the three most significant bits are. The LEDs kept this information until the ready signal from the second acoustic signal was triggered and then the LEDs were updated with the new location corresponding to the second acoustic signal. Similarly, the LEDs outputs got updated to display the location of the third acoustic signal, then the RF signal, and finally looped back to display the first acoustic signal.

Station #	Fish #
11111	1111

Station #	Fish #
11010	1010

Station #	Fish
00110	010

Figure 5.4-2 Signals arriving at different times. The LEDS kept updating as the simulation process was shifting the sequences to the signals at different times.

Next, all the sequences were outputted at the same time to check if the proioty would be given to the RF signal. As seen in Figure 5.4-3, the LEDs only showed the RFID station number (11000) and fish number (100) while ignoring the acoustic signals. The LEDs did not get updated as previously, they maitained the RFID outputs, since the RF has the highest pritory and the signals are not receiving any sequences at different times.

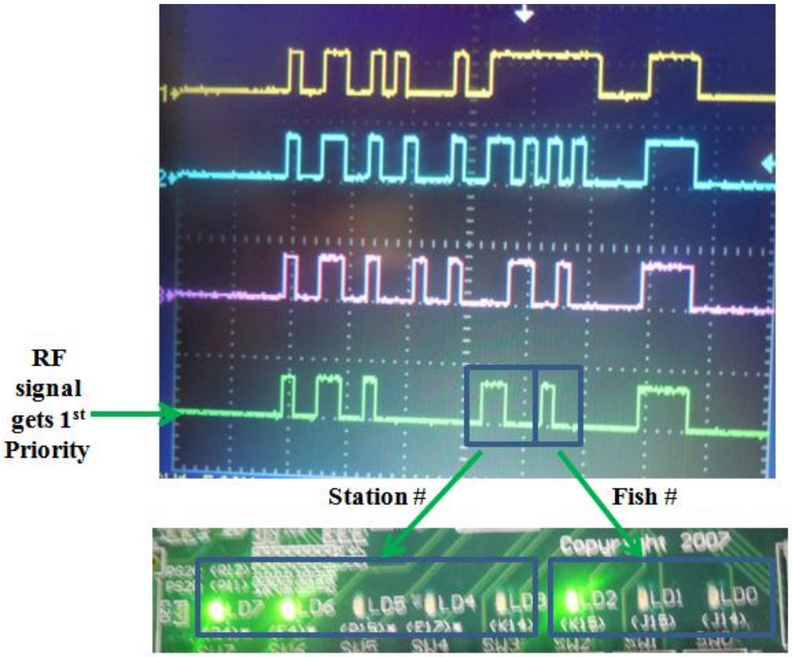


Figure 5.4-3 All signals arriving at the same time. Priory was given the RF signal. The LEDs kept the station and fish numbers corresponding to the RF signal.

Finally, the RFID signal was disabled and only the acoustic signals were received to verify that the priority would be given to the signal with the highest RSS. As seen in Figure 5.4-4, the station number (1111) and the fish number (111) outputs correspond to the first acoustic signal which has the highest RSS (1010000) compared to the RSS of the other two signals (1001000 and 1000100).

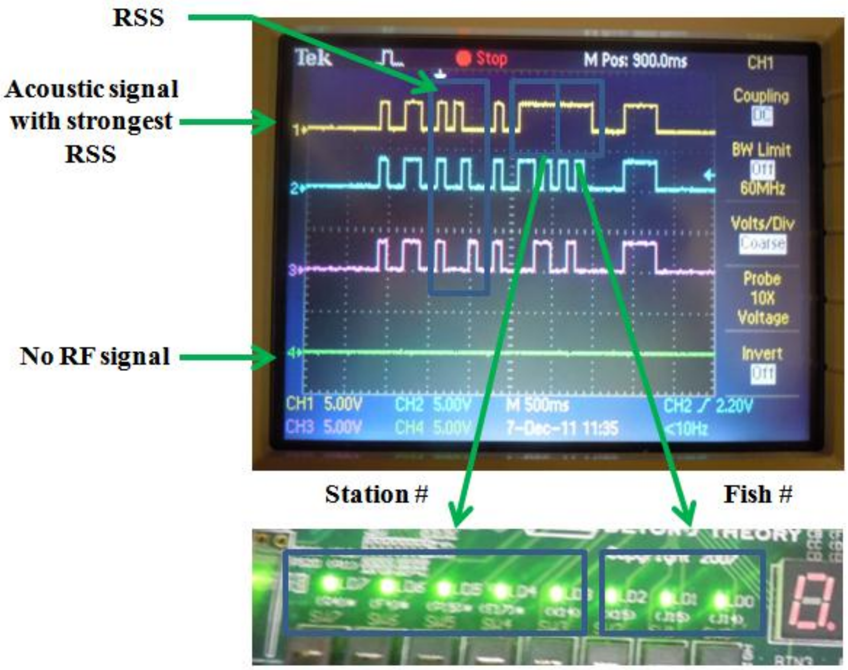


Figure 5.4-4 Acoustic signals arriving at the same time. Priority is given to the first acoustic signal which has the strongest RSS.

After the functionality of the program in mission control was verified, the FPGA was integrated with the rest of the modules to test the whole system. The clock input was mapped to an I/O pin as input and the internal clock was disabled. The results are discussed in section 5.5.

5.5. Integration Results

After the successful testing of the individual components of the project, the team integrated the components to demonstrate the functionality of the entire system. The individual components that were integrated into a complete system consisted of the three main modules: the RFID, the encoder and the mission control.

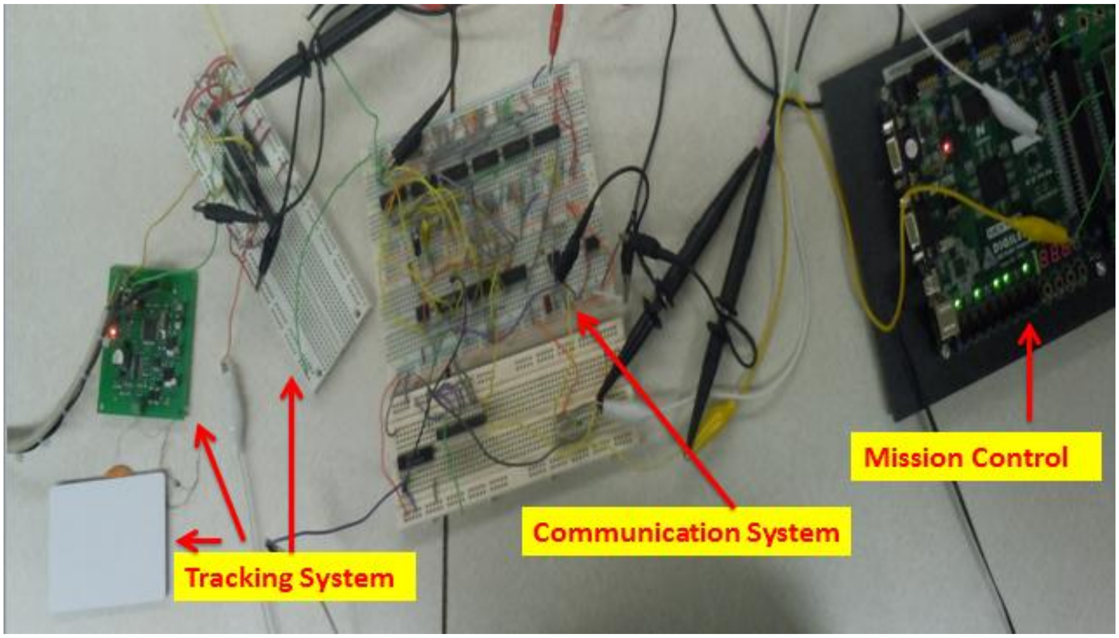


Figure 5.5-1 The RFID tracking integration. The combined system is comprised of an RFID, an encoder and a mission control system. The individual components have been labeled in the figure. This setup was used to demonstrate the functionality of the integrated system.

Figure 5.5-1 shows the integration of the tracking, communication and mission control system. The tracking system consisted of an RFID reader, tag, decoder and an antenna. The encoder consisted of a combination of multiplexers, counters and timers. The mission control is an FPGA development board. Based on the functionality of the current integration setup, when the RFID tag was not within range of the antenna, no signal was recorded and the system remained at a reset mode. However, when the tag came within range of the antenna of the RFID reader, the reader recorded the particular tag value and fed that value to a RFID decoder system. After the tracking information was processed by the RFID tracking system, it provided the encoder with 17 bits in parallel binary format along with the enable signal. When the encoder received the enable signal, it converted the parallel binary sequence into serial binary sequence as well as provided additional 9 serial bits for the header “100110010”at the start of the 17 bit data and 9 serial bits for the tail “000011110” at the end of the 17 bit data. These 17 bits were then fed to a mission control in a wired communication interface. The mission control displayed the correct station # and first three bits of the fish # on its LEDs.

The team encountered an issue with the stabilization of the 35 bit signal generated from the encoder when the tracking system was integrated with the encoder system. The output generated by the encoder was not getting locked when the enable from the tracking system was provided. After several debugging procedures, it was found that the circuit had grounding and data synchronization issues. For the synchronization of the enable signal from the tracking system and the encoder system, the team used a D-flip flop. The clock for the D-flip flop was provided by clock of the counter setup of the encoder. The enable from the tracking system was fed to the input of the D-flip flop and the output from the D-flip flop was then used as an enable signal for the encoder system. The ground connections of the tracking and the encoder system were also connected. These debugging procedures solved the stability issue of the circuit and made complete integration of the project successful.

The original design included the transmission of the tracking information wirelessly from the output of the encoder to the mission control using an FM transmitter and receiver. However, for the mission control to accurately process the data, the clock between the transmitted data and the mission control need to be synchronized, which could not be achieved in this version of the prototype. Therefore, for the proof of concept, the team used a wired interface and achieved the desired objective of tracking the fish with the current integration setup.

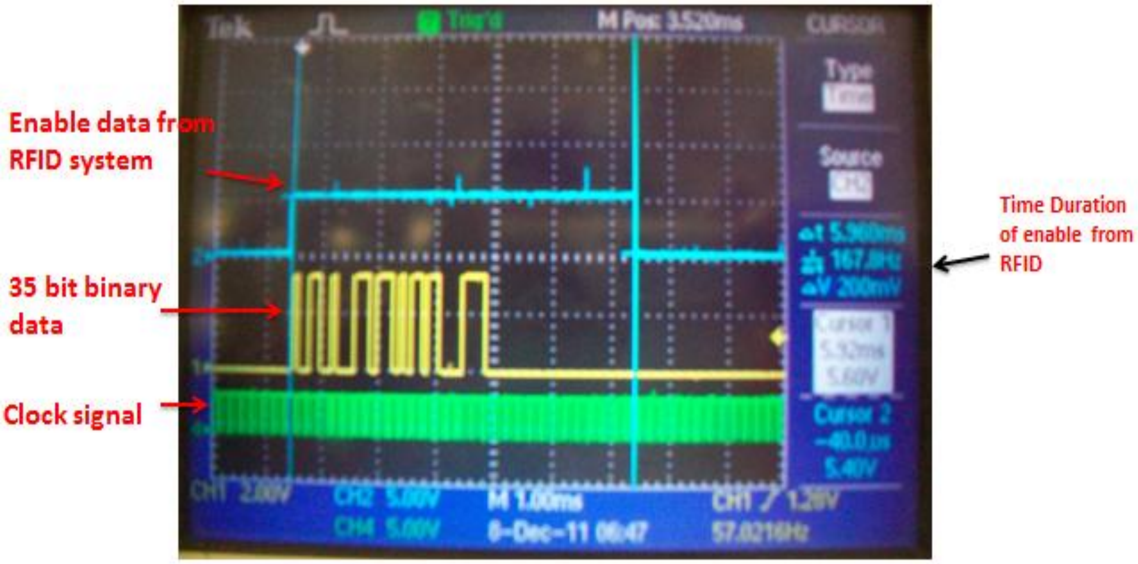


Figure 5.5-2 The integration results of the RFID and encoder integration.

Figure 5.5-2 shows the results from the RFID and encoder integration setup. When the antenna of the RFID reader detected the tag the encoder is enabled for5.96 ms. This time duration is being shown by the difference in the cursor positions of channel 2 in Figure 5.5-2. The frequency of the clock of the encoder was set to 10 kHz so that it could transmit the 35 bit binary sequence within the enable time and so that each bit had the same duration of 100 us. Therefore, the total time duration of the 35 bit sequence is 3.5 ms, which is well within the enable time provided by the RFID tracking system. The serial binary information, as shown in channel 1, was generated by the encoder and it represents the tracking information of the fish. This is shown in the figure below.

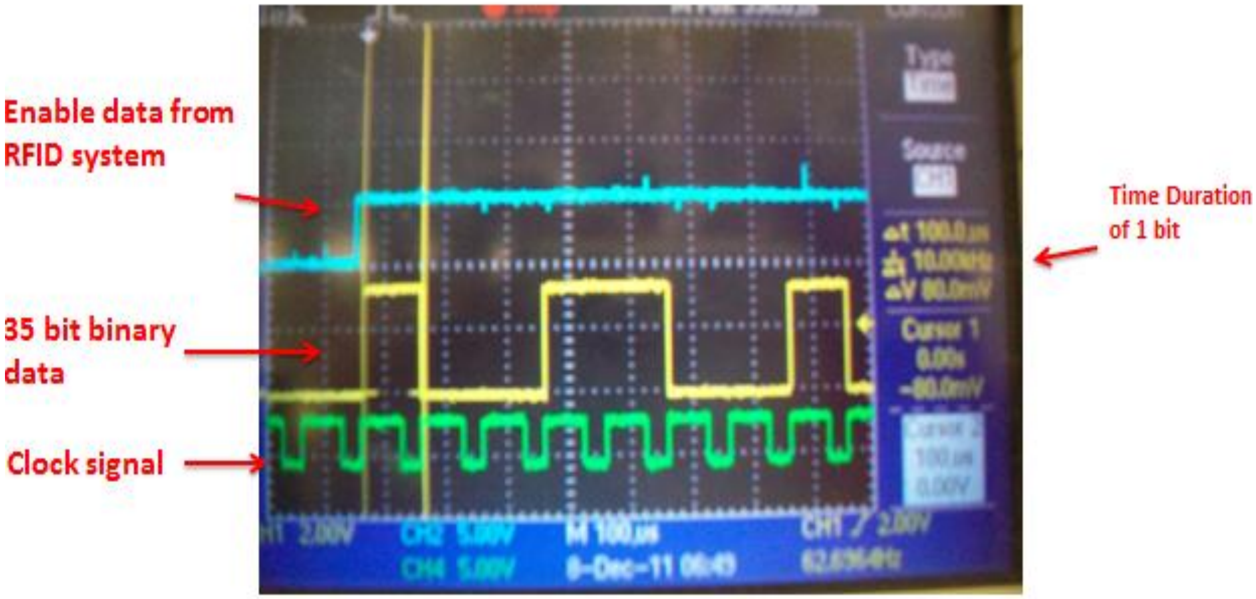


Figure 5.5-3 High resolution version of the output waveforms of the RFID and encoder setup.

Figure 5.5-3 shows the high resolution version of Figure 5.5-2. It can be seen in Figure 5.5-3, from the difference in cursor position of channel 1, that the time duration of a single bit of the data is 100 us, representing a 10 kHz frequency value.

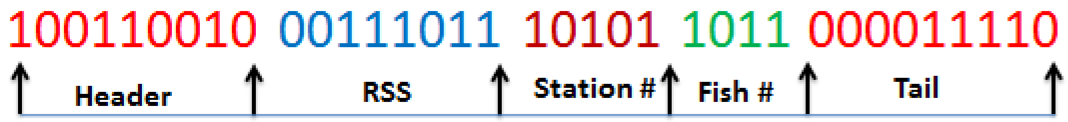


Figure 5.5-4 35 bit serial binary sequence generated by the encoder. The header consists of 9 bits, RSS consists of 8 bits, station # consists of 5 bits, fish # consists of 4 bits and tail consists of 9 bits.

Figure 5.5-4 shows the 35 bit sequence that is generated by the encoder. This data was fed to the mission control which processed and displayed the tracking information of the fish. The current setup of the mission control shows the station number on its LED display.

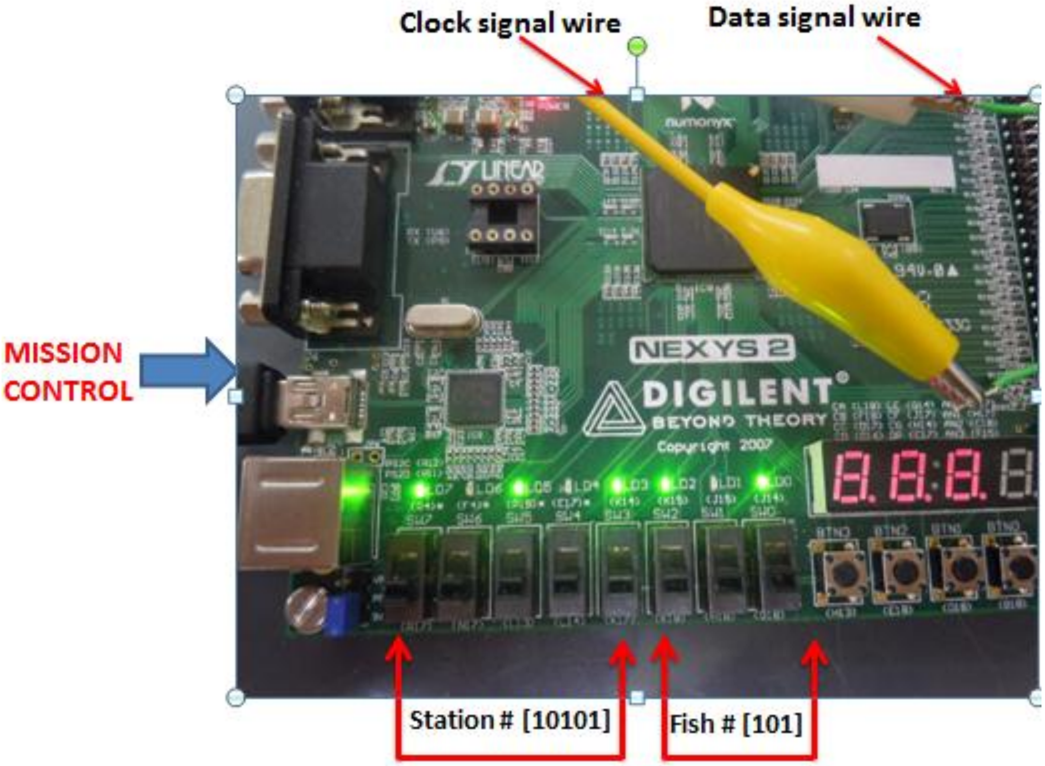


Figure 5.5-5 The mission control result. The first 5 LEDs from the left most side (displayed as LDD7, LD6, LD5, LD4, LD3) represents the station number of the tracking system. RFID was set up to "10101". For logic 1, LED turns on and therefore, the current display of LEDs starting from the left most side displays RFID # [10101]. The remaining LEDs (LD2, LD1, LD0) represents the first three bits of the fish # [1010]

Figure 5.5-5 shows the LED display that represents the tracking information of the fish. The 8 LEDs display the 5 bits of station # and first three bits of the fish # starting from the left end of the LED display.

The successful results obtained from the integration setup demonstrate the proof of concept for the project. The tracking system recorded the position of the tag when it came in proximity of the antenna of the RFID reader. It then fed the tracking information in the form of parallel binary sequence to the encoder circuitry. The encoder circuitry successfully converted the parallel binary sequence of data into serial binary sequence and then fed the data to the mission control. The mission control processed the information and displayed the accurate data in terms of Station # and fish # on its LED display.

5.6. Summary field trials and experimental results

This chapter discussed in-depth the different experiments that were conducted in the five different modules of this proof of concept design. The piezoelectric bender was successfully tested using a motor and was able to harvest energy. The RFID system was able to build an antenna that increased the read range by over 600%. The acoustic receiver was able to clearly show that the different frequency values could be recognized. In addition, the tag and receiver circuit were able to communicate with each other under water. The mission control was tested using test inputs and successfully determined the closest fish and by which station it was. Finally, through integration the communications system was successfully demonstrated and was able to connect the link between the tracking and processing portions of the system.

6.0 Conclusion and Future Work

6.1. Conclusions

The purpose of this chapter is to describe the conclusions and future work associated with each module of the full system. Though this project was only a proof of concept, there were many final conclusions that could be drawn. And because of time and budget constraints, there are many things that could be implemented in the system as future work to enhance the tracking and improve the accuracy and efficiency of the system. Each modules conclusions and future work is detailed below.

6.1.1. Piezoelectric Energy Harvester

One of the main objectives of the project was to develop a self-powered tracking system. After researching several options for energy harvesting, such as rotational energy and thermal energy, piezoelectricity presented as the most viable option. The first piezo bender that was tested was inexpensive and poorly made and in turn was not able to harvest any energy. A more expensive kind was then used and it fulfilled the objective of powering the acoustic transmitting module as the bender bends back and forth at different frequencies. The bender was used along with an energy harvesting IC that converts the piezo energy into a useful output that accumulates charge over time. In case the piezo bender ceases to produce enough energy, this module employs the use a back-up battery system to operate the acoustic receiver. The bender was able to charge the output capacitor to 3.6 V in less than 1 second when the bender was tuned to oscillate at a frequency of 18 Hz. Our device was not implemented on the fish but it served as a proof of concept that it is viable to harvest energy from the motion of a swimming fish.

6.1.2. Tracking

The tracking portion of this system met all of the initial requirements. As a whole, both the acoustic and RFID tracking systems performed their respective role as intended. The RFID system can successfully detect a tag whenever a fish passes through the RFID antenna gate. The acoustic system can detect any fish within 100 meters in a direct line of sight, and can also detect the strength of the signal received at each listening station. Both systems can be seamlessly integrated with the mission control, to form a complete system. The RFID system takes an input from the RFID tag, and outputs 17 bits in parallel corresponding to the fish id number (4), the station id number (5), and the signal strength (8) to the communication system. The acoustic tag is powered by the energy harvesting system and outputs a signal at a preset frequency for ten seconds, once every 52 seconds. Each listening station can receive signals as low as half a volt peak, and process the signal to determine the fish number and the approximate distance to the fish. This information is output to the communication system as the same 17 bits as the output of the RFID system.

RFID System

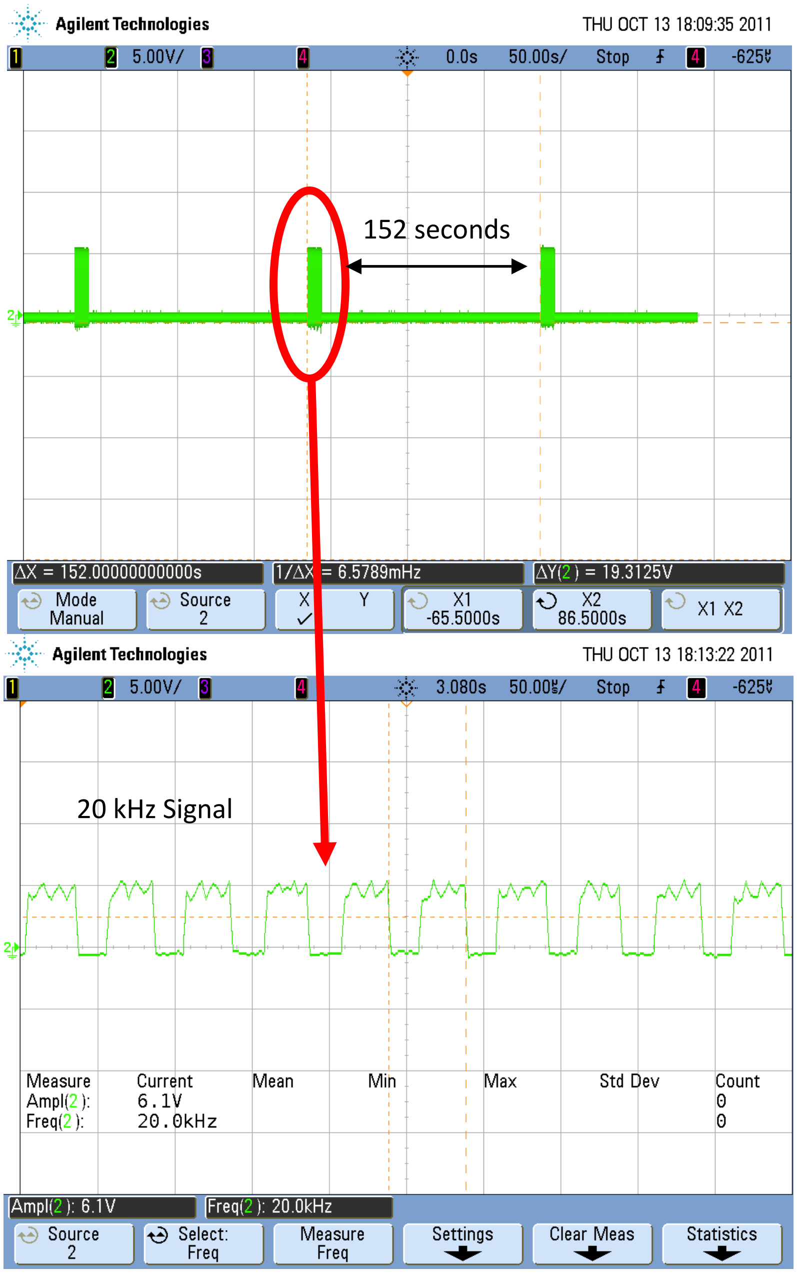
The RFID system implemented in this project contained an antenna, an RFID reader, and a decoding circuit. The antenna was built to be able to detect any fish that passes through it. The antenna used in the project can detect any fish passing through it, as well as being able to detect a fish that comes within 10 centimeters of either side of the antenna. The RFID reader scans for the tag and once detected sends a signal to the decoder circuit which converts the information to the 17 bit signal to be sent to the communications circuit. The decoder circuit takes the tag information and outputs the binary tag code to the communications circuit along with the signal strength of "11111111". The RFID signal is always given the maximum signal strength to give it priority over any acoustic signal because the RFID circuit is more precise than the acoustic circuit.

The RFID system will only fail to detect a fish if the fish manages to travel through the 20 centimeter long section that the antenna covers, in less than 175 miliseconds, which is the time it takes the RFID reader to detect a tag and receive a response. The RFID reader is also not capable of reading more than one tag at a time. If multiple tags are within the range of the antenna then the system will not be able to detect any of the fish passing through.

Acoustic System

As previously mentioned, the acoustic station consists of the acoustic tag, and the listening stations. The acoustic tag is powered by the energy harvesting circuit, and is supplied with 5 volts and 7mA. The tag successfully produces a 20 kHz square wave for ten seconds, every 152 seconds, as shown in Figure 6.1-1.

The listening circuit is capable of detecting tags which are transmitting at three different frequencies, 20, 40, and 60 kHz. One problem that the circuit has is that it cannot differentiate between two signals if the signals are received simultaneously. However, as long as only one tag is in range of a station, then the station can correctly identify which fish is transmitting and output the proper information to the communication system. The output of the listening circuit is the transmission of the fish ID number and the strength of the signal, as well as a ready signal that indicates the data is stable and ready for transmission to the communication circuit.



ΔX = 152.00000000000s

1/ΔX = 6.5789mHz

ΔY(2) = 19.3125V

Measure	Current	Mean	Min	Max	Std Dev	Count
Ampl(2):	6.1V					0
Freq(2):	20.0kHz					0

Ampl(2): 6.1V

Freq(2): 20.0kHz

Figure 6.1-1 The output from the acoustic tag. the first image is the output occuring every 152 seconds, and the second image shows that output to be a square wave at 20 kHz, with a jagged top.

The listening stations can detect a signal up to 100 meters away if there is a direct line of sight, and therefore each station should be placed 150 meters apart allowing the position of a fish to be determined within a 150 meter long section of the river.

6.1.3. Communication

A system was developed that was able to transmit the location information of a particular fish from an RFID array and the listening stations to a central location for further processing. The location information of the fish obtained from the RFID array and listening stations was encoded in a parallel binary sequence. An encoder, comprising of multiplexers and a counter was designed and implemented to convert the parallel logic sequence into serial logic sequence that was compatible with the FM transmitter chipset. The FM transmitter was used to transmit the digital information in the air and a FM receiver chipset was used to receive this data wirelessly.

The communication portion of the project sufficiently met the design requirements. The encoder circuit performed as intended, receiving the tracking information of the fish in the form of 17 bit parallel sequence from the RFID or a listening station circuit. It then processed the data into a serial binary sequence. The encoder circuit also fed 9 serial bits for the header at the start of the 17 bits and 9 serial bits for the tail at the end of the 17 bits. The enable time provided by the RFID system was 6 ms and enable time provided by the acoustic circuit was 100 ms. With the use of 10 kHz clock for the counter, the encoder transmitted the data in 3.36 ms, showing that the encoder circuit performed well within the enable times provided by the tracking system. The monostable configured 555 timer performed its desired function of resetting the encoder the 35th bit of data was transmitted, until another set of data, from either the RFID or listening station, was ready to be transmitted, indicated by an enable from one of the tracking circuits..

The wireless communication system performed its desired function on a component level. The 433 MHz FM transmitter chipset transmitted the 35 bit binary sequence and the 433 Mhz FM receiver chipset received the signal. The received signal was accurate and replicated the original 35 bit binary sequence. However, due to clock synchronization problem, it was not able to fully function in integration with the mission control. For the mission control to accurately process the data, the clock between the transmitted data and the mission control need to be synchronized, which could not be achieved in this version of the prototype.

From the wireless feasibility tests conducted, several conclusions were reached. The 1.2 mH antennas were tuned for a range of frequencies from 80 kHz to 250 kHz by changing the capacitor values attached in a parallel configuration to the antenna. For this particular antenna, 200 kHz seemed to be the best operating frequency, as shown in Figure 5.3-2 of section 5.3. Additionally, it was concluded that water to air radio communication is a viable option for low frequency values, an option that could potentially be pursued in future as an improvement to the current communication system.

6.1.4. Mission Control

The mission control subsystem operated successfully when tested separately and when integrated with the rest of the modules. Multiple test cases were developed in order to evaluate the code functionality. In each test case, the FPGA was capable of reading four signals from both the RF reader and acoustic listening stations, and outputting the correct sequences on the LEDs. Although the mission control functionality was limited to the display of the current fish location, its viability was demonstrated to fulfill the project objectives. With further development, the mission control could be upgraded to be capable of storing the data for future analysis.

6.2. Future Work

As the goal of this MQP was a proof of concept system, there are several areas where the each modules can be improved. The future work could be implemented as either a second MQP or even as another research project. These improvements would increase the interest in producing the system as a whole.

The energy harvesting module could be further developed before being implemented on a real fish by using a piezo bender that could be easily bent. The current material could easily break if the oscillation is too fast or and the load is too heavy. In addition, for increased power, two piezoelectric benders could be used, each attached on a different side of the fish's' tail. The usage of the energy harvesting IC restrained the output of the energy harvesting prototype to a maximum voltage of 3.6 V to the acoustic transmitter, because this requires 5 V, a step up converter had to be used. For a future prototype, it is recommended to have a new design, eliminating the energy harvesting IC, that can allow a higher output voltage. Finally, implementing the design on a PCB board and using smaller components to miniaturize the prototype, would allow the device to fit on the fish without causing any discomfort to the fish.

Both the acoustic system and the RFID system each have several areas that stand to be enhanced with future work. First in the RFID system, additional testing with the full scale RFID antenna would be the first priority. Increasing the length of the cable available can increase the power output and likely allow the antenna to function. Most of the circuitry in the RFID system and the acoustic listening stations could be implemented with a microcontroller. This would increase the flexibility of the system by allowing set values, such as the station number, to be easily changed, and would allow additional features to be implemented in the system depending on the capabilities of the tag in use. Additionally, using a microcontroller at the listening stations should improve the accuracy of the acoustic frequency detector and allow for a narrower spacing of transmitted frequencies resulting in an increased number of tags being tracked by the same system. Second, the acoustic tag and both receiving systems would need to be condensed into integrated circuits to decrease the size of the stations on shore. This improvement would also include the waterproofing of the tag to allow testing on fish. Also, each station could be powered by solar panels, which would eliminate the need for batteries at each station, and therefore, the need to go out to each station and change the batteries. These improvements should enable the system to be at a level where the system could be produced and sold competitively.

There are several significant improvements that can be made to the communication system in the future to further improve the accuracy and efficiency of communicating the tracking information of the fish. The first improvement that can be made to the communication system is to change the water to air communication to wirelessly communicate the information obtained from the tracking system. This improvement will open up various opportunities to further enhance the accuracy of the collected tracking information of the fish. If wireless communication of the tracking information can only be done in air medium, the listening stations will have to be placed along the sides of a river. However, if the wireless communication can be done through water, the listening stations can be placed at any point in the river and not only at the side of the river. For example, the listening stations could be placed strategically around larger obstacles in the river, avoiding the large loss of signal caused by a path being blocked by debris. This would minimize the signal loss and maximize the validity of the tracking information.

The second improvement that can be made to the communication system is the miniaturization of the encoder circuitry. An integrated chip can be designed and built to perform the same functionality as the current encoder circuitry. This miniaturization would decrease the spatial requirements of the communication system on shore, making the system both portable and durable. The encoder circuit, along with the wireless transmitting modules, could be implemented on a PCB board for improved reusability and enhanced durability of the communication system. Finally, solar panels could be used to power up the communication system which would eliminate the use of the batteries, as well as the need to replace the batteries, improving efficiency and making ita cost effective solution in the future generations of the system.

Several improvements could be made to the mission control module to develop a more effective prototype for future generations. Although the microcontroller presented as a more suitable option according to the design decisions, performing mathematical calculations and communicating with other devices more efficiently, due to time constraints and availability of parts, an FPGA was used for the mission control instead of a microcontroller. Therefore, the first step in the development and refining of the mission control would be to switch to a microcontroller instead of an FPGA. Furthermore, the mission control should be able to continuously store the fish location until the information is downloaded to a computer for analysis. For the data storage, an SD card could be used, as it requires low power consumption and can hold a lot of memory, and then a PC can be used to extract the data from the SD card. An additional improvement could allow the collected data to be transmitted to a mobile device using SMS. This would increase the mobility of the system, and eliminate the need for contact with the physical mission control.

The system as a whole was able to prove the concept that fish could be tracked in a river using acoustic and RFID tracking. Each module was proven successful and then integrated to form a fully functional system. Though everything didn’t perform as expected, the concept was proved and improvements were suggested for future work to enhance the system as a whole.

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7.0 Appendices

Appendix A: Mission Control Code

-- VHDL program:

```
library IEEE;
use IEEE.STD_LOGIC_1164.ALL;
use IEEE.STD_LOGIC_ARITH.ALL;
use IEEE.STD_LOGIC_UNSIGNED.ALL;

-- entity declaration
entity states is
  Port ( tag1                    : in   STD_LOGIC; -- 1st acoustic signal
      tag2                       : in   STD_LOGIC; -- 2nd acoustic signal
                          tag3                    : in   STD_LOGIC; -- 3rd acoustic signal
                          tag_rf                  : in   STD_LOGIC; -- RF signal

      clk                        : in   STD_LOGIC; -- internal clock
                  farzan                 : in   STD_LOGIC; -- lock input from comms module
                          reset                   : in    STD_LOGIC;


                          sig1                    : out STD_LOGIC; -- test aoucstic signal 1
                          sig2                    : out STD_LOGIC; -- test acoustic signal 2
                          sig3                    : out STD_LOGIC; -- test acoustic signal 3
                          sig_rf                  : out STD_LOGIC; -- test RF signal

                         test_ready               : out STD_LOGIC;
                         test_clk                 : out STD_LOGIC;
                         test_t1                  : out STD_LOGIC;


      closest_tag  : out  STD_LOGIC_VECTOR(4 downto 0); -- station number
                          which_fish   : out  STD_LOGIC_VECTOR(3 downto 0)); -- fish number
end states;

architecture Behavioral of states is

        type state_tag1 is (header1_t1, header2_t1, header3_t1, header4_t1, header5_t1, header6_t1,
header7_t1, header8_t1, header9_t1, RSS1_t1, RSS2_t1 ,RSS3_t1, RSS4_t1, RSS5_t1, RSS6_t1, RSS7_t1,
RSS8_t1,tagnum1_t1, tagnum2_t1, tagnum3_t1, tagnum4_t1, tagnum5_t1, fishnum1_t1, fishnum2_t1,
fishnum3_t1, fishnum4_t1, tail1_t1, tail2_t1, tail3_t1, tail4_t1, tail5_t1, tail6_t1, tail7_t1, tail8_t1,
tail9_t1);
        signal current_state1, next_state1 : state_tag1;

        type state_tag2 is (header1_t2, header2_t2, header3_t2, header4_t2, header5_t2, header6_t2,
header7_t2, header8_t2, header9_t2, RSS1_t2, RSS2_t2 ,RSS3_t2, RSS4_t2, RSS5_t2, RSS6_t2, RSS7_t2,
RSS8_t2,tagnum1_t2, tagnum2_t2, tagnum3_t2, tagnum4_t2, tagnum5_t2, fishnum1_t2, fishnum2_t2,
```

```
fishnum3_t2, fishnum4_t2, tail1_t2, tail2_t2, tail3_t2, tail4_t2, tail5_t2, tail6_t2, tail7_t2, tail8_t2,
tail9_t2);
        signal current_state2, next_state2 : state_tag2;

        type state_tag3 is (header1_t3, header2_t3, header3_t3, header4_t3, header5_t3, header6_t3,
header7_t3, header8_t3, header9_t3, RSS1_t3, RSS2_t3 ,RSS3_t3, RSS4_t3, RSS5_t3, RSS6_t3, RSS7_t3,
RSS8_t3,tagnum1_t3, tagnum2_t3, tagnum3_t3, tagnum4_t3, tagnum5_t3, fishnum1_t3, fishnum2_t3,
fishnum3_t3, fishnum4_t3, tail1_t3, tail2_t3, tail3_t3, tail4_t3, tail5_t3, tail6_t3, tail7_t3, tail8_t3,
tail9_t3);
        signal current_state3, next_state3 : state_tag3;

        type state_rf   is (header1_rf, header2_rf, header3_rf, header4_rf, header5_rf, header6_rf,
header7_rf, header8_rf, header9_rf, RSS1_rf, RSS2_rf, RSS3_rf, RSS4_rf, RSS5_rf, RSS6_rf, RSS7_rf,
RSS8_rf,tagnum1_rf, tagnum2_rf, tagnum3_rf, tagnum4_rf, tagnum5_rf, fishnum1_rf, fishnum2_rf,
fishnum3_rf, fishnum4_rf, tail1_rf, tail2_rf, tail3_rf, tail4_rf, tail5_rf, tail6_rf, tail7_rf, tail8_rf, tail9_rf);
        signal current_state_rf, next_state_rf : state_rf;

        type state_output is (whos_ready, output_rf , compare_all, compare_two, pick_one);
        signal current_state_o, next_state_o : state_output;

        -- signals declarations

        signal clk_10Hz             : std_logic := '0';
        signal clk_20Hz             : std_logic := '0';


        signal ready        : std_logic_vector(2 downto 0) := "000";
        signal ready_rf      : std_logic := '0';

        signal tagtemp1             : std_logic_vector( 4 downto 0) := "00000";
        signal tagtemp2             : std_logic_vector( 4 downto 0) := "00000";
        signal tagtemp3      : std_logic_vector( 4 downto 0) := "00000";
        signal tagtemp_rf    : std_logic_vector( 4 downto 0) := "00000";

        signal rsstemp1             : std_logic_vector( 7 downto 0) := "00000000";
        signal rsstemp2             : std_logic_vector( 7 downto 0) := "00000000";
  signal rsstemp3             : std_logic_vector( 7 downto 0) := "00000000";
        signal rsstemp_rf             : std_logic_vector( 7 downto 0) := "00000000";


        signal fishtemp1                    : std_logic_vector( 3 downto 0) := "0000";
        signal fishtemp2                    : std_logic_vector( 3 downto 0) := "0000";
  signal fishtemp3            : std_logic_vector( 3 downto 0) := "0000";
  signal fishtemp_rf       : std_logic_vector( 3 downto 0) := "0000";

        signal sequence1                    : std_logic_vector (69 downto 0);
  signal sequence2                    : std_logic_vector (69 downto 0);
        signal sequence3                    : std_logic_vector (69 downto 0);
```

```
  signal sequence4                    : std_logic_vector (69 downto 0);



begin

                    -- state memory for tag1
                    state_memory1: process(farzan,reset)
                              begin
                                        if reset = '1' then
                                                  current_state1 <= header1_t1;
                                        elsif farzan'event and farzan ='1' then
                                                  current_state1 <= next_state1;
                                        end if;
                              end process state_memory1;

                    -- state memory for tag2
                    state_memory2: process(farzan,reset)
                              begin
                                        if reset = '1' then
                                                  current_state2 <= header1_t2;
                                        elsif farzan'event and farzan ='1' then
                                                  current_state2 <= next_state2;
                                        end if;
                              end process state_memory2;

                    -- state memory for tag3
                    state_memory3: process(farzan,reset)
                              begin
                                        if reset = '1' then
                                                  current_state3 <= header1_t3;
                                        elsif farzan'event and farzan ='1' then
                                                  current_state3 <= next_state3;
                                        end if;
                              end process state_memory3;

                    -- state memory for rf tag
                    state_memory_rf: process(farzan,reset)
                              begin
                                        if reset = '1' then
                                                  current_state_rf <= header1_rf;
                                        elsif farzan'event and farzan ='1' then
                                                  current_state_rf <= next_state_rf;
                                        end if;
                              end process state_memory_rf;
```

```
-- state memory for output
state_memory_output: process(clk,reset)
        begin
                if reset = '1' then
                        current_state_o <= whos_ready;
                elsif clk'event and clk ='1' then
                        current_state_o <= next_state_o;
                end if;
        end process state_memory_output;

-- configuration for the next state and output logic for tag1
state_configuration1: process(tag1, current_state1, next_state1)
        begin

                        case current_state1 is
                   -- first checks for header sequence
                                when header1_t1  =>

                                        if tag1 ='1' then
                                                 next_state1 <= header2_t1;
                                        else next_state1 <= header1_t1;
                                        end if;



                                        ready(0) <= '0';


                                when header2_t1 =>

                                        if tag1 ='0'   then
                                                 next_state1 <= header3_t1;
                                        else next_state1 <= header1_t1;
                                        end if;

                                        ready(0) <= '0';


                                when header3_t1 =>

                                        if tag1 ='0'   then
                                                 next_state1 <= header4_t1;
                                        else next_state1 <= header1_t1;
                                        end if;

                                        ready(0) <= '0';
```

```
          when header4_t1  =>

                   if tag1 ='1' then
                             next_state1 <= header5_t1;
                   else next_state1 <= header1_t1;
                   end if;

                   ready(0) <= '0';

          when header5_t1  =>

                   if tag1 ='1' then
                             next_state1 <= header6_t1;
                   else next_state1 <= header1_t1;
                   end if;

                   ready(0) <= '0';


          when header6_t1 =>

                   if tag1 ='0'   then
                             next_state1 <= header7_t1;
                   else next_state1 <= header1_t1;
                   end if;

                   ready(0) <= '0';


          when header7_t1 =>

                   if tag1 ='0'   then
                             next_state1 <= header8_t1;
                   else next_state1 <= header1_t1;
                   end if;

                   ready(0) <= '0';

          when header8_t1 =>

                   if tag1 ='1'   then
                             next_state1 <= header9_t1;
                   else next_state1 <= header1_t1;
                   end if;

                   ready(0) <= '0';

   when header9_t1 =>
```

```
                if tag1 ='0'   then
                        next_state1 <= RSS1_t1;
                else next_state1 <= header1_t1;
                end if;

                ready(0) <= '0';

        when RSS1_t1 =>
                -- starts storing the RSS for computation
                rsstemp1(7) <=  tag1;
                next_state1 <=  RSS2_t1;

                ready(0) <= '0';

        when RSS2_t1 =>

                rsstemp1(6) <=  tag1;
                next_state1 <=  RSS3_t1;

                ready(0) <= '0';

        when RSS3_t1 =>

                rsstemp1(5) <=  tag1;
                next_state1 <=  RSS4_t1;

                ready(0) <= '0';

        when RSS4_t1 =>

                rsstemp1(4) <=  tag1;
                next_state1 <=  RSS5_t1;

                ready(0) <= '0';

        when RSS5_t1 =>

                rsstemp1(3) <=  tag1;
                next_state1 <=  RSS6_t1;

                ready(0) <= '0';


        when RSS6_t1 =>

                rsstemp1(2) <=  tag1;
                next_state1 <=  RSS7_t1;
```

```
                ready(0) <= '0';


        when RSS7_t1 =>

                rsstemp1(1) <=  tag1;
                next_state1 <=  RSS8_t1;

                ready(0) <= '0';


        when RSS8_t1 =>

                rsstemp1(0) <=  tag1;
                next_state1 <=  tagnum1_t1;

                ready(0) <= '0';


        when tagnum1_t1 =>
                -- stores the station number
                tagtemp1(4) <=  tag1;
                next_state1 <=  tagnum2_t1;

                ready(0) <= '0';

        when tagnum2_t1 =>

                tagtemp1(3) <=  tag1;
                next_state1 <=  tagnum3_t1;

                ready(0) <= '0';

        when tagnum3_t1 =>

                tagtemp1(2) <=  tag1;
                next_state1 <=  tagnum4_t1;

                ready(0) <= '0';

        when tagnum4_t1 =>

                tagtemp1(1) <=  tag1;
                next_state1 <=  tagnum5_t1;

                ready(0) <= '0';
```

```
when tagnum5_t1 =>

          tagtemp1(0) <=  tag1;
          next_state1 <=  fishnum1_t1;

          ready(0) <= '0';

when fishnum1_t1 =>
          -- stores the fish number
          fishtemp1(3) <=  tag1;
          next_state1 <=  fishnum2_t1;

          ready(0) <= '0';

when fishnum2_t1 =>

          fishtemp1(2) <=  tag1;
          next_state1 <=  fishnum3_t1;

          ready(0) <= '0';

when fishnum3_t1 =>

          fishtemp1(1) <=  tag1;
          next_state1 <=  fishnum4_t1;

          ready(0) <= '0';

when fishnum4_t1 =>

          fishtemp1(0) <=  tag1;
          next_state1 <=  tail1_t1;

          ready(0) <= '0';

when tail1_t1 =>
          -- checks the tail
          if tag1 = '0' then
                    next_state1 <= tail2_t1;
          else next_state1 <= header1_t1;
          end if;

          ready(0) <= '0';

when tail2_t1 =>

          if tag1 = '0' then
                    next_state1 <= tail3_t1;
```

```
        else next_state1 <= header1_t1;
        end if;

        ready(0) <= '0';

when tail3_t1 =>

        if tag1 = '0' then
                next_state1 <= tail4_t1;
        else next_state1 <= header1_t1;
        end if;

        ready(0) <= '0';

when tail4_t1 =>

        if tag1 = '0' then
                next_state1 <= tail5_t1;
        else next_state1 <= header1_t1;
        end if;

        ready(0) <= '0';


when tail5_t1 =>

        if tag1 = '1' then
                next_state1 <= tail6_t1;
        else next_state1 <= header1_t1;
        end if;

        ready(0) <= '0';

when tail6_t1 =>

        if tag1 = '1' then
                next_state1 <= tail7_t1;
        else next_state1 <= header1_t1;
        end if;

        ready(0) <= '0';

when tail7_t1 =>

        if tag1 = '1' then
                next_state1 <= tail8_t1;
        else next_state1 <= header1_t1;
        end if;
```

```
                            ready(0) <= '0';

                        when tail8_t1 =>

                            if tag1 = '1' then
                                next_state1 <= tail9_t1;
                            else next_state1 <= header1_t1;
                            end if;

                            ready(0) <= '0';

                        when tail9_t1 =>

                            if tag1 = '0' then
                                ready(0) <= '1'; -- outputs a ready
signal to the output process
                            else ready(0) <= '0';
                            end if;

                            next_state1 <= header1_t1;

                    end case;

        end process state_configuration1;

        -- configuration for the next state and output logic for tag2
        state_configuration2: process(tag2, current_state2, next_state2)
            begin

                    case current_state2 is

                        when header1_t2  =>

                            if tag2 ='1' then
                                next_state2 <= header2_t2;
                            else next_state2 <= header1_t2;
                            end if;

                            ready(1) <= '0';


                        when header2_t2 =>

                            if tag2 ='0'   then
                                next_state2 <= header3_t2;
                            else next_state2 <= header1_t2;
                            end if;
```

```
            ready(1) <= '0';


    when header3_t2 =>

            if tag2 ='0'   then
                    next_state2 <= header4_t2;
            else next_state2 <= header1_t2;
            end if;

            ready(1) <= '0';

    when header4_t2  =>

            if tag2 ='1' then
                    next_state2 <= header5_t2;
            else next_state2 <= header1_t2;
            end if;

            ready(1) <= '0';

    when header5_t2  =>

            if tag2 ='1' then
                    next_state2 <= header6_t2;
            else next_state2 <= header1_t2;
            end if;

            ready(1) <= '0';


    when header6_t2 =>

            if tag2 ='0'   then
                    next_state2 <= header7_t2;
            else next_state2 <= header1_t2;
            end if;

            ready(1) <= '0';


    when header7_t2 =>

            if tag2 ='0'   then
                    next_state2 <= header8_t2;
            else next_state2 <= header1_t2;
            end if;
```

```
                    ready(1) <= '0';

            when header8_t2 =>

                    if tag2 ='1'   then
                            next_state2 <= header9_t2;
                    else next_state2 <= header1_t2;
                    end if;

                    ready(1) <= '0';

        when header9_t2 =>

                    if tag2 ='0'   then
                            next_state2 <= RSS1_t2;
                    else next_state2 <= header1_t2;
                    end if;

                    ready(1) <= '0';

            when RSS1_t2 =>

                    rsstemp2(7) <=  tag2;
                    next_state2 <=  RSS2_t2;

                    ready(1) <= '0';

            when RSS2_t2 =>

                    rsstemp2(6) <=  tag2;
                    next_state2 <=  RSS3_t2;

                    ready(1) <= '0';

            when RSS3_t2 =>

                    rsstemp2(5) <=  tag2;
                    next_state2 <=  RSS4_t2;

                    ready(1) <= '0';

            when RSS4_t2 =>

                    rsstemp2(4) <=  tag2;
                    next_state2 <=  RSS5_t2;

                    ready(1) <= '0';
```

```
when RSS5_t2 =>

          rsstemp2(3) <=  tag2;
          next_state2 <=  RSS6_t2;

          ready(1) <= '0';


when RSS6_t2 =>

          rsstemp2(2) <=  tag2;
          next_state2 <=  RSS7_t2;

          ready(1) <= '0';


when RSS7_t2 =>

          rsstemp2(1) <=  tag2;
          next_state2 <=  RSS8_t2;

          ready(1) <= '0';


when RSS8_t2 =>

          rsstemp2(0) <=  tag2;
          next_state2 <=  tagnum1_t2;

          ready(1) <= '0';


when tagnum1_t2 =>

          tagtemp2(4) <=  tag2;
          next_state2 <=  tagnum2_t2;

          ready(1) <= '0';

when tagnum2_t2 =>

          tagtemp2(3) <=  tag2;
          next_state2 <=  tagnum3_t2;

          ready(1) <= '0';

when tagnum3_t2 =>
```

```
                    tagtemp2(2) <=  tag2;
                    next_state2 <=  tagnum4_t2;

                    ready(1) <= '0';

                when tagnum4_t2 =>

                    tagtemp2(1) <=  tag2;
                    next_state2 <=  tagnum5_t2;

                    ready(1) <= '0';

                when tagnum5_t2 =>

                    tagtemp2(0) <=  tag2;
                    next_state2 <=  fishnum1_t2;

                    ready(1) <= '0';

                when fishnum1_t2 =>

                    fishtemp2(3) <=  tag2;
                    next_state2 <=  fishnum2_t2;

                    ready(1) <= '0';

                when fishnum2_t2 =>

                    fishtemp2(2) <=  tag2;
                    next_state2 <=  fishnum3_t2;

                    ready(1) <= '0';

                when fishnum3_t2 =>

                    fishtemp2(1) <=  tag2;
                    next_state2 <=  fishnum4_t2;

                    ready(1) <= '0';

                when fishnum4_t2 =>

                    fishtemp2(0) <=  tag2;
                    next_state2 <=  tail1_t2;

                    ready(1) <= '0';
```

```
when tail1_t2 =>

        if tag2 = '0' then
                next_state2 <= tail2_t2;
        else next_state2 <= header1_t2;
        end if;

        ready(1) <= '0';

when tail2_t2 =>

        if tag2 = '0' then
                next_state2 <= tail3_t2;
        else next_state2 <= header1_t2;
        end if;

        ready(1) <= '0';

when tail3_t2 =>

        if tag2 = '0' then
                next_state2 <= tail4_t2;
        else next_state2 <= header1_t2;
        end if;

        ready(1) <= '0';

when tail4_t2 =>

        if tag2 = '0' then
                next_state2 <= tail5_t2;
        else next_state2 <= header1_t2;
        end if;

        ready(1) <= '0';


when tail5_t2 =>

        if tag2 = '1' then
                next_state2 <= tail6_t2;
        else next_state2 <= header1_t2;
        end if;

        ready(1) <= '0';

when tail6_t2 =>
```

```
                                if tag2 = '1' then
                                        next_state2 <= tail7_t2;
                                else next_state2 <= header1_t2;
                                end if;

                                ready(1) <= '0';

                        when tail7_t2 =>

                                if tag2 = '1' then
                                        next_state2 <= tail8_t2;
                                else next_state2 <= header1_t2;
                                end if;

                                ready(1) <= '0';

                        when tail8_t2 =>

                                if tag2 = '1' then
                                        next_state2 <= tail9_t2;
                                else next_state2 <= header1_t2;
                                end if;

                                ready(1) <= '0';

                        when tail9_t2 =>

                                if tag2 = '0' then
                                        ready(1) <= '1';
                                else ready(1) <= '0';
                                end if;

                                next_state2 <= header1_t2;

                end case;

end process state_configuration2;

-- configuration for the next state and output logic for tag3
state_configuration3: process(tag3, current_state3, next_state3)
        begin

                case current_state3 is

                        when header1_t3  =>

                                if tag3 ='1' then
                                        next_state3 <= header2_t3;
```

```
                else next_state3 <= header1_t3;
                end if;

                ready(2) <= '0';


            when header2_t3 =>

                if tag3 ='0'   then
                        next_state3 <= header3_t3;
                else next_state3 <= header1_t3;
                end if;

                ready(2) <= '0';


            when header3_t3 =>

                if tag3 ='0'   then
                        next_state3 <= header4_t3;
                else next_state3 <= header1_t3;
                end if;

                ready(2) <= '0';

            when header4_t3  =>

                if tag3 ='1' then
                        next_state3 <= header5_t3;
                else next_state3 <= header1_t3;
                end if;

                ready(2) <= '0';

            when header5_t3  =>

                if tag3 ='1' then
                        next_state3 <= header6_t3;
                else next_state3 <= header1_t3;
                end if;

                ready(2) <= '0';


            when header6_t3 =>

                if tag3 ='0'   then
                        next_state3 <= header7_t3;
```

```
            else next_state3 <= header1_t3;
            end if;

            ready(2) <= '0';


      when header7_t3 =>

            if tag3 ='0'   then
                  next_state3 <= header8_t3;
            else next_state3 <= header1_t3;
            end if;

            ready(2) <= '0';

      when header8_t3 =>

            if tag3 ='1'   then
                  next_state3 <= header9_t3;
            else next_state3 <= header1_t3;
            end if;

            ready(2) <= '0';

when header9_t3 =>

            if tag3 ='0'   then
                  next_state3 <= RSS1_t3;
            else next_state3 <= header1_t3;
            end if;

            ready(2) <= '0';

      when RSS1_t3 =>

            rsstemp3(7) <=  tag3;
            next_state3 <=  RSS2_t3;

            ready(2) <= '0';

      when RSS2_t3 =>

            rsstemp3(6) <=  tag3;
            next_state3 <=  RSS3_t3;

            ready(2) <= '0';

      when RSS3_t3 =>
```

```
                    rsstemp3(5) <=  tag3;
                    next_state3 <=  RSS4_t3;

                    ready(2) <= '0';

          when RSS4_t3 =>

                    rsstemp3(4) <=  tag3;
                    next_state3 <=  RSS5_t3;

                    ready(2) <= '0';

          when RSS5_t3 =>

                    rsstemp3(3) <=  tag3;
                    next_state3 <=  RSS6_t3;

                    ready(2) <= '0';


          when RSS6_t3 =>

                    rsstemp3(2) <=  tag3;
                    next_state3 <=  RSS7_t3;

                    ready(2) <= '0';


          when RSS7_t3 =>

                    rsstemp3(1) <=  tag3;
                    next_state3 <=  RSS8_t3;

                    ready(2) <= '0';


          when RSS8_t3 =>

                    rsstemp3(0) <=  tag3;
                    next_state3 <=  tagnum1_t3;

                    ready(2) <= '0';


          when tagnum1_t3 =>

                    tagtemp3(4) <=  tag3;
```

```
          next_state3 <=  tagnum2_t3;

          ready(2) <= '0';

when tagnum2_t3 =>

          tagtemp3(3) <=  tag3;
          next_state3 <=  tagnum3_t3;

          ready(2) <= '0';

when tagnum3_t3 =>

          tagtemp3(2) <=  tag3;
          next_state3 <=  tagnum4_t3;

          ready(2) <= '0';

when tagnum4_t3 =>

          tagtemp3(1) <=  tag3;
          next_state3 <=  tagnum5_t3;

          ready(2) <= '0';

when tagnum5_t3 =>

          tagtemp3(0) <=  tag3;
          next_state3 <=  fishnum1_t3;

          ready(2) <= '0';

when fishnum1_t3 =>

          fishtemp3(3) <=  tag3;
          next_state3 <=  fishnum2_t3;

          ready(2) <= '0';

when fishnum2_t3 =>

          fishtemp3(2) <=  tag3;
          next_state3 <=  fishnum3_t3;

          ready(2) <= '0';

when fishnum3_t3 =>
```

```
          fishtemp3(1) <=  tag3;
          next_state3 <=  fishnum4_t3;

          ready(2) <= '0';

when fishnum4_t3 =>

          fishtemp3(0) <=  tag3;
          next_state3 <=  tail1_t3;

          ready(2) <= '0';

when tail1_t3 =>

          if tag3 = '0' then
                    next_state3 <= tail2_t3;
          else next_state3 <= header1_t3;
          end if;

          ready(2) <= '0';

when tail2_t3 =>

          if tag3 = '0' then
                    next_state3 <= tail3_t3;
          else next_state3 <= header1_t3;
          end if;

          ready(2) <= '0';

when tail3_t3 =>

          if tag3 = '0' then
                    next_state3 <= tail4_t3;
          else next_state3 <= header1_t3;
          end if;

          ready(2) <= '0';

when tail4_t3 =>

          if tag3 = '0' then
                    next_state3 <= tail5_t3;
          else next_state3 <= header1_t3;
          end if;

          ready(2) <= '0';
```

```
          when tail5_t3 =>

                if tag3 = '1' then
                      next_state3 <= tail6_t3;
                else next_state3 <= header1_t3;
                end if;

                ready(2) <= '0';

          when tail6_t3 =>

                if tag3 = '1' then
                      next_state3 <= tail7_t3;
                else next_state3 <= header1_t3;
                end if;

                ready(2) <= '0';

          when tail7_t3 =>

                if tag3 = '1' then
                      next_state3 <= tail8_t3;
                else next_state3 <= header1_t3;
                end if;

                ready(2) <= '0';

          when tail8_t3 =>

                if tag3 = '1' then
                      next_state3 <= tail9_t3;
                else next_state3 <= header1_t3;
                end if;

                ready(2) <= '0';

          when tail9_t3 =>

                if tag3 = '0' then
                      ready(2) <= '1';
                else ready(2) <= '0';
                end if;

                next_state3 <= header1_t3;

    end case;
```

```
end process state_configuration3;

-- configuration for the next state and output logic for rf tag
state_configuration_rf: process(tag_rf, current_state_rf, next_state_rf)
        begin

                        case current_state_rf is

                                when header1_rf  =>

                                        if tag_rf ='1' then
                                                next_state_rf <= header2_rf;
                                        else next_state_rf <= header1_rf;
                                        end if;

                                        ready_rf <= '0';


                                when header2_rf =>

                                        if tag_rf ='0'   then
                                                next_state_rf <= header3_rf;
                                        else next_state_rf <= header1_rf;
                                        end if;

                                        ready_rf <= '0';


                                when header3_rf =>

                                        if tag_rf ='0'   then
                                                next_state_rf <= header4_rf;
                                        else next_state_rf <= header1_rf;
                                        end if;

                                        ready_rf <= '0';

                                when header4_rf  =>

                                        if tag_rf ='1' then
                                                next_state_rf <= header5_rf;
                                        else next_state_rf <= header1_rf;
                                        end if;

                                        ready_rf <= '0';


                                when header5_rf  =>
```

```
        if tag_rf ='1' then
                next_state_rf <= header6_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';


when header6_rf =>

        if tag_rf ='0'   then
                next_state_rf <= header7_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';


when header7_rf =>

        if tag_rf ='0'   then
                next_state_rf <= header8_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';

when header8_rf =>

        if tag_rf ='1'   then
                next_state_rf <= header9_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';

when header9_rf =>

        if tag_rf ='0'   then
                next_state_rf <= RSS1_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';

when RSS1_rf =>
```

```
          rsstemp_rf(7) <=  tag_rf;
          next_state_rf <=  RSS2_rf;

          ready_rf <= '0';

when RSS2_rf =>

          rsstemp_rf(6) <=  tag_rf;
          next_state_rf <=  RSS3_rf;

          ready_rf <= '0';

when RSS3_rf =>

          rsstemp_rf(5) <=  tag_rf;
          next_state_rf <=  RSS4_rf;

          ready_rf <= '0';

when RSS4_rf =>

          rsstemp_rf(4) <=  tag_rf;
          next_state_rf <=  RSS5_rf;

          ready_rf <= '0';

when RSS5_rf =>

          rsstemp_rf(3) <=  tag_rf;
          next_state_rf <=  RSS6_rf;

          ready_rf <= '0';

when RSS6_rf =>

          rsstemp_rf(2) <=  tag_rf;
          next_state_rf <=  RSS7_rf;

          ready_rf <= '0';

when RSS7_rf =>

          rsstemp_rf(1) <=  tag_rf;
          next_state_rf <=  RSS8_rf;

          ready_rf <= '0';

when RSS8_rf =>
```

```
                    rsstemp_rf(0) <=  tag_rf;
                    next_state_rf <=  tagnum1_rf;

                    ready_rf <= '0';

            when tagnum1_rf =>

                    tagtemp_rf(4) <=  tag_rf;
                    next_state_rf <=  tagnum2_rf;

                    ready_rf <= '0';

            when tagnum2_rf =>

                    tagtemp_rf(3) <=  tag_rf;
                    next_state_rf <=  tagnum3_rf;

                    ready_rf <= '0';

            when tagnum3_rf =>

                    tagtemp_rf(2) <=  tag_rf;
                    next_state_rf <=  tagnum4_rf;

                    ready_rf <= '0';

            when tagnum4_rf =>

                    tagtemp_rf(1) <=  tag_rf;
                    next_state_rf <=  tagnum5_rf;

                    ready_rf <= '0';

            when tagnum5_rf =>

                    tagtemp_rf(0) <=  tag_rf;
                    next_state_rf <=  fishnum1_rf;

                    ready_rf <= '0';

            when fishnum1_rf =>

                    fishtemp_rf(3) <=  tag_rf;
                    next_state_rf <=  fishnum2_rf;

                    ready_rf <= '0';
```

```
when fishnum2_rf =>

        fishtemp_rf(2) <=  tag_rf;
        next_state_rf <=  fishnum3_rf;

        ready_rf <= '0';

when fishnum3_rf =>

        fishtemp_rf(1) <=  tag_rf;
        next_state_rf <=  fishnum4_rf;

        ready_rf <= '0';

when fishnum4_rf =>

        fishtemp_rf(0) <=  tag_rf;
        next_state_rf <=  tail1_rf;

        ready_rf <= '0';

when tail1_rf =>

        if tag_rf = '0' then
                next_state_rf <= tail2_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';

when tail2_rf =>

        if tag_rf = '0' then
                next_state_rf <= tail3_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';

when tail3_rf =>

        if tag_rf = '0' then
                next_state_rf <= tail4_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';
```

```
when tail4_rf =>

        if tag_rf = '0' then
                next_state_rf <= tail5_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';


when tail5_rf =>

        if tag_rf = '1' then
                next_state_rf <= tail6_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';

when tail6_rf =>

        if tag_rf = '1' then
                next_state_rf <= tail7_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';

when tail7_rf =>

        if tag_rf = '1' then
                next_state_rf <= tail8_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';

when tail8_rf =>

        if tag_rf = '1' then
                next_state_rf <= tail9_rf;
        else next_state_rf <= header1_rf;
        end if;

        ready_rf <= '0';


when tail9_rf =>
```

```
                            if tag_rf = '0' then
                                ready_rf <= '1';
                            else ready_rf <= '0';
                            end if;

                            next_state_rf <= header1_rf;

                    end case;

        end process state_configuration_rf;

        -- configuration for the next state and output logic for the output
        state_output_configuration: process(current_state_o, next_state_o, ready_rf, ready,
fishtemp_rf, rsstemp1, rsstemp2, rsstemp3, tagtemp1, fishtemp1, tagtemp2, fishtemp2, tagtemp3,
fishtemp3, tagtemp_rf, fishtemp_rf)
            begin

                    case current_state_o is
                  -- first state checks which ready signals are enabled
                        when whos_ready  =>

                            if      ready_rf ='1' then
                                        next_state_o <= output_rf; --
gives the highest priority to the RF signal
                            else    if ready = "111" then
                                            next_state_o <=
compare_all; -- when all acoustic signals arrive at the same time -> compare RSS
                                    elsif ready = "011" or ready =
"101" or ready = "110" then

                                            next_state_o <=
compare_two;
                                    elsif ready = "001" or ready =
"010" or ready = "100" then

                                            next_state_o <=
pick_one;

                                    else  next_state_o <=
whos_ready;

                                    end if;

                            end if;

                        when output_rf   =>
                          -- outputs the RF information for station and fish
numbers

                                closest_tag <= tagtemp_rf;
                                which_fish  <= fishtemp_rf;
```

```
                                next_state_o <= whos_ready;

                        when compare_all =>
                          -- outputs the information coresponding to the signal
with the highest RSS

                                if rsstemp1 > rsstemp2 and rsstemp1>
rsstemp3 then
                                    closest_tag <= tagtemp1;
                                    which_fish  <= fishtemp1;
                                elsif rsstemp2 > rsstemp1 and rsstemp2
> rsstemp3 then
                                    closest_tag <= tagtemp2;
                                    which_fish  <= fishtemp2;
                                else
                                    closest_tag <= tagtemp3;
                                    which_fish  <= fishtemp3;
                                end if;

                                next_state_o <= whos_ready;


                        when compare_two =>

                             -- outputs the information coresponding to
the signal with the highest RSS

                                if ready = "110" then

                                    if rsstemp3 > rsstemp2 then
                                        closest_tag <=
tagtemp3;
                                        which_fish <=
fishtemp3;
                                    else
                                        closest_tag <=
tagtemp2;
                                        which_fish <=
fishtemp2;
                                    end if;

                                elsif ready = "101" then

                                    if rsstemp3 > rsstemp1 then
                                        closest_tag <=
tagtemp3;
                                        which_fish <=
fishtemp3;
```

```
                                    else
                                        closest_tag <=
tagtemp1;
                                        which_fish <=
fishtemp1;
                                    end if;

                                    next_state_o <= whos_ready;

                                else
                                    if rsstemp2 > rsstemp1 then
                                        closest_tag <=
tagtemp2;
                                        which_fish <=
fishtemp2;
                                    else
                                        closest_tag <=
tagtemp1;
                                        which_fish <=
fishtemp1;
                                    end if;
                                end if;

                                next_state_o <= whos_ready;

                            when pick_one =>
                                 -- outputs -- outputs the information
coresponding to the current signal

                                    if ready ="001" then

                                    closest_tag <=  tagtemp1;
                                    which_fish   <= fishtemp1;

                                    elsif ready = "010" then

                                    closest_tag <=  tagtemp2;
                                    which_fish   <= fishtemp2;

                                    else

                                    closest_tag <=  tagtemp3;
                                    which_fish   <= fishtemp3;

                                    end if;

                                next_state_o <= whos_ready;
```

```
                     end case;

                              end process state_output_configuration;



                    -- state memory for simulating inputs
                    simulate_memory: process(farzan,reset)
                              begin
                                        if reset = '1' then
                                                  sequence1 <= "0000" & "100110010" & "10000100" & "11111"
& "1111" & "000011110" & "0000000000000000000000000000000";
                                                  sequence2 <= "0000" & "100110010" & "01000100" & "11010"
& "1010" & "000011110" & "0000000000000000000000000000000";
                                                  sequence3 <= "0000" & "100110010" & "00100100" & "00110"
& "0100" & "000011110" & "0000000000000000000000000000000";
                                                  sequence4 <= "0000" & "000000000" & "00000000" & "00000"
& "0000" & "000000000" & "0000000000000000000000000000000";



                                        elsif farzan'event and farzan ='1' then

                                           -- right shiff the MSB to loop through the sequence
                                                  sequence1 <= sequence1(68 downto 0) & sequence1(69);
                                                  sequence2 <= sequence2(68 downto 0) & sequence2(69);
                                                  sequence3 <= sequence3(68 downto 0) & sequence3(69);
                                                  sequence4 <= sequence4(68 downto 0) & sequence4(69);

                                          sig1   <=  sequence1(69);
                                                  sig2   <=  sequence2(69);
                                                  sig3   <=  sequence3(69);
                                                  sig_rf <=  sequence4(69);



                                        end if;
                              end process simulate_memory;

                              test_clk <= farzan;
                              test_t1 <= tag1;
                              test_ready <= ready(0);


end Behavioral;
```

-- UCF file:

```
// reset and internal clock signal
NET "reset" LOC = "H13";
NET "clk" LOC = "B8";

// outputs to LEDs
NET "closest_tag<4>" LOC = "R4";
NET "closest_tag<3>" LOC = "F4";
NET "closest_tag<2>" LOC = "P15";
NET "closest_tag<1>" LOC = "E17";
NET "closest_tag<0>" LOC = "K14";

NET "which_fish<3>" LOC = "K15";
NET "which_fish<2>" LOC = "J15";
NET "which_fish<1>" LOC = "J14";

// I/O pins
NET "tag1" LOC = "E7"; // IO9
NET "sig1" LOC = "A6"; // IO10

NET "tag2" LOC = "E9"; // IO15
NET "sig2" LOC = "C9"; // IO16

NET "tag3" LOC = "A10"; // IO21
NET "sig3" LOC = "B10"; // IO22

NET "tag_rf" LOC = "B13"; //IO33
NET "sig_rf" LOC = "E13"; //IO34

// clock input from comms modules
NET "farzan" LOC = "E10"; //  IO25
NET "farzan" CLOCK_DEDICATED_ROUTE = FALSE ;
```

Appendix B: Range Testing Tables

Frequency Scan				
Input		Output		
Freq (kHz)	Amplitude (V pk-pk)	Freq (kHz)	Amplitude (V pk-pk)	Percent Received (%)
20	20	20	16.6	83
30	20	30	16.6	83
40	20	40	15.3	76.5
50	20	50	16.6	83
60	20	60	14.7	73.5
70	20	6	13.3	66.5
80	20	80	11.8	59
90	20	90	8.9	44.5
100	20	100	8.2	41
110	20	110	7.6	38
120	20	120	4.6	23
130	20	130	5.3	26.5
140	20	140	11.25	56.25
150	20	150	11.5	57.5
160	20	160	10	50
170	20	170	8.8	44
180	20	180	7.9	39.5
190	20	190	6.9	34.5
200	20	200	6.4	32
210	20	210	5.7	28.5
220	20	220	5.25	26.25
230	20	230	5	25
240	20	240	4.5	22.5
250	20	250	4.1	20.5
260	20	260	3.8	19
270	20	270	3.4	17
280	20	280	3.3	16.5
290	20	290	3	15
300	20	300	2.6	13
310	20	310	2.2	11
320	20	320	1.7	8.5
330	20	330	2.9	14.5
340	20	340	2.9	14.5
350	20	350	2.2	11
360	20	360	2.9	14.5

370	20	370	2.5	12.5
380	20	380	2.2	11
390	20	390	2.1	10.5
400	20	400	2	10
410	20	410	1.9	9.5
420	20	420	1.8	9
430	20	430	1.6	8
440	20	440	1.5	7.5
450	20	450	1.4	7
460	20	460	1.3	6.5
470	20	470	1.3	6.5
480	20	480	1.2	6
490	20	490	1.1	5.5
500	20	500	1.5	7.5
510	20	510	1.4	7
520	20	520	1.3	6.5
530	20	530	1.2	6
540	20	540	1.1	5.5
550	20	550	1	5
560	20	560	0.9	4.5
570	20	570	0.8	4
580	20	580	0.8	4
590	20	590	0.8	4
600	20	600	0.7	3.5
610	20	610	0.7	3.5
620	20	620	0.7	3.5
630	20	630	0.7	3.5
640	20	640	0.7	3.5
650	20	650	0.7	3.5
660	20	660	0.7	3.5
670	20	670	0.7	3.5
680	20	680	0.7	3.5
690	20	690	0.7	3.5
700	20	700	0.5	2.5
710	20	710	0.5	2.5
720	20	720	0.5	2.5
730	20	730	0.5	2.5
740	20	740	0.5	2.5
750	20	750	0.5	2.5
760	20	760	0.4	2
770	20	770	0.4	2

780	20	780	0.4	2
790	20	790	0.4	2
800	20	800	0.4	2
810	20	810	0.4	2
820	20	820	0.3	1.5
830	20	830	0.3	1.5
840	20	840	0.3	1.5
850	20	850	0.3	1.5
860	20	860	0.3	1.5
870	20	870	0.3	1.5
880	20	880	0.3	1.5
890	20	890	0.3	1.5
900	20	900	0.2	1
910	20	910	0.2	1
920	20	920	0.2	1
930	20	930	0.2	1
940	20	940	0.2	1
950	20	950	0.2	1
960	20	960	0.2	1
970	20	970	0.2	1
980	20	980	0.2	1
990	20	990	0.1	0.5
1000	20	1000	Too much noise	

Focused Frequncy Scan			
Input		**Output**	
Freq	**Amplitude**	**Amplitude**	**Percentage**
20	20	16.6	83
21	20	16.1	80.5
22	20	15.9	79.5
23	20	15.8	79
24	20	15.8	79
25	20	15.8	79
26	20	15.8	79
27	20	16.1	80.5
28	20	16.4	82
29	20	16.6	83
30	20	16.4	82
31	20	15.7	78.5
32	20	16.8	84
33	20	15.8	79

34	20	15.5	77.5
35	20	15.2	76
36	20	15.2	76
37	20	15.1	75.5
38	20	15	75
39	20	15.3	76.5
40	20	15.2	76
41	20	15.3	76.5
42	20	15.6	78
43	20	15.9	79.5
44	20	16.4	82
45	20	16.7	83.5
46	20	17	85
47	20	17	85
48	20	16.9	84.5
49	20	16.6	83
50	20	16.4	82
51	20	16.4	82
52	20	16.1	80.5
53	20	15.8	79
54	20	15.6	78
55	20	15.3	76.5
56	20	15.2	76
57	20	15	75
58	20	14.8	74
59	20	14.7	73.5
60	20	14.5	72.5
61	20	14.3	71.5
62	20	14.1	70.5
63	20	13.9	69.5
64	20	13.8	69
65	20	13.8	69
66	20	13.9	69.5
67	20	13.8	69
68	20	13.5	67.5
69	20	13.3	66.5
70	20	13.1	65.5