Next Generation IMPAQT Miniaturized Underwater Transmitter System Design

Hamed Jafarzadeh
Tyndall National Institute
University College Cork
Cork, Ireland
e-mail: hamed.jafarzadeh@tyndall.ie

Marco Belcastro
Tyndall National Institute
University College Cork
Cork, Ireland
e-mail: marco.belcastro@tyndall.ie

Brendan O'Flynn
Tyndall National Institute
University College Cork
Cork, Ireland
e-mail: brendan.oflynn@tyndall.ie

***Abstract* - In recent years, terrestrial wireless sensor networks and Internet of Things (IoT) technologies have developed rapidly. However, due to the limitations of Electromagnetic (EM) signal propagation in water, there is less development and advancement in the underwater wireless sensor networks domain. As part of the IMPAQT project, a novel wireless underwater telemetry platform using acoustics has been proposed. This telemetry platform has the potential to replace the underwater sensors cables and provide a wireless method to collect and transmit a variety of environmental sensor data under water. The proposed platform system architecture consists of several ultrasonic transmitter nodes and a gateway buoy as a data aggregator node to transmit the data from the sensors to the cloud for analytics to be carried out. Transmitter nodes will read the attached sensor data and transmit it to the gateway buoy. The gateway buoy will send the collected data to a data management system using a Long Range (LoRa) communication link. The next generation IMPAQT Transmitter node developed is a compact, low-cost, low-power acoustic transmitter node that has an external sensor interface to receive data from attached sensors is described in detail in this paper. In addition, the potential for short-range EM-based underwater LoRa communication is evaluated and described.**

Keywords- Biotelemetry; Underwater communication; Underwater sensors network; Acoustic communications, underwater sensor node.

I. INTRODUCTION

This paper is an extension of a previous conference submission [1]. According to the latest United Nations world population estimation, by the year 2050, the population of the earth will reach approximately 10 billion people [2], and this increase will result in a higher demand for food and consequently seafood as it is one of the primary sources of protein and nutrition for many people. In the past, capture fisheries productions were the primary source of seafood, but this has changed in 2012, where aquaculture production volumes exceeded that of the traditional capture fisheries, and it is seen to be increasing rapidly in recent years to meet demand [3].

To provide more sustainability, reduce environmental impacts, and promote economic gains, integrated multi-trophic aquaculture (IMTA) is gaining popularity among marine farmers. In IMTA, farmers combine fed species (e.g., fish, shrimp, oysters) with extractive species (e.g., seaweed, mussels), and the extractive species will use the by-products of the fed species, reducing the environmental impact of the sites and also providing commercial profit to farmers.

IMPAQT [4] is a European project aimed at promoting and supporting the development of IMTA sites by providing a multi-purpose (Inland, coastal, offshore), multi-sensing (heterogeneous sensors, biosensors, smart systems), and multi-functional (Monitoring, data analytics, decision making) data management platform [5]. The IMPAQT project also aims at providing training based on the obtained data to the farmers and improving farming sector performance [6]. In Figure 1, an overview of the IMPAQT project has been proposed by Michalek et al. [7].

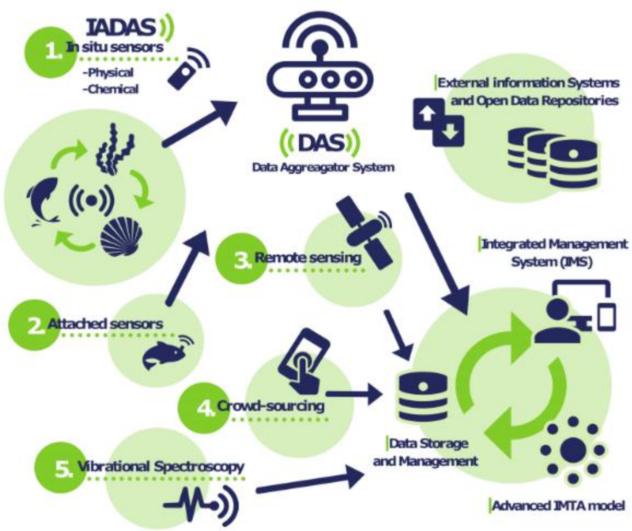


Figure 1. IMPAQT Project overview [7].

As part of the IMPAQT Data acquisition system, a communications device was required to collect information from the underwater sensors and transmit it to the data aggregator system (DAS) to provide accurate, real-time, and relevant information about the underwater environment.

As a result, a novel miniaturized low-power and low-cost underwater acoustic transmitter node and a gateway buoy receiver have been proposed as a telemetry system and evaluated to collect data from sensors and transmit it to the inland data aggregators.

The transmitter node has an optional extension sensor board, and the transmitter node is capable of interfacing with external commercially off-the-shelf sensor modules using an external sensor connector. Due to its small size and lightweight design, it has little impact on the working environment and the artefacts to which the sensors are attached.

In Section II, the related research projects, and specifically underwater monitoring systems, is summarised. Section III describes the LoRa underwater EM communications experiments that were carried out as part of this work to clarify the reasons that electromagnetics cannot be used for underwater communications except for very short-range applications. Section III continues by describing the methodology and development of the acoustic transmitter node circuit, design parameters and also describes the power analysis of the circuit to maximize system lifetime underwater. Section IV discusses the obtained results, and Section V addresses the result of the project and future work.

II. BACKGROUND AND RELATED WORK

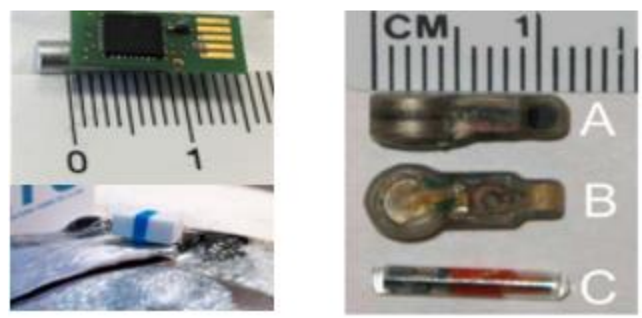
With the rapidly increasing and evolving aquaculture market sector, it is essential to monitor and analyze the effects of the methods that have been used in aquaculture to reduce the costs and improve the stability and sustainability of sea farms. Experimental monitoring in labs and tanks can help in establishing optimal best practices. However, due to the differences between the experimental environment and real aquaculture environments, it is hard to compare the findings accurately, especially when it comes to the biasing caused by the handling of marine animals [8]. In [9], M. Føre et al. proposed the concept of Precision Fish Farming intending to use scientific methods to manage fish production by enabling farmers to monitor, control and document the biological processes in fish farms. With the advancement of chemical and electrical sensing technologies, it is now possible to develop miniaturized attached sensor devices to track and study the natural behaviour of marine animals and plants in their natural environment. This section includes an overview of the current marine monitoring platforms and also acoustic telemetry platforms and modems.

A. *State-of-art marine monitoring platforms*

To achieve the goal of precision aquaculture and fish farming, in [10], J. A. Martos-Sitcha et al. describe the development of the AE-FishBIT, shown in Figure 2A, an ultra-low-power sensor device, for monitoring physical activities and respiratory frequency of the farmed fish, using the on-board accelerometer sensor. AE-FishBIT is a small non-invasive monitoring sensor with a footprint of 14mm x 7mm x 7mm and a total mass of 600mg. AE-FishBIT is not able to transmit the data, and the fish is required to be captured to download the sensors data.

Almeida et al. [11] monitored the behaviour of the Lusitanian toadfish using accelerometry data provided by the externally attached AccelTag, which was able to recognize and log behaviour activities of the fish. It is capable of continuously recording tilt, roll, forward acceleration, lateral acceleration, vertical acceleration of fish for more than 7 hours. To download the recorded data, the tag needs to be extracted and connected to a computer to download its data.

There are also devices for tracking the movement of the fish in dams, fisheries, and cages. In [12][13], authors have developed the Juvenile Salmon Acoustic Telemetry System (*JSATS*), shown in Figure 2B, to identify and track the movement of juvenile salmon in dams and rivers. *JSATS* tags are incredibly compact that can be injected using a needle into the fish's body. They can transmit ultrasonic pings for a year with a 15-second ping interval. But *JSATS* tags are only capable of transmitting a pre-programmed unique identification code and temperature data, and as they are sealed, they cannot provide any other sensor data. According to the report published in the journal of “review of scientific instruments” [14], the latest version of the *JSATS* tags can last up to 285 days with the ping rate of 15 seconds and 98 days with the ping rate of 5 seconds at 163dB sound level, and each ping can travel up to 500m.



A B

Figure 2. (A) AE-FishBIT Tags [10] (B) JSATS Tags [12]

In [15], C. Brockmann et al. implemented an energy-efficient system for monitoring fish in freshwater using high-frequency RF transceivers, capable of operating for one month using a single coin cell battery, with a measurement and transmission duty cycle of once every second. They utilized a low-power sub-GHz RF transceiver, CC1101 [16], which transmits at 866 MHz. They implemented an EMG sensor and a temperature sensor inside the module. They reported that the device was able to transmit data out of the fish cage, and they measured -70.52 dBm as the Received Signal Strength Indicator (RSSI) outside of the fish cage. They also reported that the module was able to cover one cubic meter of signal traveling distance in the water, which is not suitable for open-water communication requiring a more significant range.

Monitoring the marine environment parameters such as wave motion and light intensity, which are known to impact plant growth and harvest levels, is important in IMTA aquaculture scenarios. In a recent research, Peres et al. [17] developed a seaweed monitoring tag named AquaBit, shown in Figure 3, to record the accelerometry data of seaweed movement alongside recording the temperature, light intensity, and water pressure of the marine environment that it is deployed in. This novel miniature low-power NFC-enabled tag records the relevant seaweed growth parameters for roughly two weeks at a 52 Hz sampling rate, and the recorded data can be downloaded using the on-board NFC transceiver and a mobile phone or using a USB cable and provided Python-based host application.

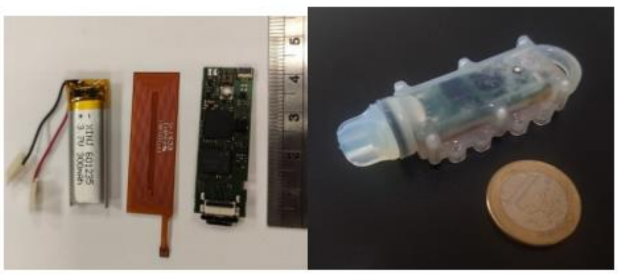


Figure 3. AquaBit seaweed monitoring tag [17].

Another method to monitor the marine environment is to use unmanned underwater vehicles. SeaSmart has introduced three patented wireless drones to collect environmental data, such as oxygen, salinity, biomass, and temperature, by travelling through the cage to collect data and returning to the surface to transmit the collected information to the cloud. It can also measure where the fish are in the cage, which can help farmers in their production and also feeding procedures. The SeaSmart Sensor Drone, depicted in Figure 4, can run 24/7 for six months on a single battery charge [18].

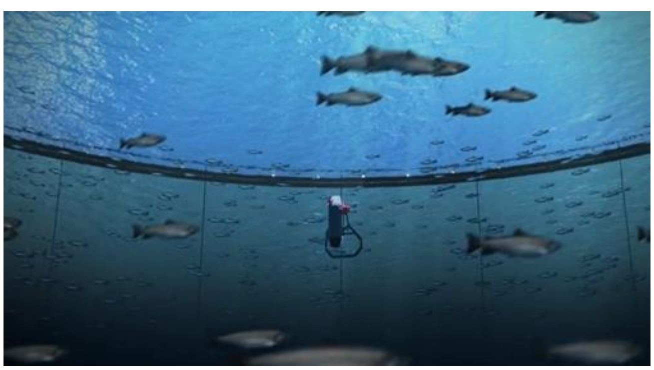


Figure 4. SeaSmart drone [18].

The Waterlinked company also has a solution for sensing aquaculture cages, called CageSense, shown in Figure 5. It is a network of various sensors and gateways that provide real-time underwater sensing [19]. They provide a wireless sensor that can be attached to cages using zip ties, and they can report the oxygen, salinity level, and cage's tilt and depth. There is a limited amount of information regarding these sensors at the time of writing this paper.

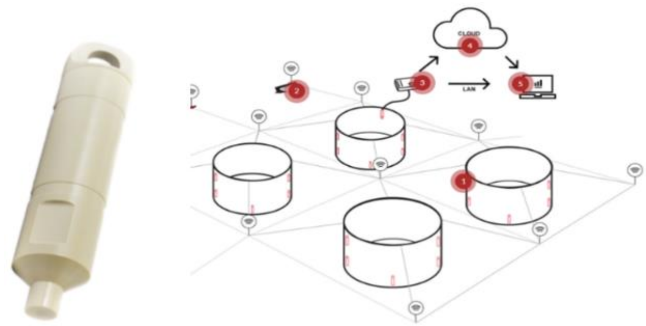


Figure 5. Waterlinked Cage Sense monitoring system [19].

There are also efforts on monitoring IMTA and aquaculture sites using remote sensing technologies; in [20], C. C. Krueger et al. have used multi-sensor (satellite, unmanned aerial vehicle, and ground spectroradiometer) remote sensing techniques to monitor seaweed aquaculture in the Yellow Sea.

There are also underwater modems that are of large size, bulky and designed for specific purposes, i.e., Underwater Robotics, etc. [21][22], and these are not designed for general-purpose marine environmental monitoring and are not reported in this paper.

In summary, various sensors can be used underwater for monitoring applications, but in order to extract their datasets, many of these need to be retrieved for data download at regular intervals. Wired sensors also exist, but there are limited numbers of sensors with underwater wireless communications capability for data download and analysis in real time.

III. MATERIALS AND METHOD

As it can be inferred from the state-of-the-art monitoring systems, there is a lack of a general-purpose miniaturized, low-power, wireless underwater transmitter that can be integrated with other commercial and research sensors to provide a telemetry system to collect sensors' information wirelessly.

The focus of the IMPAQT telemetry platform is on providing a communication link for monitoring IMTA sites, where all sensors will be deployed in a bounded area, and it is considered that the gateway buoy will be located at a maximum distance 100m from each sensor tag. Although an ultrasonic platform would be the optimum telemetry platform, there is also the possibility to use an ElectroMagnetic (EM) based solution at the shorter range, where the gateway is installed at the water surface of a cage right above the sensor, where a range of few meters would be required.

The transmitter needs to be miniaturized to enable integration with a wide range of sensors without requiring special mounting, and it should run on its own battery, to be able to communicate with the gateway node even in the case that the external sensor's battery is depleted. Having an internal battery and a battery management system also makes it easier to manage the battery health and estimate the charging status.

Considering the IMPAQT deployment requirements, there is a possibility of using electromagnetic waves communication at ultra-short range and ultrasonic waves communications at longer ranges. In the next section, the possibility of underwater electromagnetic communication is discussed, and a practical experiment carried out to confirm the results is explained.

A. *Underwater electromagnetic communication*

In various publications, researchers have studied electromagnetic waves propagation underwater [15][23]–[25]. In underwater communications, the transmission range is dependent on all the power gains and losses that a communication signal experiences during the transmission process. The most significant factor in establishing underwater communication is path loss. Path loss is the amount of wave signal degradation that occurs when a wave propagates in a medium, and it degrades as it moves in the medium channel. The amount of degradation depends on the conductivity and distance that the signal has travelled, and it is usually called path loss attenuation.

There are two primary path loss (PL) types that could happen in underwater RF communication. Attenuation loss and complex permittivity are shown as $L_{\alpha,\varepsilon}$ in an underwater environment, and reflection loss (L_R) at the surface, as shown in equation (1) below.

$$PL = L_{\alpha,\varepsilon} + L_R \tag{1}$$

The path loss model for an underwater environment is extensively discussed in [24][25] for far-field electromagnetic communication and in [26] for near-field communications (i.e. NFC, RFID). Although there are various theoretical models available, there are limited numbers of publications describing practical experiments. To evaluate the potential for short-range (all that is possible according to theory and modelling) EM underwater communication, a series of practical experiments were carried out in a freshwater river using off-the-shelf LoRa transceivers to validate the theoretical models. According to the theoretical studies, lower frequency EM signals should attenuate less in the water, maximizing the range as much as possible. However, lower frequency EM transceivers require a longer antenna, which is not optimal for IMPAQT project context. For the evaluation of EM waves underwater, it has been decided to use a general purpose LoRa transceivers. Current state-of-the-art LoRa transceivers by Semtech, SX127x series, offer a receiver sensitivity of -133 dBm with the most optimal configuration [40] and they are working in a range of 169MHz to 868MHz, According to Maxwell equation and experimental models such as Lioyd [19] and Hattab et al. [33] models, at the frequency of 169MHz the maximum travelling distance for the SX127x series should be around 2.3 meter in freshwater and less than 20cm in Seawater. Similarly, at 868MHz frequency, the travelling distance is limited to less than 110cm in freshwater and less than 13cm in seawater.

For the experiment, a LoPy4 radio node has been selected as the controller and RF module. LoPy4 [27] is a compact MicroPython enabled radio node based on SX1276 transceivers, designed to work at 868 MHz frequency. A transmitter and a receiver with identical setups have been prepared to communicate at 868 MHz frequency range, The diagram of the setup is shown in Figure 6, and the prepared setup is shown in Figure 7. An STM32F4-Disco board [28] has been used to control custom made SX1276RF1IAS modules, which have not been used in this test. It also monitors the external start switch to initiate the test procedure and synchronise the transmitter and receiver's timings for logging purposes.

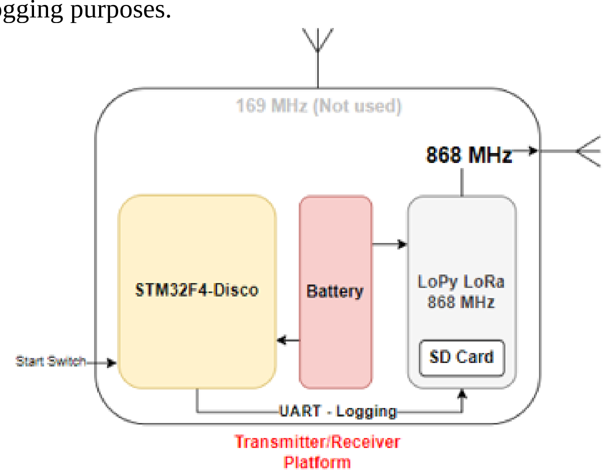


Figure 6. Underwater RF evaluation board diagram.

An SD Card is used for logging the communication packets statistics and network quality of service. As these evaluation setups are intended to be immersed underwater, two IP68 plastic containers [29] were used as system enclosures, and a silicon sealant material was used to seal the antenna connectors and control switches. Airtight plastic bags are also used to cover the enclosure and antenna to provide an extra level of water protection. Using a 70 micrometer airtight plastic bag adds an extra layer of plastic between the antenna and water, which is inevitable. However, based on the practical experiments by Donmez [30] on 1mm plastic material and another experiment demonstration at 10 GHz frequency on a range of plastic materials [31], the effect of a thin plastic layer can be considered to be negligible.

Initially, an urban environment communication range test in free space was performed to confirm that the modules were correctly configured. The non-line-of-sight urban communication test was carried out near *Tyndall National Institute* [32] in *Cork* [51.898736, -8.483184]. In these tests, the transmitter characterisation node was installed on the second floor of a four-level building in the urban area and received signal strength was recorded while increasing the distance of transmission.

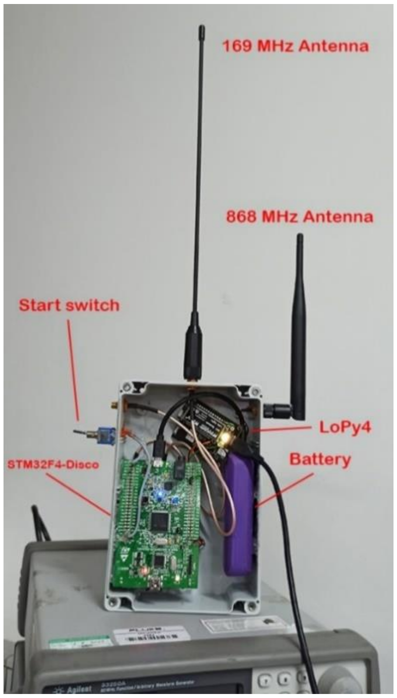


Figure 7. Underwater RF Evaluation platform.

In Figure 8, an aerial image of the test and average RSSI is shown. The red line shows the path taken with the transmitter board. The LoPy4 868 MHz receiver node managed to receive the transmitter signals up to 240 meters away from the starting point, with no line-of-sight, with the presence of dense and high buildings in between the transmitter and receiver and the transmitter located inside a four-level building. This indicates that the setup was working as expected, and there were no loose connections or deficiencies in the RF transceiver setup.

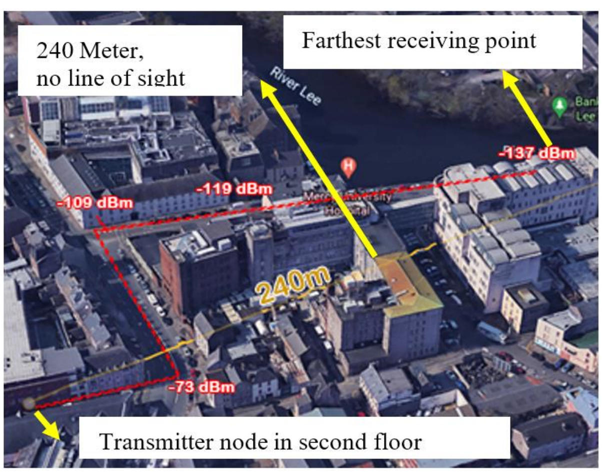


Figure 8. RF Evaluation platform air communication test.

After testing the EM waves communication in the air, River Lee in Cork [51.898757, -8.483163] was selected for performing the EM waves underwater communication test. First, the salinity of the water was measured using a salinity refractometer. “Refractometers measure the degree to which the light changes direction, called the angle of refraction. A refractometer takes the refraction angles and correlates them to refractive index (nD) values that have been established. Using these values, you can determine the concentrations of solutions” [33]. The salinity of the River Lee water was measured, and it was approximately 0%, which means that it is a freshwater river.

In the test scenario, the 868MHz transceivers were kept underwater while the receiver was recording the RSSI values. Then the distance between transmitter and receiver increased from 50cm to 120cm, as shown Figure 9. At 50cm, the average RSSI was -112 dBm, decreased to -120dBm at 100cm, however at 100cm, the percentage of packet drops increased significantly, and at approximately 120cm, the communications were significantly degraded, and the average RSSI of the limited received packets were -130dbm approximately.

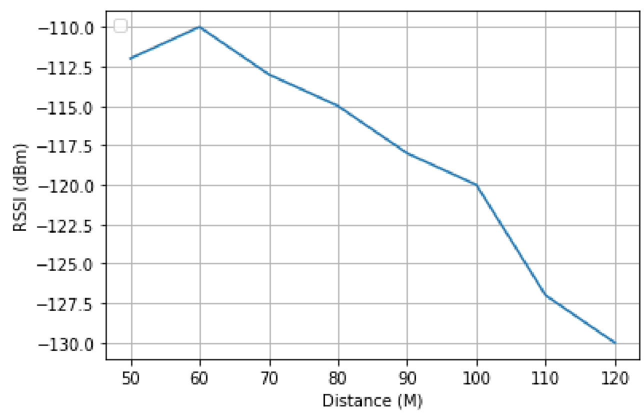


Figure 9. EM RSSI vs Distance Underwater at 868MHz.

The experiment proved that communication underwater using high-frequency, high-power radio frequencies is not an optimal solution even at a range of a few metres, as a consequence, starting from 100cm, the signals are seen to be significantly attenuated, and a stable communication link was not possible. The result is generally in line with the theoretical background, however, the signals got more attenuated possibly due to the transceivers antenna misalignment, refraction, and diffraction caused by the environmental factors in a non-ideal environment.

By validating the theoretical results for underwater electromagnetic communication, it is concluded that the solution for IMPAQT sites would be using acoustic communication rather than electromagnetic communication. In the next section, underwater acoustic communication is discussed, and the relevant telemetry platform is proposed.

B. Underwater acoustic communication

As in most Aquaculture sites, a long-range communications system is required to get data from the deployment site to the mainland, an ultrasonic underwater telemetry platform was developed as an alternative to the short-range EM transceiver system described in the previous section. In Figure 10, the proposed IMPAQT telemetry platform concept is shown, and this is described in the rest of this paper, and also the design method of the ultrasonic transmitter node is described. The goal of the transmitter is to transmit sensors data provided by an externally connected sensor to the gateway buoy using acoustic waves. The IMPAQT telemetry platform has been previously discussed in [34]. In comparison with the previous publication about the IMPAQT transmitter node design [34], in this publication, a simpler design with fewer components and smaller size is proposed. The on-board sensors were removed to lower the transmitter node cost, size and increase the battery life.

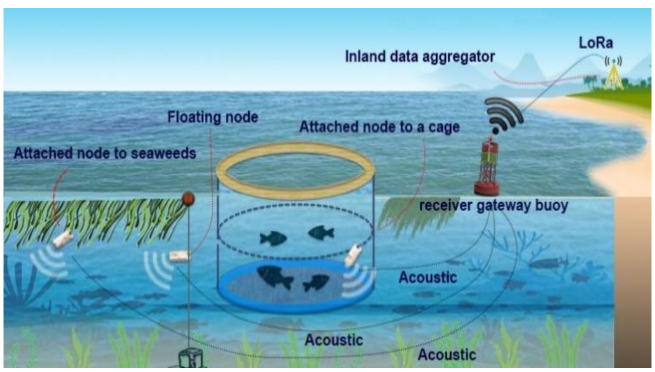


Figure 10. IMPAQT telemetry platform.

The transmitter node needs to be miniaturized to minimize its impact on the deployment environment, and the system block diagram design is shown in Figure 11.

The focus of this publication is on the detail associated with the ultrasonic transmitter design. It is anticipated that the complete transceiver platform (gateway and transmitter) and its deployment will be described in full in a follow on publication when the system as a whole is fully characterised.

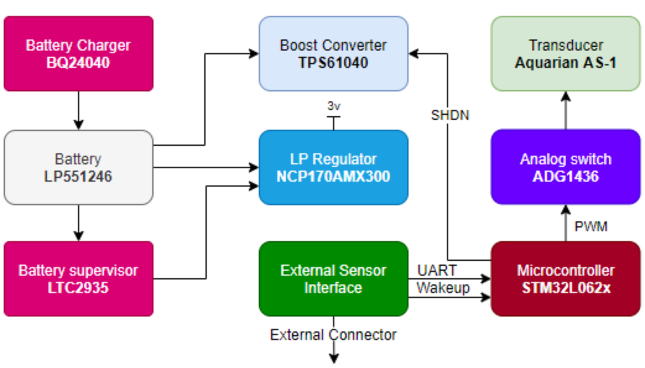


Figure 11. IMPAQT Ultrasonic Transmitter.

An ultrasonic transmitter, in the simplest form, generally consists of a transducer (usually piezoelectric) to produce acoustic waves, a transducer driver to apply the voltage and current to the transducer terminals, a controller to modulate the data, and a boost converter to step-up the battery voltage to provide adequate ultrasonic vibration wave amplitude level for the acoustic transmission. In the rest of this section, each of these elements is discussed for the IMPAQT transmitter node.

1) Transducer Element

Acoustic waves are the result of variations of pressure in a medium. The variation of pressure can be made by acoustic transducers. Piezoelectric materials are one the materials that are being used to convert electrical energy to mechanical displacement and vice versa. PZT (lead zirconate titanate (Pb[Zr(x)Ti(1-x)]O3)) materials are one of the widely used piezoelectric materials, and they have been used in different applications, in particular as fish tags [11][12][35]. In [36], four types of PZT materials' (Customized Type VI, Type VI, Type I, and Type II) energy consumption, source-level, and frequency response have been compared in operation. From the energy consumption aspect, PZT Type I and II consume the least amount of energy per transmission compared to other types, but they provide a lower source level and lower frequency response compared to others. However, in source level and frequency response, the difference between the four types is about 6dB, for short-range applications such as those in the IMPAQT project is not a primary factor.

As a result of the above comparison and also the availability of the commercial transducers, three commercial hydrophones have been short-listed, shown in Table I. From the provided list, for the receiver side, BII-7003 has been selected as it covers a wide range of frequencies, virtually enabling us to research various miniaturized transducers. It also has reasonable sensitivity and working depth.

TABLE I AVAILABLE COMMERCIAL HYDROPHONES

Manufacturer Part number	Frequency range	Receiver Sensitivity (dB re 1 V/μPa)	Working depth (m)	Type
BII-7003 [37]	1 Hz to 560 kHz	-211	400	Type I
AS-1 [38]	1 Hz to 100 kHz	-208	200	Type II
H3 [39]	10 Hz to 100 kHz	-192	80	Type II

For the transmitter, AS-1 from Aquarian scientific was selected since it has a wide frequency range of 1Hz to 100kHz, and it is compact in size with a good working depth appropriate for the IMPAQT application. It is encapsulated in a polyurethane material, and its dimension is 12mm D x 40mm L; it can operate up to 200m depth. It is important to note that AS-1 can act as a transmitter and also receiver. In transmitter mode, the transmitting sensitivity is 140dB SPL re 1μPa, 1 Vrms input at 1 meter, at 90kHz frequency [38].

2) Acoustic path loss and transducer driver

The pressure of the acoustic waves produced by a transducer has a direct relationship with the voltage applied to the transducer's terminal. To estimate the required driving voltage for the piezo transducer, to provide sufficient detection range in any application, it is necessary to understand underwater acoustic models and associated signal path loss. The ultrasonic wave emitted by the piezo transducers is attenuated by two main factors in an aquatic environment, spherical spreading loss and absorption loss [40]. The absorption loss coefficient (α) depends on two variables, viscous absorption [41], and chemical relaxation effect [42]. Viscous absorption is significant at high frequency (above 100 kHz). At the low-frequency range (up to a few kHz), boric acid chemical relaxation is the primary source of absorption and for intermediate range (up to few 100 kHz) magnesium sulphate is the main source of absorption [43]. In the IMPAQT Project, the ultrasonic frequency range will be used to communicate, and in the ultrasonic frequency range, viscous absorption and the magnesium sulphate relaxation effect is seen to be significant. The absorption loss coefficient (α) can be estimated by the following simplified equation [43] :

$$\alpha = 0.106\frac{f_1 f^2}{f^2 + f_1^2}e^{(pH-8)/0.56}$$
$$+0.52\left(1+\frac{T}{43}\right)\left(\frac{S}{35}\right)\frac{f_2 f^2}{f^2+f_2^2}e^{-z/6}$$
$$+0.00049f^2e^{-\left(\frac{T}{27}+\frac{Z}{17}\right)} \quad (2)$$

Where in the proposed design and operating environment, f=42KHz (Piezo resonance frequency), T = 8°C (water temperature), S = 35ppt (seawater salinity), pH = 8.1 (current ocean pH level [44]), z = 50m (estimated working depth), and relevant relaxation frequencies are:

$$f_1 = 0.78\left(\frac{S}{35}\right)^{\frac{1}{2}}e^{\frac{T}{26}} \quad \text{(for boron),} \quad (3)$$
$$f_2 = 42e^{\frac{T}{17}} \text{ (for magnesium) .} \quad (4)$$

Using (2) by substituting the parameters, an absorption loss of 12.3 dB per kilometer has been estimated for an infinitely narrow acoustic beam; however, in practice, beams spread as they propagate through the water, and as their area increase, they lose more power. If a transducer radiates waves equally in all directions, the waves will spread spherically from it. Thus, the transmission loss due to the spherical loss can be estimated using the following equation:

$$TL_1 = 20\text{logR} \quad (5)$$

Where TL_1 is the transmission loss due to the spherical loss, and R represents the distance from the source in metre. It is important to note that R is the horizontal distance in water rather than depth. Using the equation (2) and (5), the transmission loss (TL) at the distance of R can be estimated using equation (6) [40]:

$$TL = TL_1 + \alpha R \quad (6)$$

In the IMPAQT project, a maximum distance of 100m is considered between the transmitter and receiver nodes, which leads to an overall transmission loss of 41.2 dB at 100m. There is an online absorption loss calculator provided by *National Physical Laboratory of United Kingdom*, that can be useful to estimate the absorption loss coefficient [45]. The transmission loss as a function of distance for 42 KHz frequency (for the IMPAQT project) is shown in Figure 12.

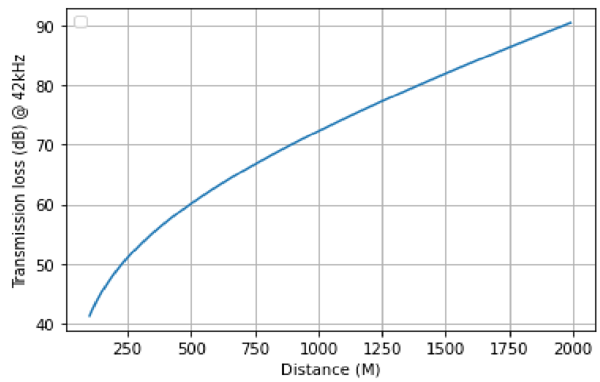


Figure 12. Acoustic transmission loss vs. Distance at 42kHz.

To provide an adequate ultrasonics level, a voltage booster circuit has been implemented using the TPS61040 controller, which can boost the 2.5-3.7v (LiPo cell voltage) up to 28v. In the proposed transmitter design, a voltage booster is configured to boost the voltage to 20v. Having a voltage over 25V requires capacitors in the voltage range of 50V, which are bulky and not suitable for a miniaturized system. Hence, it has been decided to use 20V as the driving voltage level. It is 5V less than the maximum voltage of the capacitors, but it provides a safe margin in case of a high-voltage ripple when driving the transducer. The average current of the piezo transducer can be estimated by (7) [46] :

$$I_{Avg} = \frac{2Q}{T} = 2CVf \quad (7)$$

Where Q = Charge in the piezoelectric transducer, T=Period of the driving signal, C= 5nF (Static capacitance), V = 20v (Maximum Driving voltage), F = 42KHz (Resonance frequency). Using the parameters of the selected hydrophone, the average current would be about 8.4mA while transmitting at the highest sound level. At F=100KHz, the average current of AS-1 transducer would 24.72mA. It is important to note that these current consumptions are from 20v (boosted voltage) supply. If needed, these values can be converted to the equivalent current drawn from the battery using the Electrical Power (P) equations [76] and booster efficiency value.

As the on-board microcontroller cannot handle the boosted voltage level and also cannot handle the required current directly, a driver is needed to supply the voltage and current to the ultrasonic transducer. The driver should be able to perform driving at the designated frequency (42KHz), and it needs to be low power and small size. Hence, an ADG1436 analog switch IC has been used to drive the piezo terminals at the boosted voltage using PWM modulation provided by the microcontroller. ADG1436 has a 4mm x 4mm footprint, with 125ns transition period; theoretically, it can reach up to 8MHz input frequency, which is significantly above 42kHz.

3) *Sensors and external interface*

In the previous publication regarding the first design of the tag, an accelerometer sensor (LIS3DH), and a pressure and temperature sensor (MS5837-30BA) were included in the IMPAQT transmitter tag design to monitor the aquaculture environment and tag's movement. In the latest version of the transmitter, these embedded sensors were considered surplus to requirements for the use case in question and that the transmitter would be used in conjunction with external environmental sensors. The external infrared sensor interface, TFBS4650, was also removed, as it required a specific external sensor design with infrared interface capabilities to be able to communicate with the tag. The infrared communications interface was replaced with a wired serial UART connector, which simplifies the integration of the tags with other commercial-off-the-shelf sensors. Removing the internal sensors and also the infrared interface not only reduced the transmitter's cost significantly but also improved the expected battery life. It also simplifies the transmitter's integration so that other researchers may be able to use it with few modifications in their own systems and sensors in the future.

In the latest version of the node, external sensors can trigger the IMPAQT transmitter node to wake up from sleep mode to read the external sensor's data using the wake-up pin fitted on the external connector. Also, there is an option to schedule a program for the node to wake up and read the external sensor data and transmit the collected data.

4) *Power consumption and battery management*

The transmitter tag runs on a 1200mAh LiPo battery with the Part number LP503562 [47]. There is a compact battery charger and a battery supervisor circuit on the board to charge and cut off the battery in the case of a full discharge. The transmitter consumes 10.5µA in the sleep mode, 62545µA in the transmitting logic-one, and 1290µA in transmitting logic-zero (refer to Table II, which is based on data available on individual product datasheets) and considering the 1200mA battery, based on user configuration and desired transmission cycle, the battery can last from two weeks to six months. The current consumption for the STM32 microcontroller is estimated using STM32CubeMX microcontroller power profile estimator.

TABLE II COMPONENTS POWER CONSUMPTION

Component	Sleep current (µA)	Max Supply Current (µA) when transmitting logic-one	Max Supply Current (uA)- when transmitting logic-zero
BQ24040	1	1	1
LTC2935	0.5	0.5	0.5
TPS6104	1	25	25
NCP170AMX300	0.5	0.9	0.9
ADG1436	1	170	170
STM32L062x	0.41	1150	1093
AS-1 [38] + 10m Cable	0	61200	0
Total	**4.41**	**62547.4**	**1290.4**

To maximize the battery life, the tag can be programmed via an external interface to wake up and read the sensor's data at regular intervals, while also an external sensor or module can force the tag to wake up using the wake-up pin.

IV. COMMUNICATIONS TEST RESULTS

The transceiver system prototype boards, shown in Figure 13, have been developed and evaluated in seawater, and 100 bits per second achieved using on-off-keying at 42KHz modulation frequency at the range of 92m.

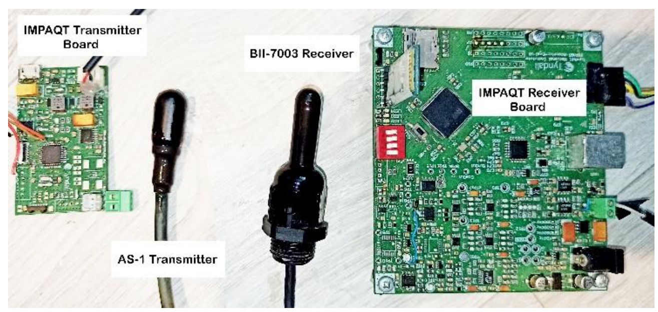


Figure 13. IMPAQT telemetry platform evaluation board.

Regarding the communication range test, the system was evaluated in the Cork Harbour Marina pier (51.845202, -8.332210), shown in Figure 14.

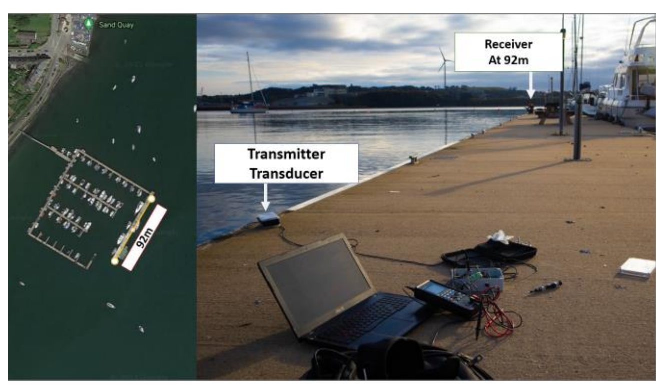


Figure 14. Range test in Cork Harbour Marina.

During the test, the signal to noise ratio (SNR) value has been recorded while increasing the distance between the transmitter and receiver up to the range of 92m. The same test was carried out at two different depths to study the effect of depth on the SNR value. The SNR values are shown in Figure 15, and it can be seen that by increasing the depth, the SNR improved. This was concluded to be as a result of noise affecting the signal from the water surface and terrestrial environment, and also less sound reflection from the water surface. The G percentage shows the receiver gain, which was adjusted based on the distance. The 100% gain in the receiver board is equivalent to 52dB, and 6% is 3.12 dB.

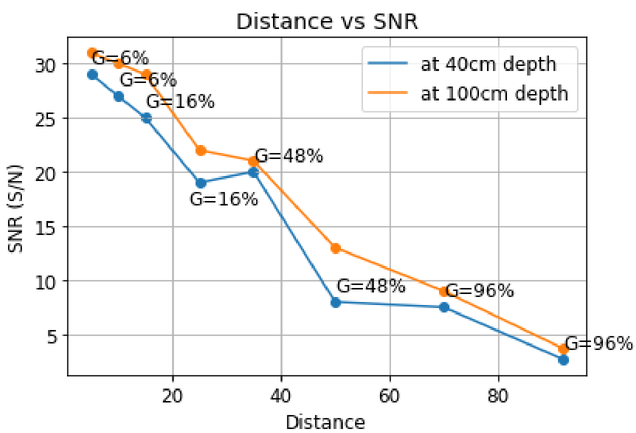


Figure 15. Distance vs Acoustic SNR in seawater.

In addition to the deployment tests in a real marine environment, a collection of analog datasets has been captured in a tank environment, which is accessible in a GitHub repository for further studies and analysis [48]. The dataset contains the captured signal by the receiver board where the transmitter was transmitting a fixed batch of data in on-off-keying modulation and binary-phase-shift-keying modulation. A sample captured dataset is shown in Figure 16, where (B) is the ground-truth data that transmitted, (A) is the binary-phase-shift modulation received on the receiver side, and (C) is the On-Off-Keying modulation received on the receiver side.

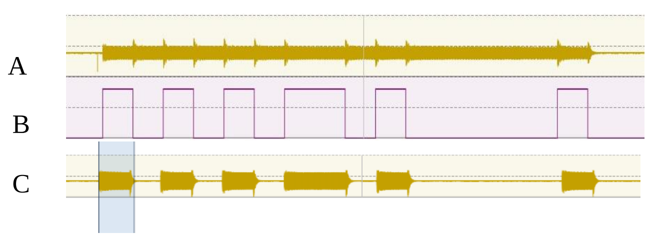


Figure 16. A sample dataset visualization in PulseView Software.

A) Captured BPSK signal B) Ground truth binary data

C) Received OOK signal

The datasets for each modulation are provided independently, and in the above figure, they merged for demonstration purposes only.

V. CONCLUSION AND FUTURE WORK

By evaluating electromagnetic communications underwater, it is concluded that it is not suitable for far-field communications other than for extremely short-range applications, as the communication got blocked at approximately 100cm range at 868MHz transmission frequency, using high-power LoRa modules. An alternative longer-range communications mechanism was investigated by evaluating the effective parameters in acoustic communication underwater, and finally, the IMPAQT next-generation ultrasonic transmitter has been proposed. This ultrasonic transmitter using an acoustic transmitter and a gateway buoy can help farmers and researchers to monitor and analyze the underwater environment wirelessly. It also enables the researchers to develop sensors and deploy them in the water without the need for a cable to be connected. The main novelty of this work is its size, the novel low-cost transmitter design, and that it is designed to be attachable to other sensors and modules with multiple sensor interface options.

In the future, more studies can be done on the optimization of the battery consumption, bitrate improvement, and a more miniaturized design. Also, there would be an opportunity to connect the tag to the sensors developed by other colleagues in the IMPAQT project to provide a better understanding of underwater environments.

Based on the components that have been selected, it is estimated that the final dimension of the tag would be less than 4 cm x 2 cm x 2 cm. This system will be tested in an aquatic environment alongside other sensors developed by the partners in the IMPAQT project and will report on in a subsequent publication.

This project is a work in progress, and it is considered to improve aquaculture sites monitoring as a part of the IMPAQT project, which is ongoing, and deployment in the marine environment are planned for the coming period.

ACKNOWLEDGMENTS

This work is part of IMPAQT project (https://impaqtproject.eu/) – and it has received funding from the European Union’s Horizon 2020 research and innovation programme under Grant Agreement No 774109. Aspects of this publication have been funded in part by a research grant from Science Foundation Ireland (SFI) - co-funded under the European Regional Development Fund under Grant Number 16/RC/3835 – VISTAMILK and 13/RC/2077 - CONNECT.

References

[1] H. Jafarzadeh, M. Belcastro, and B. O'Flynn, "IMPAQT Miniaturized Underwater Acoustic Telemetry Platform: Transmitter Node System Design," in *Proc. SENSORCOMM*, Nov. 2020, pp. 34–37. 2021.05.14. [Online]. Available: http://www.thinkmind.org/index.php?view=article&articleid=sensorcomm_2020_1_60_10031

[2] "World Population Prospects - Population Division - United Nations." https://population.un.org/wpp/Graphs/DemographicProfiles/Line/900 2020.09.16.

[3] "Seafood production: wild fish catch vs aquaculture," *Our World in Data*. https://ourworldindata.org/grapher/capture-fisheries-vs-aquaculture-farmed-fish-production 2020.09.16.

[4] "IMPAQT – Intelligent Management Systems for Integrated Multi-Trophic Aquaculture." https://impaqtproject.eu/ 2021.05.18.

[5] U. Acar *et al.*, *Designing An IoT Cloud Solution for Aquaculture*. 2019, p. 6. doi: 10.1109/GIOTS.2019.8766428.

[6] "OLCreate: PUB_4560_1.0 Integrated Multi-Trophic Aquaculture and Precision Aquaculture." https://www.open.edu/openlearncreate/course/view.php?id=7116 2021.08.08.

[7] K. Michalek, A. MacLeod, A. Ditchfield, and M. Stanley, *Towards an Intelligent Management System for Integrated Multi-Trophic Aquaculture*. 2019.

[8] E. Baras and J.-P. Lagardère, "Fish telemetry in aquaculture: review and perspectives," *Aquac. Int.*, vol. 3, no. 2, pp. 77–102, Jun. 1995, doi: 10.1007/BF00117876.

[9] M. Føre *et al.*, "Precision fish farming: A new framework to improve production in aquaculture," *Biosyst. Eng.*, vol. 173, pp. 176–193, Sep. 2018, doi: 10.1016/j.biosystemseng.2017.10.014.

[10] J. A. Martos-Sitcha *et al.*, "Ultra-Low Power Sensor Devices for Monitoring Physical Activity and Respiratory Frequency in Farmed Fish," *Front. Physiol.*, vol. 10, 2019, doi: 10.3389/fphys.2019.00667.

[11] P. R. de Almeida, T. J. Pereira, B. R. Quintella, A. Gronningsaeter, M. J. Costa, and J. L. Costa, "Testing a 3-axis accelerometer acoustic transmitter (AccelTag) on the Lusitanian toadfish," *J. Exp. Mar. Biol. Ecol.*, vol. 449, pp. 230–238, Nov. 2013, doi: 10.1016/j.jembe.2013.09.015.

[12] T. N. Pearsons, "The Juvenile Salmon acoustic telemtry system : a new tool," *Fisheries*, vol. 35, no. 1, pp. 23–31, Jan. 2010, doi: 10.1577/1548-8446-35.1.23.

[13] M. A. Weiland *et al.*, "A Cabled Acoustic Telemetry System for Detecting and Tracking Juvenile Salmon: Part 1. Engineering Design and Instrumentation," *Sensors*, vol. 11, no. 6, pp. 5645–5660, May 2011, doi: 10.3390/s110605645.

[14] J. Lu *et al.*, "A small long-life acoustic transmitter for studying the behavior of aquatic animals," *Rev. Sci. Instrum.*, vol. 87, no. 11, p. 114902, Nov. 2016, doi: 10.1063/1.4967941.

[15] C. Brockmann, V. Großer, J. Hefer, S. Guttowski, and H. Reichl, "Miniaturized Implantable Wireless Sensor System for Realtime Measurement of Well-Being of Fishes," in *2010 Fourth International Conference on Sensor Technologies and Applications*, Jul. 2010, pp. 453–457. doi: 10.1109/SENSORCOMM.2010.72.

[16] "CC1101 data sheet, product information and support | TI.com." https://www.ti.com/product/CC1101 2021.11.29.

[17] C. Peres, M. Emam, H. Jafarzadeh, M. Belcastro, and B. O'Flynn, "Development of a Low-Power Underwater NFC-Enabled Sensor Device for Seaweed Monitoring," *Sensors*, vol. 21, no. 14, Art. no. 14, Jan. 2021, doi: 10.3390/s21144649.

[18] "SeaSmart AS (EN)." https://www.seasmart.no/english.html 2020.10.19.

[19] "CageSense Wireless Sensors – Water Linked AS." https://waterlinked.com/cagesense/ 2021.07.09.

[20] C. C. Krueger *et al.*, "Acoustic telemetry observation systems: challenges encountered and overcome in the Laurentian Great Lakes," *Can. J. Fish. Aquat. Sci.*, vol. 75, no. 10, pp. 1755–1763, Dec. 2017, doi: 10.1139/cjfas-2017-0406.

[21] B.-C. Renner, J. Heitmann, and F. Steinmetz, "ahoi: Inexpensive, Low-power Communication and Localization for Underwater Sensor Networks and AUVs," *ACM Trans. Sens. Netw.*, vol. 16, no. 2, p. 18:1-18:46, Jan. 2020, doi: 10.1145/3376921.

[22] L. Freitag, M. Grund, S. Singh, J. Partan, P. Koski, and K. Ball, "The WHOI micro-modem: an acoustic communications and navigation system for multiple platforms," in *Proceedings of OCEANS 2005 MTS/IEEE*, Sep. 2005, pp. 1086-1092 Vol. 2. doi: 10.1109/OCEANS.2005.1639901.

[23] I. F. Akyildiz, D. Pompili, and T. Melodia, "Underwater acoustic sensor networks: research challenges," *Ad Hoc Netw.*, vol. 3, no. 3, pp. 257–279, May 2005, doi: 10.1016/j.adhoc.2005.01.004.

[24] L. B. Vkbr, "Underwater Radio Communication," *Amateur Radio*, pp. 1–8, 1987.

[25] G. Hattab, M. El-Tarhuni, M. Al-Ali, T. Joudeh, and N. Qaddoumi, "An Underwater Wireless Sensor Network with Realistic Radio Frequency Path Loss Model," *Int. J. Distrib. Sens. Netw.*, vol. 9, no. 3, p. 508708, Mar. 2013, doi: 10.1155/2013/508708.

[26] C. Peres *et al.*, "Theoretical models for underwater RFID and the impact of water salinity on the design of wireless systems," *Int. J. Adv. Netw. Serv.*, vol. 13, no. 34, pp. 45–59, Dec. 2020.

[27] "The LoPy4 is a quadruple bearer MicroPython enabled development board including LoRa, Sigfox, WiFi and Bluetooth," *Pycom*. https://pycom.io/product/lopy4/ 2021.08.25.

[28] "STM32F4DISCOVERY - Discovery kit with STM32F407VG MCU * New order code STM32F407G-DISC1 (replaces STM32F4DISCOVERY) - STMicroelectronics." https://www.st.com/en/evaluation-tools/stm32f4discovery.html 2021.08.25.

[29] "1554H2GYCL - Plastic Enclosure, Small, Polycarbonate, 61 mm, 119 mm, 180 mm, IP68." https://ie.farnell.com/hammond/1554h2gycl/small-enclosure-small-pc-grey/dp/2988671 2020.10.31.

[30] R. G. Donmez, "A STUDY ON PATH LOSS FOR INDOOR WIRELESS COMMUNICATION NETWORKS," p. 70.

[31] w8bya, *RF Attenuation of Common Plastics at 10 GHz*, (Jun. 28, 2020). 2021.11.03. [Online Video]. Available: https://www.youtube.com/watch?v=-olT_qjKwFw

[32] "Tyndall National Institute - Excellence in ICT Research." https://www.tyndall.ie/ 2021.08.25.

[33] "What is a Refractometer & How Does it Work - Cole-Parmer." https://www.coleparmer.com/tech-article/refractometers 2020.10.31.
[34] H. Jafarzadeh, M. Belcastro, and B. O'Flynn, "IMPAQT miniaturized underwater acoustic sensors network platform," vol. 2020, pp. A216-0010, Dec. 2020.
[35] R. B. Mitson and T. J. Storeton-west, "A transponding acoustic fish tag," *Radio Electron. Eng.*, vol. 41, no. 11, pp. 483–489, Nov. 1971, doi: 10.1049/ree.1971.0147.
[36] H. Li, Z. D. Deng, Y. Yuan, and T. J. Carlson, "Design Parameters of a Miniaturized Piezoelectric Underwater Acoustic Transmitter," *Sensors*, vol. 12, no. 7, Art. no. 7, Jul. 2012, doi: 10.3390/s120709098.
[37] "BII-7003Datasheet Technical document." 2020.11.01. [Online]. Available: https://www.benthowave.com/products/Specs/BII-7003Datasheet.pdf
[38] "AS-1 Hydrophone." https://www.aquarianaudio.com/as-1-hydrophone.html 2020.11.01.
[39] "H3 Technical document." 2020.11.01. [Online]. Available: https://www.aquarianaudio.com/AqAudDocs/H3_manual.pdf
[40] "4. FORMING THE ACOUSTIC EQUATIONS." http://www.fao.org/3/X5818E/x5818e05.htm 2020.09.24.
[41] "Calculation of absorption of sound in seawater - Underlying Physics." http://resource.npl.co.uk/acoustics/techguides/seaabsorption/physics.html 2021.11.12.
[42] "relaxation phenomenon | physics and chemistry | Britannica." https://www.britannica.com/science/relaxation-phenomenon 2021.11.12.
[43] M. A. Ainslie and J. G. McColm, "A simplified formula for viscous and chemical absorption in sea water," *J. Acoust. Soc. Am.*, vol. 103, no. 3, pp. 1671–1672, Mar. 1998, doi: 10.1121/1.421258.
[44] "Ocean Acidification | Smithsonian Ocean." http://ocean.si.edu/ocean-life/invertebrates/ocean-acidification 2020.09.25.
[45] "Calculation of absorption of sound in seawater." http://resource.npl.co.uk/acoustics/techguides/seaabsorption/ 2020.09.25.
[46] "Please tell me a current consumption by a Piezoelectric Sounder (External Drive Type). | Murata Manufacturing Co., Ltd." https://www.murata.com/en-us/support/faqs/products/sound/sounder/char/sch0003 2020.09.27.
[47] "503562 Battery document." 2021.10.28. [Online]. Available: https://cdn-shop.adafruit.com/datasheets/503562+1200mah.pdf
[48] HamedJafarzadeh, *HamedJafarzadeh/IMPAQT-Telemetery-Platform*. 2021. 2021.08.10. [Online]. Available: https://github.com/HamedJafarzadeh/IMPAQT-Telemetery-Platform