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Development of LoRaWAN-based Wireless Sensors for Monitoring Climate Changes in the Venice Lagoon

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MASTER THESIS IN ICT FOR INTERNET AND MULTIMEDIA

Development of LoRaWAN-based Wireless Sensors for Monitoring Climate Changes in the Venice Lagoon

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To my family
and my friends

Abstract

Coastal areas, particularly those exemplified by the Venice lagoon, are intricate ecosystems characterized by a multitude of channels and rivers that transport diverse sediments. These regions, serving as biodiversity hotspots within the European Natura 2000 protected areas, possess a unique allure, owing to the intricate network of waterways and sediments that define their landscapes. Nonetheless, their complex nature has long hindered comprehensive study. Real-time monitoring is essential to comprehend the impacts of climate change in these areas. This thesis aims to bridge the existing knowledge gap by introducing SENSWICH, a cost-effective, low-power, and real-time monitoring wireless sensing device. Collaborating with experts from the Chioggia Marine Hydrobiological Station at the University of Padova, the device incorporates a LoRaWAN node and a comprehensive suite of water quality sensors. SENSWICH's inaugural deployment at the station will facilitate the real-time transmission of data to an inland server, revolutionizing data collection in terms of both temporal and spatial coverage.

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List of Acronyms

ADCP Acoustic Doppler Current Profiler

CSS Chirp Spread Spectrum

DO Dissolved Oxygen

EC Electrical Conductivity

IoT Internet of Things

ISM Industrial, Scientific, and Medical

LPWAN Low-Power Wide Area Network

LoRaWAN Long Range Wide Area Network

MCU Microcontroller Unit

MPU Micro-Processing Unit

TSS Total Suspended Solids

TTN The Things Network

1

Introduction

In the introductory segment of this thesis, the primary aim is to immerse deeply into the foundational concept of Low-Power Wide Area Network (LPWAN), an integral communication protocol employed for the transmission of measurement data within a network. In the specific context of my research, this network is referred to as The Things Network (TTN). Subsequently, we shall embark upon an extensive overview of TTN, elucidating the specific configurations that have been meticulously tailored to meet the demands of my research endeavor. Following this, we will expound upon the underlying rationale that propels the pursuit of this ambitious project.

The discourse will venture into an expansive exploration of the profound and far-reaching consequences of climate change, with an acute and meticulous focus on the cataclysmic impact it exerts on coastal and littoral regions worldwide. These regions, in particular, find themselves acutely susceptible to the caprices of nature, experiencing phenomena such as seaquakes and floods in a manner that is both immediate and unrelenting. Furthermore, the specter of global warming looms ominously, threatening to orchestrate dramatic alterations in the biodiversity of rivers, seas, and lakes, encompassing areas of immense ecological significance, as outlined by the European Commission in the Natura 2000 protected areas [12]. Additionally, pollution, an equally perilous agent, exacerbates the already precarious state of these fragile ecosystems. Addressing these multifaceted challenges necessitates an unwavering commitment to large-scale, long-term action. Initiatives such as the European Biodiversity Strategy for 2030 and the United Nations Decade of Ocean Science for Sustainable Development

(2021-2030) embody this commitment, striving to safeguard nature, reverse the degradation of ecosystems, and bolster international cooperation in the pursuit of scientific research and innovative technologies that can bridge the gap between ocean science and societal needs.

In this context, it is of paramount importance to recognize that the deployment of cutting-edge solutions, such as smart sensors, holds the key to effectively monitoring aquatic environmental parameters. These sensors constitute indispensable tools in the prediction, management, and mitigation of the adverse effects wrought by climate change on coastal areas. Yet, the very nature of coastal ecosystems, characterized by their spatial heterogeneity and temporal variability across short (daily), medium (seasonal), and long (interannual) timescales, presents a formidable challenge in the quest to establish reliable and cost-effective monitoring systems.

One of the intriguing aspects we took into account while working on the project revolved around an exceptionally distinctive and demanding ecosystem: the Venice Lagoon in Italy. This brackish, shallow body of water is punctuated by numerous salt marshes and is subject to an intense tidal cycle, rendering it a particularly challenging environment for researchers. Unlike the open sea, where environmental changes follow more predictable patterns, the Venice Lagoon's dynamic nature makes quantitative analysis of water parameters an intricate undertaking. Presently, measurements within this complex ecosystem rely on periodic sampling campaigns that necessitate the deployment of boats and dedicated personnel to retrieve water samples from specific hotspot areas. This method has two significant drawbacks: it incurs substantial costs in terms of resources, including equipment, fuel, and boat maintenance, and it yields data with limited granularity in both spatial and temporal dimensions. Data can be collected only a few times per day at very few locations, resulting in a patchy and incomplete understanding of the environment.

The proposed solution to address these limitations involves the implementation of a low-cost, densely distributed wireless sensor network. This innovative approach promises to furnish researchers with data that exhibit much finer granularity, both spatially and temporally. As a result, it allows for a more comprehensive and nuanced characterization of the observed environment, a critical requirement in the pursuit of meaningful insights into the intricate dynamics of the Venice Lagoon.

It is worth noting that the selection and design of the sensors that constitute the backbone of this network have been carried out in close collaboration with the experts at the Chioggia Marine Hydrobiological Station of the University of Padova, Italy, in conjunction with the Italian National Center for Biodiversity [20]. Given the diverse nature of data required for this study, three distinct types of nodes have been envisioned for the final deployment specifically as follows.

- Underwater nodes: these nodes are equipped with acoustic modems and are tasked with sampling the water sediments.
- Surface nodes: equipped with radio devices, these nodes are responsible for measuring water quality parameters.
- Gateway buoys: these nodes are equipped with both acoustic and radio frequency modems. They serve as pivotal components in the network, forwarding the data collected from submerged nodes to the shore for further analysis and interpretation.

To provide a summary of what this thesis will cover, in Section 2, we will explore how LoRaWAN and TTN are used as techniques to transmit data and monitor it in real-time. Section 3 delves into the unique environmental circumstances of the Venice Lagoon, where we intend to implement the SENSWICH device. Additionally, we will see how climate change will impact our research. Section 4 explores existing literature and research relevant to our field. Section 5 offers an extensive examination of the sensor node architecture and deployment strategies. Section 6 provides a comprehensive account of the experimental setup, including the development of the SENSWICH device, created at the SIGNET lab at the University of Padova. This device, named SENSWICH due to its resemblance to a sandwich, will be used for real-time water quality measurement in coastal areas. Section 7 elucidates the preliminary tests that have been conducted. In Chapter 8, we will discuss a significant conference in this field, which took place recently. I took part in this event in October 2023, supporting my professors and the University of Padova for this project. Finally, in Section 9, we present concluding remarks that summarize the significance of our research in the broader context of mitigating the adverse effects of climate change on coastal areas.

2

From Sensor to Screen: Enabling Real-Time Information Transfer and Visualization

2.1 A Brief Overview of LoRaWAN Technology

The vision of the Internet of Things (IoT) necessitates an ever-growing number of interconnected sensor nodes and a network solution capable of accommodating these requirements effectively. Within wireless sensor networks, there exist devices with limited energy resources, making energy-saving techniques a significant area of research. Additionally, considerations such as latency, coverage range, and bandwidth are crucial aspects in the context of IoT, particularly when dealing with the massive number of expected nodes connected to the Internet.

In response to these challenges, the LPWAN has emerged as a promising solution. It operates at the data-link layer, offering long-range connectivity, low power consumption, and a low bit rate. In this framework, end devices utilize LoRa technology to communicate with gateways directly, without the need for intermediate hops [23].

2.1.1 LPWAN

LPWAN networks represent the evolution of wireless sensor networks tailored for the IoT concept, which involves linking sensors to the Internet. In contrast to traditional data networks, LPWAN networks prioritize characteristics like scalability, extended communication range, cost-effectiveness, and energy efficiency [26]. As per Cisco's findings [4], there are already roughly 20 billion interconnected devices, with estimates for 2020 exceeding 50 billion connected devices. However, only a small fraction of these devices currently utilize LPWAN networks, as many are connected through Wi-Fi and Bluetooth. The potential of LPWAN networks remains substantial.

Currently, there exist numerous low-power wireless communication protocols, which can be categorized based on their communication range as follows.

- Low-power wireless networks with a range of less than 1000 meters. This category encompasses protocols like IEEE 802.15.4, ZigBee, Z-Wave, Bluetooth, etc., facilitating extensive coverage through mesh communication network topologies.
- Low-power wireless networks with a communication radius exceeding 1,000 meters, resembling the architecture of cellular networks utilizing a star-type network topology. Protocols within this category include LoRaWAN, Sigfox, and DASH7.

2.1.2 What is LoRaWAN?

Starting from 2015, the LoRa Alliance has established Long Range Wide Area Network (LoRaWAN), a communication protocol that relies on LoRa, a patented spread spectrum technology operating within the unlicensed sub-GHZ band [17]. LoRa's Chirp Spread Spectrum (CSS) modulations ensure robust bidirectional communication, producing a low-noise signal that is highly resilient to interference and challenging to detect or disrupt [21]. In the realm of LoRaWAN, every message transmitted by an end device is picked up by all base stations operating within range, enhancing communication reliability. Nonetheless, this redundancy necessitates the deployment of numerous base stations within each region, consequently driving up network infrastructure expenses. The backend system manages this redundancy by verifying security, sending acknowledgments to the end device, forwarding the message to the respective application servers, and filtering out duplicate receptions.

LoRaWAN wireless sensor networks prioritize energy efficiency, particularly because most nodes rely on battery power. The longevity of a wireless node must span multiple years since replacing batteries is often impractical. Figure 2.1 illustrates the LoRaWAN communication stack, highlighting the patented LoRa modulation technique by Semtech. The LoRa Alliance has established the LoRaWAN communication protocol specifications built upon LoRa modulation, situated at the physical level.

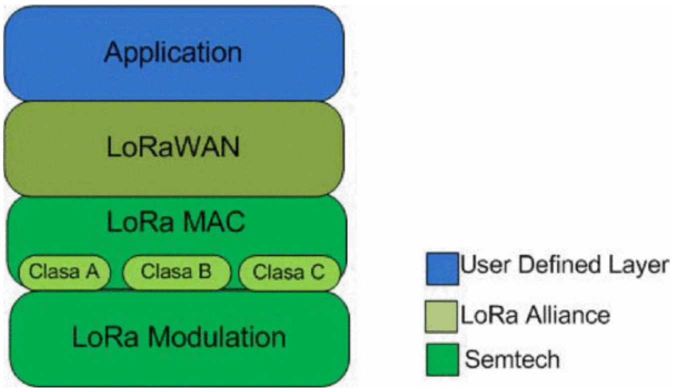


Figure 2.1: LoRaWAN communication stack, taken from [16].

LoRa technology emerges as a viable solution to various IoT challenges. It operates within the unlicensed Industrial, Scientific, and Medical (ISM) frequency band, employing a star network topology. Consequently, each node can directly communicate with the Gateway module, offering a communication range extending over kilometers. To achieve this extended range, data rates are compromised, while operating within a frequency bandwidth below 1 GHz (e.g., 868 MHz for the European region) [16].

LoRaWAN technology provides three distinct classes to accommodate a wide range of IoT applications, each with its strengths and trade-offs. The choice of class depends on your specific requirements, whether it is long battery life, reduced latency, or a balance between the two. We have three classes: Class A, Class B, and Class C [3] (Figure 2.2):

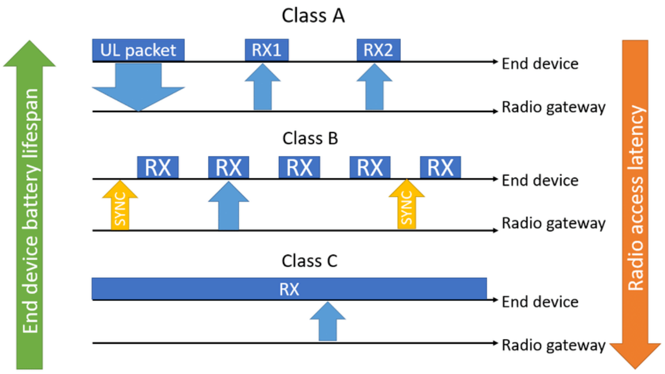


Figure 2.2: LoRaWAN classes, taken from [3].

- class A is the most economical of the three LoRaWAN classes. Devices belonging to this class are designed to operate on minimal power consumption, allowing their batteries to last for several years. The secret behind this impressive power efficiency lies in their operating mode. In Class A, the device is active for a short time, specifically during the transmission of its data on a programmed schedule. Furthermore, after each transmission, it remains active for a brief additional period to enable network communication with the device. The rest of the time, the device remains in a power-saving sleep mode. Class A employs an Aloha-type communication design, enabling unscheduled communication initiated solely by the end device. It features two short receive windows, Rx1 and Rx2, which follow the uplink transmission. These receive windows allow the network to send downlink messages to the device, making it an ideal choice for applications that require quick communication after the uplink transmissions have been completed.

- Class B is a step up from Class A, offering enhanced communication capabilities and reduced latency. One of its significant improvements over Class A is the ability to schedule downlink transmission windows during designated downlink ping slots. This functionality allows applications to send control messages without waiting for an outbound message from the device. To make use of Class B, devices must first achieve timing synchronization with the network. Once synchronized, they can receive downlink messages from the gateway during their designated slots. This synchronization and proactive approach significantly reduce latency, making Class B an excellent choice for applications that require real-time or near-real-time communication. Class B provides a more power-efficient solution compared to Class C, as it doesn't require the receiver to be powered continuously. The device enters receive mode during its ping slots, ensuring it can receive any downlink communications from the network promptly.

- Class C, the third LoRaWAN class, offers a unique approach to communication. End devices operating in Class C mode typically keep their receive windows open most of the time, only closing them when actively transmitting data. This continuous open state makes Class C devices consume more power compared to Class A or Class B devices. However, in return,

> Class C devices provide the quickest response time for communication from the server to the end device. A device can temporarily switch to Class C mode, often done to carry out a firmware upgrade for a battery-powered device. For example, a battery-powered Class A device might switch to Class C for a brief period to receive a firmware update via an over-the-air broadcast. Once the update is successfully received, the device can revert to its default low-power Class A mode of operation. Class C end devices have the same two receive windows as Class A devices, but they maintain the RX2 window open until they send their next transmission to the server. This means they can receive downlink data in the RX2 window at almost any time. Additionally, a short window at the RX2 frequency and data rate is available between the end of a transmission and the start of the RX1 receive window.

In our situation, we utilized class A and implemented the corresponding setup on both the Arduino MKRWAN 1310 and TTN.

2.1.3 Integration of LoRaWAN Communication in Our Project

To begin, it is essential to understand the functioning of LoRaWAN communication. As illustrated in Figure 2.3, LoRaWAN operates by transmitting data packets using a shared radio frequency, facilitating communication among devices. This communication relies on a network of gateways that serve as data collectors, permitting LoRaWAN devices to send and receive data via the radio frequency. In our project, we used MultiTech MTCDTIP-266A-868 gateway which has also IP67 standard and it optimized for outdoor usage (Figure 2.4). These gateways are linked to the internet, which enables the transfer of device data to a LoRaWAN server for subsequent access by end-users. In our case, we used TTN as we mentioned before to see the real-time result [23].

Data packets are transferred utilizing the LoRa modulation technique, allowing data transmission across a wide range of frequencies and distances. This capability empowers low-power, long-range communication with minimal latency.

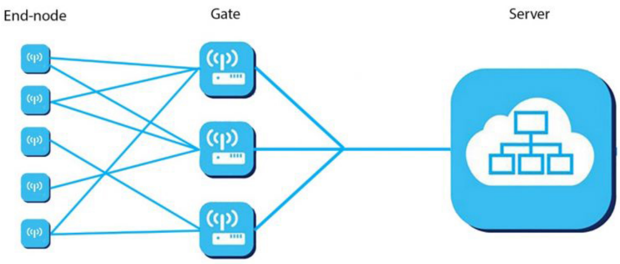


Figure 2.3: LoRaWAN simple communications structure, taken from [23].

Figure 2.4: MultiTech MTCDTIP-266A-868 gateway.

a LoRaWAN Gateway, exemplified by the MultiTech MTCDTIP-266A-868 Gateway in our context, serves as a device employed for extending LoRaWAN coverage, akin to a cellular network. Its primary function is to facilitate communication between LoRaWAN devices and their respective server and application owners. In essence, it functions as the intermediary between the physical world and the virtual realm. The gateway receives data from LoRaWAN devices and subsequently relays it to the network server, which not only stores the data but also disseminates it as per the specific application requirements. Furthermore, these gateways are equipped to support bidirectional communication, allowing cloud-based applications to interact with physical devices.

LoRaWAN sensors, as exemplified by the Arduino MKRWAN 1310 in our case, are devices that utilize the LoRaWAN protocol to facilitate the exchange of data with a gateway and its associated network server. These sensors find application in the Internet of Things (IoT) domain for purposes like asset tracking, environmental condition monitoring, and remote data collection. Notably, these sensors are designed to be power-efficient and possess long-range communication capabilities. Additionally, they offer the advantage of adaptive data rate control, enabling flexible configuration to support efficient data transmission over both long and short distances [23].

2.2 The Things Network (TTN)

TTN is a global collaborative Internet of Things ecosystem that creates networks, devices and solutions using LoRaWAN. The Things Network runs The Things Stack Community Edition, which is a crowdsourced, open, and decentralized LoRaWAN® network. This network is a great way to get started testing devices, applications, and integrations, and get familiar with LoRaWAN [25].

2.2.1 Clusters

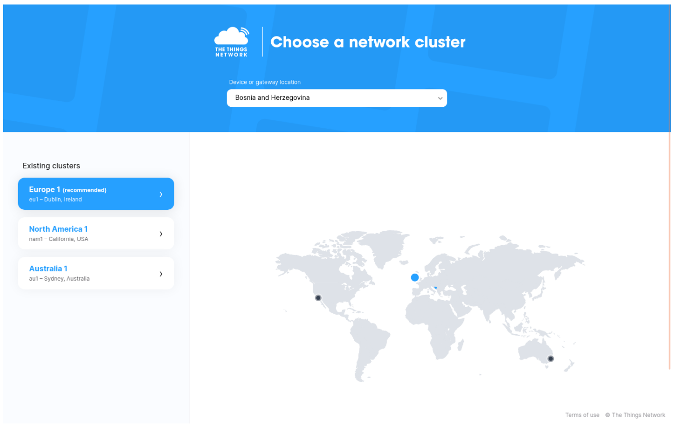
The Things Stack Community Edition (run by TTN) is a multi-cluster deployment. This means that while your account information is stored in a central location, you can connect your gateways to a closer cluster, and route all your IoT traffic in that cluster. This can significantly reduce latency because your traffic would not have to cross half the planet.

Table 2.1 provides information about the current clusters available in The Things Stack Community Edition [25].

Table 2.1: The Things Stack Community Edition Clusters

Cluster ID	Name	Location
au1	Australia 1	Sydney, Australia
eu1	Europe 1	Ireland
nam1	North America 1	California, USA

In this project, we opted for the European cluster as our primary choice, aligning as our goal is optimize all our efforts for the Venice lagoon (Figure 2.5).



Device or gateway location: Bosnia and Herzegovina

Figure 2.5: TTN EU1 cluster.

2.3 Arduino IDE

In our project, we harnessed the dynamic Arduino IDE environment. Arduino's Integrated Development Environment, also known as Arduino Software (IDE), boasts an array of essential components: a robust code editor, a dynamic message hub, a versatile text console, a user-friendly toolbar equipped with an array of functions, and an intuitive menu system. This multifaceted IDE seamlessly interfaces with Arduino hardware to facilitate program uploads and real-time communication. For a glimpse into this environment, refer to Figure 2.6.

AnalogReadSerial | Arduino IDE 2.0.0-rc9

Arduino MKR WiFi 1010

```
/*
  AnalogReadSerial

  Reads an analog input on pin 0, prints the result to the Serial Monitor.
  Graphical representation is available using Serial Plotter (Tools > Serial Plotter menu).
                    in of a potentiometer to pin A0, and the outside pins to +5V and ground.

  This example code is in the public domain.

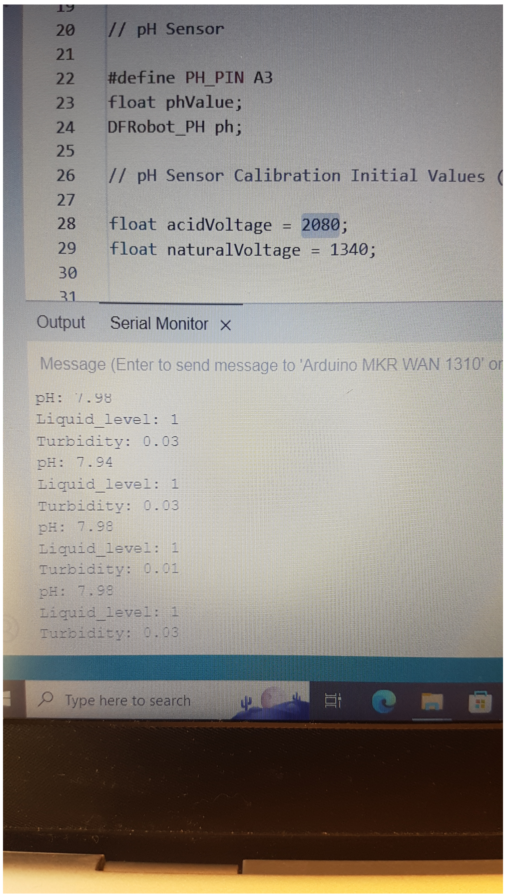
  https://www.arduino.cc/en/Tutorial/BuiltInExamples/AnalogReadSerial
*/

// the setup routine runs once when you press reset:
void setup() {
  // initialize serial communication at 9600 bits per second:
  Serial.begin(9600);
}

// the loop routine runs over and over again forever:
void loop() {
  // read the input on analog pin 0:
  int sensorValue = analogRead(A0);
  // print out the value you read:
  Serial.println(sensorValue);
```

Figure 2.6: Arduino IDE environment. Source: Arduino website (`https://www.arduino.cc`).

Our project was fueled by the potent C++ programming language. While navigating the Arduino IDE, you'll discover a dedicated *serial monitor* section, enabling real-time result monitoring as Arduino establishes a connection with our PC via a serial port (see Figure 2.7).



```
// pH Sensor

#define PH_PIN A3
float phValue;
DFRobot_PH ph;

// pH Sensor Calibration Initial Values (

float acidVoltage = 2080;
float naturalVoltage = 1340;
```

```
pH: 7.98
Liquid_level: 1
Turbidity: 0.03
pH: 7.94
Liquid_level: 1
Turbidity: 0.03
pH: 7.98
Liquid_level: 1
Turbidity: 0.01
pH: 7.98
Liquid_level: 1
Turbidity: 0.03
```

Figure 2.7: Exemplary serial monitor section.

3

Climate Situation in Coastal Areas, with a Special Focus on Venice Lagoon

3.1 UNDERSTANDING THE IMPACT OF CLIMATE CHANGE ON COASTAL AND LITTORAL AREAS

In today’s rapidly changing world, one of the most pressing issues we face is climate change. The consequences of global warming are felt across the globe, but nowhere is it more evident than in coastal and littoral areas. These regions are not only vulnerable to rising sea levels but also to the increasing frequency of seaquakes and floods. Furthermore, the intricate ecosystems of rivers, seas, and lakes, including vital biodiversity hotspots like the Natura 2000 protected areas [12], are facing dramatic changes due to the effects of climate change and pollutants. In this thesis, we will delve into the significant impact of climate change on coastal and littoral areas and explore the initiatives being undertaken to protect and preserve these vital ecosystems.

3.1.1 THE VULNERABILITY OF COASTAL AND LITTORAL AREAS

One of the most immediate and visible consequences of climate change in coastal areas is the rise in sea levels. As global temperatures continue to increase, polar ice caps melt, causing oceans to expand. This expansion, combined with the melting of glaciers and ice sheets, leads to higher sea levels. Coastal communities worldwide are experiencing the encroachment of seawater into their territories, resulting in coastal erosion, loss of land, and displacement of populations.

Climate change has also been linked to an increase in the frequency and intensity of seaquakes and floods. The warming of ocean waters can contribute to the instability of tectonic plates, potentially triggering seaquakes. Additionally, the higher temperatures can lead to more intense rainfall events, which, coupled with rising sea levels, can result in catastrophic flooding in coastal regions.

3.1.2 Impact on Biodiversity

Natura 2000 is a network of protected areas in Europe designed to conserve biodiversity [20]. These areas encompass a wide range of ecosystems, including coastal habitats. However, the changing climate poses a significant threat to the biodiversity within these protected zones. Rising sea levels can disrupt the delicate balance of these ecosystems, endangering numerous species of plants and animals.

The impact of climate change is compounded by pollution. Pollutants from human activities, such as industrial runoff and agricultural chemicals, find their way into rivers and oceans. These pollutants harm aquatic life and further stress the delicate ecosystems of coastal and littoral areas.

3.1.3 Long-Term Action and Strategies

Recognizing the severity of the situation, the European Union has launched the European Biodiversity Strategy for 2030. This ambitious initiative aims to protect nature and reverse the degradation of ecosystems. It seeks to restore damaged ecosystems, make biodiversity a priority across all policy areas, and address the main drivers of biodiversity loss, including climate change.

On a global scale, the United Nations has declared the Decade of Ocean Science for Sustainable Development (2021-2030). This initiative aims to strengthen international cooperation to develop scientific research and innovative technologies that bridge the gap between ocean science and societal needs. It is an essential step toward understanding and addressing the challenges faced by coastal and littoral areas.

3.1.4 Innovative Solutions for Monitoring

Given the complexity and variability of coastal systems, monitoring them effectively is a challenging task. However, innovative solutions are emerging. Smart sensors are being deployed to monitor various environmental parameters in aquatic ecosystems. These sensors provide real-time data that can be used to predict, manage, and mitigate the effects of climate change and pollution.

3.2 Exploring the Potential of Wireless Sensor Networks in Venice Lagoon Research

The Venice lagoon in Italy is a unique and challenging ecosystem that has captured the attention of researchers for many years. This brackish, shallow body of water, which you can see in Figure 3.1,is dotted with salt marshes and experiences a significant tidal cycle. However, studying the water parameters in this environment is no easy task. In this thesis, we will delve into the specific case of the Venice lagoon and explore how the deployment of a low-cost dense wireless sensor network can revolutionize research in this remarkable area.

Figure 3.1: Lagoon of Venice, NASA, Aug 7, 2017.

3.2.1 The Complexity of Venice Lagoon

The Venice lagoon is an important ecosystem characterized by its brackish waters and intricate network of salt marshes. This distinct environment presents significant challenges for researchers, as it differs from the relatively stable conditions found in the open sea, making the quantitative analysis of water parameters complex.

One of the key characteristics of the Venice lagoon is its intense tidal cycle. The constant ebb and flow of tides impact water salinity, temperature, and other critical parameters. Understanding these fluctuations is essential for comprehending the lagoon's ecology, but it requires continuous monitoring at various locations.

3.2.2 The Current Research Method

At present, researchers rely on periodic sampling campaigns to collect data from the Venice lagoon. These campaigns involve sending boats and personnel to hotspot areas to retrieve water samples. While this method provides valuable information, it has notable drawbacks.

The drawbacks of this methodology can be depicted as follows:

Firstly, periodic sampling campaigns are expensive. They require significant resources for equipment, fuel, and boat maintenance. Moreover, a considerable amount of human power is dedicated to these campaigns, which could be used for more analytical work.

Secondly, the data collected through periodic sampling campaigns is sparse. Samples can only be taken a few times per day and at very few locations within the lagoon. This limited granularity in both time and space makes it challenging to capture the true dynamics of this unique ecosystem.

3.2.3 The Promise of Wireless Sensor Networks

The deployment of a low-cost dense wireless sensor network holds the promise of revolutionizing research in the Venice lagoon. By strategically placing sensors throughout the lagoon, researchers can collect data with a much finer granularity.

Wireless sensor networks provide real-time data, enabling researchers to monitor changes in water parameters as they occur. This feature allows for a more immediate response to significant events or variations in the lagoon's conditions.

Compared to traditional sampling campaigns, wireless sensor networks are a cost-efficient solution. They reduce the need for frequent boat trips and minimize human labor, ultimately saving both time and money.

3.3 Exploring Underwater Sensors: Innovations in Marine Science

In recent years, advancements in marine science and biology have been greatly facilitated by the development and analysis of cutting-edge underwater sensors. These devices, designed to measure various characteristics of the marine environment, have opened up new frontiers of knowledge for researchers and scientists. In this section, we will delve into the world of underwater sensors, their types, applications, and the pivotal role they play in advancing our understanding of marine ecosystems.

The sensors of interest for biologists and marine scientists have been analyzed with the help of the staff of the Chioggia Marine Hydrobiological Station of the University of Padova, Italy, in synergy with the Italian National Center for Biodiversity [20]. Due to the fact that some of these sensors need to measure the characteristics of the water close to the surface, while some other sensors take measurements of the sea sediments, three different types of nodes are envisioned in the final deployment: (i) underwater nodes, equipped with an acoustic modem, that sample the water sediments; (ii) surface nodes, equipped with radio devices, that measure the water quality; and (iii) gateway buoys, equipped with both acoustic and radio frequency modems, that forward the data collected from submerged nodes to shore.

In this project, we first present the architecture and the preliminary tests on the surface node, which integrates a complete set of sensors, and exploits the Long Range (LoRa) modulation and the associated LoRa Wide Area Network (LoRaWAN) protocol stack for data transmission.

3.3.1 Related Works in Underwater Sensor Technology

Underwater sensor technology has made significant strides in recent years. Researchers have been tirelessly working on enhancing the accuracy, reliability, and versatility of these sensors. Innovations such as miniaturization and improved data transmission methods have paved the way for groundbreaking discoveries.

One of the key innovations in underwater sensor technology is the use of acoustic modems in underwater nodes. These modems enable the sensors to communicate effectively even in the challenging underwater environment. The ability to sample water sediments at varying depths has revolutionized our understanding of marine ecosystems.

3.3.2 The Architecture of Sensor Nodes

Architecture Overview: To comprehend the significance of underwater sensors, it is essential to understand their architecture. These sensor nodes are designed with precision to withstand the harsh conditions of the ocean. They are equipped with a range of sensors that measure parameters such as temperature, salinity, and pressure.

The deployment of sensor nodes is a critical aspect of marine research. These nodes are strategically placed to collect data from specific areas of interest. The careful deployment ensures that researchers obtain accurate and comprehensive data about the marine environment.

3.3.3 Setting Up the Experiments

Before underwater sensors can be used in research, rigorous experimentation and testing are necessary. Scientists meticulously set up experiments to validate the performance and reliability of these sensors. This phase of research is essential to ensure the accuracy of the data collected.

3.3.4 Preliminary Tests and Results

In chapter 7, we delve into the preliminary tests conducted on underwater sensors. These tests are crucial to assess the functionality and reliability of the sensors. Researchers scrutinize the data collected during these tests to fine-tune the sensors for future use.

4

Related Works

4.1 MARINE ECOSYSTEM STUDIES WITH SMART SENSOR BUOYS

The study of the marine ecosystem with smart sensor buoys has a rich history dating back several decades. Originally designed for meteorological observations, these buoys have evolved to become indispensable tools for understanding currents and various water parameters. In recent years, the deployment of large-scale ocean observatory systems in critical areas has revolutionized marine research. This thesis delves into the fascinating world of smart sensor buoys, their technology, and their vital role in advancing our knowledge of the underwater realm.

4.1.1 THE EARLY DAYS OF MARINE EXPLORATION

Smart sensor buoys, as we know them today, owe their existence to early meteorological studies [13]. These buoys were initially designed to collect data on atmospheric conditions at sea, providing valuable insights into weather patterns and climate. In the early stages of marine exploration, scientists and researchers recognized the need for reliable data from the open sea. This realization led to the development of smart sensor buoys with a primary focus on meteorology. These early buoys were equipped with sensors to measure various atmospheric parameters, including air pressure, temperature, humidity, and wind speed. The data collected from these buoys helped meteorologists better understand oceanic weather systems, improve weather forecasting accuracy, and enhance our overall knowledge of climate patterns.

4.1.2 Venturing Deeper: Currents and Beyond

As technology advanced, so did the capabilities of smart sensor buoys. Researchers soon realized that these buoys could be used to study ocean currents [19]. This marked a significant shift in their applications, as they ventured beyond meteorology. Ocean currents play a critical role in shaping our planet's climate, distributing heat around the globe, and influencing weather patterns. Understanding these currents became crucial for a wide range of applications, from maritime navigation to climate change research. Smart sensor buoys were adapted to measure the speed, direction, and depth of ocean currents accurately. This data helped scientists create detailed current maps, contributing to safer navigation for ships and a deeper understanding of how currents affect marine ecosystems.

4.1.3 The Modern Ocean Observatory

Today, ocean observatories are awe-inspiring feats of engineering [11]. These observatories consist of mooring systems strategically deployed offshore, equipped with cutting-edge technology and sensor arrays capable of measuring water parameters at incredible depths. The modern ocean observatory represents the pinnacle of marine research technology. These observatories are strategically positioned in critical areas of the world's oceans, allowing scientists to gather data in previously inaccessible locations. The observatories are composed of mooring systems that anchor the smart sensor buoys in place. These buoys are equipped with state-of-the-art sensors, including Conductivity, Temperature, and Depth probes, Acoustic Doppler Current Profiler (ADCP), fluorometers, and meteorological sensors.

These sensors work together to collect an extensive range of data. Conductivity, Temperature, and Depth probes, for example, measure the physical properties of seawater at different depths, providing valuable information about salinity, temperature, and pressure. ADCPs use sound waves to measure ocean currents with remarkable precision. Fluorometers detect the presence of chlorophyll, helping scientists monitor phytoplankton populations and assess the health of marine ecosystems. To ensure uninterrupted data collection, these buoys are equipped with solar panels and large batteries with energy capacities that can exceed 30 MJ. This power supply is crucial for running the onboard industrial-rated PCs and supporting high-power, long-range radio and satellite communication systems [11]. Maintaining the continuous operation of smart sensor buoys in remote ocean locations is a logistical challenge. To address this, these buoys are equipped with solar panels that harness the power of the sun. These panels charge large batteries, which store energy to keep the buoy's systems running, even during extended periods of cloud cover or darkness. This power sustains the onboard industrial-rated computers that process and store the data and enables the buoys to communicate their findings in real-time via high-power radio or satellite links.

4.1.4 The Cost of Exploration

While the knowledge gained from these smart sensor buoys is invaluable, the cost of deploying and maintaining them is substantial. Each buoy in the observatory can have a price tag of a few million US dollars. This high cost is justified by the cutting-edge technology and extensive sensor arrays they carry.

The advancement of marine science through smart sensor buoys comes at a significant financial investment. The complexity of these buoys, their sophisticated sensors, and the challenges associated with deploying them in the harsh ocean environment contribute to their high price. However, this investment is justified by the wealth of data they provide and the profound insights they offer into our oceans, which play a vital role in the health of our planet.

4.1.5 Beyond Data Collection

Smart sensor buoys are not just tools for data collection; they also play a vital role in environmental impact studies. Researchers use the data they collect to assess the health of marine ecosystems, monitor pollution levels, and study the effects of climate change. The impact of human activities on marine environments has become a growing concern. Smart sensor buoys help address this by continuously collecting data that aids in environmental impact assessments. Scientists use this data to track changes in water quality, temperature, and biodiversity, helping to identify and mitigate the negative effects of pollution and climate change on marine ecosystems.

The data collected by these buoys contributes significantly to our understanding of marine ecosystems. It helps scientists make informed decisions regarding conservation efforts and sustainable resource management. As smart sensor buoys provide a wealth of data over extended periods, they enable researchers to detect long-term trends and fluctuations in marine environments. This knowledge is invaluable for making informed decisions about marine conservation and resource management. It empowers scientists and policymakers to develop strategies for preserving the health of our oceans and the countless species that rely on them.

4.2 Coastal, River, and Lagoon Monitoring: Innovative Solutions for Shallow Waters

In the realm of environmental monitoring, coastal, river, and lagoon ecosystems play a pivotal role in maintaining the delicate balance of our planet's biodiversity. However, effectively monitoring these shallow water areas, where the depth hardly exceeds 5 meters, presents unique challenges. Given the complexity of these regions, characterized by the convergence of multiple channels, the presence of various river mouths, and extensive salt marshes, deploying a single large observatory buoy may not be the most practical solution. Moreover, the high deployment and maintenance costs associated with multiple buoy observatories make it an impractical choice. In such scenarios, the deployment of a low-cost, easy-to-maintain monitoring system emerges as a more suitable alternative. In recent years, substantial efforts have been made in this direction, aiming to bridge the gap in our understanding of these critical ecosystems.

4.2.1 The Internet of Underwater Things (IoUT)

One notable breakthrough in the field of shallow-water monitoring is the development of an experimental testbed known as the IoUT as presented in [1]. This innovative system comprises two fundamental components: an underwater node and a surface node, both equipped with state-of-the-art sensing devices. What sets this system apart is its communication methodology, which relies on acoustics. The data collected by the underwater unit are transmitted to the surface unit, which, in turn, relays it to a shore server using LoRaWAN technology. This pioneering prototype, which leverages an industrial-grade acoustic modem designed for offshore applications, was primarily created to demonstrate the feasibility of the concept. It is worth noting that the IoUT system is not intended for medium- or long-term installations but serves as a proof of concept for underwater monitoring in challenging shallow-water environments.

4.3 The SubCULTron Project

The SubCULTron project, represented in [24], introduces a remarkable array of cutting-edge underwater and surface sensors and vehicles that have the potential to transform the way we perceive and study the world beneath the waves. Developed with precision and equipped with cost-effective acoustic modems and WiFi modules, these sensory systems have the power to redefine the future of coastal sensor networks.

4.3.1 H2ORobotics: Transforming Innovation into Commercial Reality

A significant development stemming from the SubCULTron project is the emergence of H2ORobotics [14], a dynamic startup company affiliated with the University of Zagreb. H2ORobotics has successfully commercialized some of the sensory systems designed within the project. Notably, they have introduced a low-cost surface vehicle into the market, signifying a pivotal step forward in making advanced underwater and surface sensors more accessible to the world.

4.3.2 The Arduino MKR WiFi Microprocessor

In [15], a feasibility study introduced a groundbreaking sensor for smart ports based on the Arduino MKR WiFi microprocessor. This compact yet powerful device, combined with a miniaturized solar panel, opens up new horizons in coastal sensor network technology. Its cost-effectiveness and versatility make it an essential component in advancing climate change and biodiversity studies.

The Arduino MKR WiFi microprocessor is a remarkable piece of technology. With its compact size, energy efficiency, and wireless capabilities, it is a game-changer in coastal monitoring. By harnessing the power of WiFi connectivity, researchers can gather and transmit data with unprecedented ease and speed.

Additionally, the integration of a miniaturized solar panel enhances its sustainability, making it an eco-friendly choice for extended deployments in coastal environments.

we will explain about Arduino MKRWAN 1310 in next chapter, which is section 5.

4.3.3 LoRaWAN: Above-Water Radio Transmission Technology

As we saw before in previous chapter, A compelling insight from the analysis performed in [2] is the prominence of LoRaWAN as the optimal above-water radio transmission technology for coastal sensor network deployment. With its remarkable range and efficiency, LoRaWAN seamlessly integrates with various sensor systems, forming a crucial part of the heterogeneous network architecture.

LoRaWAN, short for Long Range Wide Area Network, is a wireless communication technology that excels in long-distance data transmission. It is particularly well-suited for coastal sensor networks due to its ability to cover vast expanses without sacrificing data integrity. This technology ensures that data collected from coastal sensors can be transmitted reliably and efficiently, making it an indispensable asset in climate change and biodiversity studies.

4.3.4 The Prototype That Defines the Future: From Concept to Reality

Building upon the concept and network architecture presented in [2], a groundbreaking simulation study confirmed the feasibility of a heterogeneous network deployment. This network seamlessly incorporates low-cost underwater and above-water sensors, promising groundbreaking insights for climate change and biodiversity studies.

The transition from theoretical concepts to practical application is always a pivotal moment in innovation. In the case of coastal sensor networks, the SubCULTron project has successfully bridged this gap. The development of the first prototype is a testament to the project's commitment to realizing its vision. This prototype encompasses all the sensors required for in-depth climate change and biodiversity research in the Venice Lagoon, a highly dynamic and ecologically significant environment.

BEING COST-EFFECTIVE

In stark contrast to traditional observatories relying on expensive mooring systems [11], often costing millions of US dollars, our prototype stands out as an epitome of cost-efficiency. The entire system, inclusive of all sensors necessary for climate change and biodiversity research in the Venice Lagoon, costs a mere $800 USD. Moreover, this price tag can potentially be further reduced in the production phase and by opting for low-cost microcontrollers instead of Arduino boards.

The affordability of this prototype is a game-changer in the world of coastal monitoring. Traditional systems have often been prohibitively expensive, limiting their accessibility to a select few institutions and researchers. With the SubCULTron project's cost-effective approach, a broader community of researchers and environmentalists can partake in valuable studies without breaking the bank. This shift toward affordability has the potential to democratize coastal monitoring and create a global network of environmentally conscious individuals and organizations.

4.3.5 THE SIGNIFICANCE OF LOW-COST SOLUTIONS

The advent of cost-effective coastal sensor networks has far-reaching implications. It democratizes access to valuable data and empowers researchers, environmentalists, and policymakers to embark on more ambitious and comprehensive climate change and biodiversity studies. With the SubCULTron project's innovations, we can delve deeper into the complexities of our coastal ecosystems. The importance of expanding research horizons cannot be overstated. Coastal ecosystems are delicate, ever-changing environments that play a crucial role in our planet's overall health. By making advanced sensor technology accessible, we enable a more comprehensive understanding of these ecosystems. This, in turn, empowers us to make more informed decisions and policies to safeguard our coasts and the biodiversity they house.

One of the key merits of low-cost solutions is their potential for widespread adoption. By minimizing the financial barriers to entry, more regions and organizations can establish and maintain their coastal sensor networks, fostering sustainability in environmental monitoring. Sustainability is the cornerstone of the SubCULTron project's approach. By ensuring that environmental monitoring technology is accessible to a wide range of stakeholders, the project contributes to a sustainable future. Coastal regions worldwide can benefit from the insights provided by these sensors, aiding in the protection of these vital ecosystems for generations to come.

4.3.6 Looking to the Future

The SubCULTron project, H2ORobotics, and the associated technologies discussed in this thesis collectively usher in a new era of coastal sensor networks. With their cost-effectiveness, innovation, and applicability, these developments promise to reshape how we approach climate change and biodiversity studies. This low-cost approach not only revolutionizes research but also extends its benefits to a broader spectrum of researchers and stakeholders.

As we move forward, the future looks brighter for coastal monitoring. With these groundbreaking technologies and their accessibility, we can better understand and protect our coastal ecosystems. It is a promising path towards a more sustainable and informed future.

5

Structure of the System

In the ever-evolving landscape of modern technology, the IoT has emerged as a groundbreaking force, seamlessly connecting an array of devices and sensors to facilitate the efficient collection and analysis of data. Among the myriad applications of IoT, environmental monitoring stands out as a critical domain, where sensor nodes assume a central and irreplaceable role. In the ensuing discourse, we shall embark on an exploration of the intricate architecture of LoRaWAN sensor nodes, meticulously tailored for the monitoring of diverse water parameters. Our journey will encompass a detailed examination of the constituent elements, the sophisticated array of sensors, and their seamless integration, all converging to craft an astute and highly efficient environmental monitoring solution.

5.1 SYSTEM ARCHITECTURE OVERVIEW

5.1.1 SENSOR NODE ARCHITECTURE

The core of the LoRaWAN sensor node lies in its architecture, designed to acquire essential water parameters and transmit them to a remote LoRaWAN gateway. In thesis we will break down the key components that make up this system architecture.

Off-the-Shelf Sensors To collect precise data about water quality and conditions, a carefully chosen set of off-the-shelf sensors is integrated into the sensor node. These sensors have been selected in collaboration with experts from the

Chioggia Marine Hydrobiological Station at the University of Padova, ensuring their suitability for the task.

Here are the primary sensors integrated into the LoRaWAN sensor node:

- analog Industrial pH Sensor/Meter Pro Kit V2 (SEN0169-V2): this device is designed for precise pH measurement in solutions, often used in aquaponics, aquaculture, and water testing. This version offers improved accuracy and compatibility with 3.3–5 V control boards like Arduino. Its hardware-filtered signal ensures stability, and the software library supports easy two-point calibration with standard buffer solutions. The pH electrode features a sensitive glass membrane for quick and stable readings in the 0 to 14 pH range, with a reference system for reliability. This device is ideal for online monitoring and various water quality tests. The pH scale measures acidity (pH<7), alkalinity (pH>7), and neutrality (pH=7) and finds applications in medicine, chemistry, and agriculture [7]. The figure 5.1 illustrates the model which we used in our structure.

Figure 5.1: Analog industrial pH sensor.

- Analog Electrical Conductivity Sensor/Meter K = 10 (DFR0300-H): this sensor is designed for measuring high-conductivity liquids like seawater and concentrated brine, with a range of up to 100ms/cm. it is suitable for mariculture applications, such as marine fisheries and aquariums, and is compatible with 3–5 V input, working seamlessly with popular control boards like Arduino. This sensor uses an AC signal excitation source to reduce polarization effects, ensuring accuracy and probe longevity. The software library supports simple single-point calibration and automatic buffer solution detection. With this sensor, a compatible control board, and software library, you can easily create an electrical conductivity meter without soldering, offering a convenient plug-and-play solution for conductivity measurements [6]. Figure 5.2 depicts the model used in our structure.

Figure 5.2: Analog electrical conductivity sensor.

- Analog Turbidity Sensor (SEN0189): DFRobot Turbidity sensor is designed to evaluate water quality by detecting and quantifying turbidity, which is influenced by the presence of suspended particles or Total Suspended Solids (TSS) in water. This sensor functions by analyzing changes in light transmittance and scattering rates as TSS levels increase, allowing it to accurately measure turbidity. It offers both analog and digital signal output modes, with the ability to adjust the threshold for turbidity detection in the digital mode, making it adaptable for various microcontroller setups. Applications of this sensor encompass water quality assessment in rivers, wastewater analysis, sediment transport research, and laboratory investigations. It operates at a standard voltage of 5 V DC, making it compatible with common microcontroller systems like Arduino [8]. Figure 5.3 depicts the sensor we used in our structure.

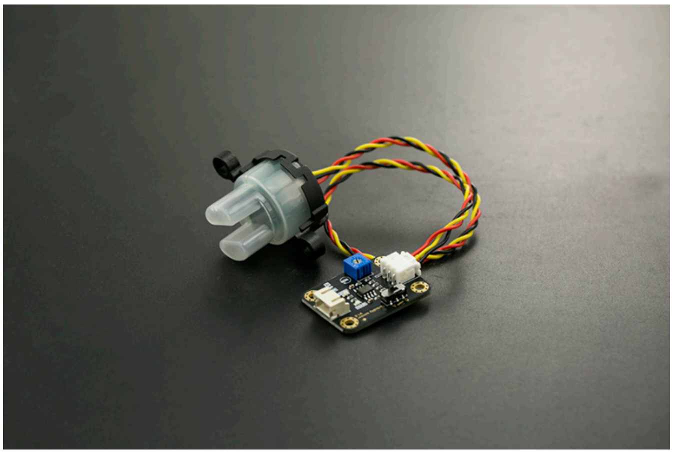


Figure 5.3: Analog turbidity sensor (SEN0189).

- GPS Module with Enclosure (TEL0094): the GPS Receiver, produced by DFRobot, is fully compatible with Arduino. It is a compact device that incorporates a GPS module and antenna within a small enclosure. By utilizing the TinyGPS library, the Arduino platform gains access to a plethora of location-related information, encompassing geographic coordinates (latitude and longitude), altitude, velocity, orientation, and GMT time. An imperative performance measure for GPS receivers is the update rate, determining the frequency at which data is refreshed. Typically, GPS units in mobile phones operate at a 1 Hz update rate, signifying that a singular data set is acquired every second. In contrast, GPS receivers with update rates spanning from 1 Hz to 10 Hz provide notably reduced data intervals, rendering them suitable for more demanding applications, such as the tracking of rapidly moving vehicles [22]. The figure 5.4 illustrates the GPS module used in our project.

Figure 5.4: GPS module with enclosure.

- Waterproof DS18B20 Temperature Sensor: this sensor is an Arduino-compatible temperature sensor, well-suited for situations that require temperature measurements in distant or damp environments. Although the sensor's operational range extends up to 125, it is noteworthy that the cable is encased in PVC, implying a recommended operating temperature not exceeding 100. Given its digital nature, this sensor maintains signal integrity even when employed over extensive distances. The DS18B20 furnishes temperature readings of 9 to 12 bits (configurable) via a 1-Wire interface, requiring only a single wire connection (in addition to ground) to a central microprocessor. Compatibility spans across 3.0–5.5 V systems. The distinct silicon serial number embedded within each DS18B20 permits the coexistence of multiple sensors on the same 1-Wire bus. This capability is particularly advantageous in applications such as HVAC environmental control, indoor temperature monitoring, machinery and equipment temperature sensing, and process supervision and regulation [10]. The figure 5.5 shows the temperature sensor used in the project.

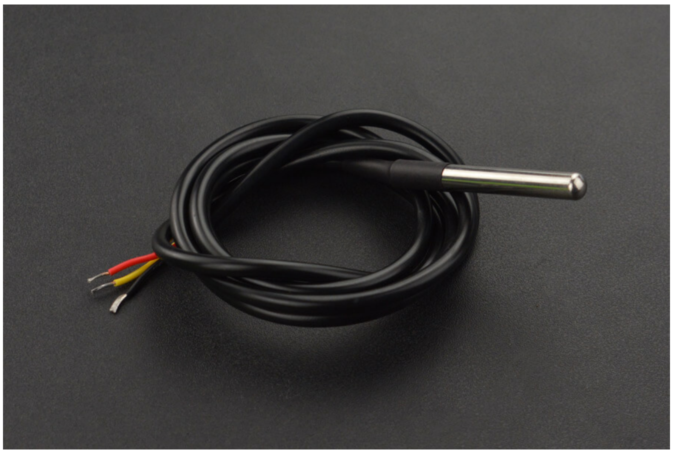


Figure 5.5: Waterproof DS18B20 temperature sensor.

- Analog Dissolved Oxygen Sensor / Meter Kit (SEN0237-A): this product comprises a dissolved oxygen sensor kit, specifically designed for the measurement of dissolved oxygen levels in water, thereby serving as an indicator of water quality. Its applications are diverse, encompassing domains such as aquaculture, environmental monitoring, and the field of natural sciences. The adage, "Good fish deserves good water," underscores the pivotal role of water quality in maintaining aquatic organisms' well-being. Among the crucial parameters reflecting water quality, dissolved oxygen assumes particular significance. Inadequate levels of dissolved oxygen can impede the respiration process of aquatic organisms, posing a threat to their survival. The sensor's probe operates on galvanic principles, obviating the need for polarization time and ensuring continuous readiness for use. Furthermore, the sensor features replaceable filling solution and membrane caps, resulting in cost-effective maintenance. Its signal converter board is plug-and-play, accommodating power inputs within the range of 3.3–5 V, rendering it compatible with a wide array of popular microcontrollers such as ESP32, Raspberry Pi, and Arduino [5]. Figure 5.6 presents an illustration related to this sensor, representing its utilization in our project.

Figure 5.6: Analog dissolved oxygen sensor.

- Photoelectric High Accuracy Liquid Level Sensor (SEN0205): this device is a photoelectric liquid level sensor that operates based on optical principles. It offers several advantages, including high sensitivity and the absence of mechanical components, reducing the need for frequent calibration. The probe, resistant to corrosion, is easily installable and can withstand both high temperatures and pressures. Additionally, it is equipped with an interface adapter designed for compatibility with DFRobot's "Gravity" interface, simplifying its use. To further streamline the application of this Arduino liquid sensor, a Gravity Interface has been incorporated for convenient plug-and-play functionality. For seamless integration with Arduino, the Arduino IO expansion shield is the optimal choice. Furthermore, the sensor's ability to operate at 3.3 V ensures compatibility with other platforms like Raspberry Pi, Intel Edison, Joule, and Curie [9]. Figure 5.7provides a visual representation of this sensor's deployment in our project.

Figure 5.7: Photoelectric high accuracy liquid level sensor.

The integration of these sensors allows the LoRaWAN sensor node to gather comprehensive data on water conditions, enabling researchers and environmentalists to make informed decisions and take appropriate actions.

At the heart of the sensor node, the Micro-Processing Unit (MPU) acts as the brain, processing data from the various sensors and coordinating the transmission of information to the LoRaWAN gateway. It plays a crucial role in data management and ensures that the sensor node operates efficiently.

The LoRaWAN module utilized in our project is the Type ABZ (CMWX1ZZABZ) module, a widely recognized LoRaWAN module with default integration on the Arduino MKRWAN1310 platform. Figure 5.8 illustrates this module. It holds certifications for compliance with radio regulations in key regions and is a pivotal component in various business networks globally. Furthermore, it supports an open Microcontroller Unit (MCU) design and can be adapted for Sigfox compatibility through software modifications. This module functions as the crucial communication gateway connecting the sensor node to the external network. Our selection of LoRaWAN technology is driven by its exceptional long-range capabilities, ensuring reliable and secure data transmission, even in remote and challenging terrains. Thus, this module plays a vital role in guaranteeing the dependable and secure transmission of collected data to its intended destination.

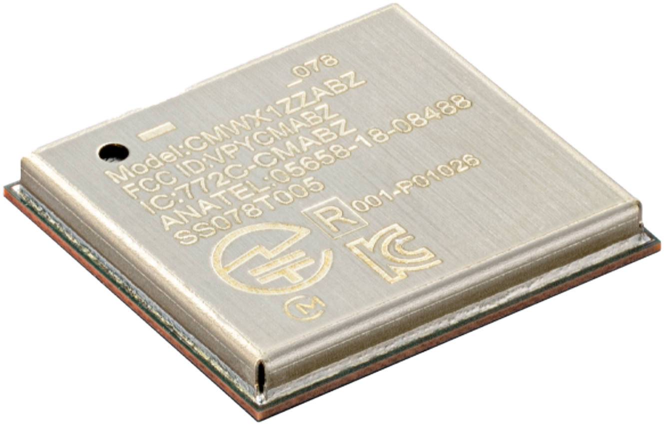


Figure 5.8: LoRaWAN module type ABZ (CMWX1ZZABZ).

To ensure uninterrupted operation, the sensor node is equipped with a reliable powering sub-system. This includes batteries or energy harvesting mechanisms, depending on the deployment scenario. The choice of power source is crucial to guarantee the longevity of the sensor node's operation. In our project, we power each sensor with 5 V DC pin on Arduino board.

5.2 Unlocking the Potential of Data Acquisition and Transmission with Arduino MKR WAN 1310

In the domain of gathering and transmitting data, precision, effectiveness, and dependability hold significant importance. The seamless collection and communication of data have grown increasingly essential across diverse sectors, including environmental monitoring and industrial automation. To address these needs, inventive solutions continue to surface, and the Arduino MKR WAN 1310 board stands out as a noteworthy example.

5.2.1 Deep into the Arduino MKR WAN 1310

The Arduino MKR WAN 1310, depicted in Figure 5.9, transcends the conventional boundaries of development boards. It stands as a formidable instrument, merging a SAMD21 Cortex-M0+ 32-bit low-power ARM MCU with the Murata CMWX1ZZABZ LoRaWAN chip. This amalgamation empowers the board to function seamlessly across multiple frequency bands, encompassing 433, 868, and 915 MHz. This versatile device is poised to revolutionize the domain of data acquisition and transmission.

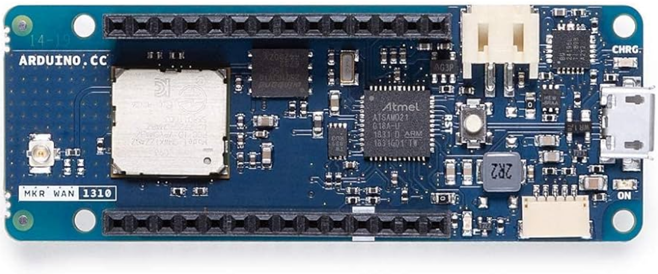


Figure 5.9: Arduino MKR WAN 1310.

One of the features of the Arduino MKR WAN 1310 is its ability to consolidate numerous functions onto a single platform. As you can see in Appendix A, With 7 analog input pins and 8 digital I/O pins, this board offers exceptional versatility. This means that multiple sensors can be seamlessly connected to a single Arduino MKR WAN 1310 board, simplifying the setup and reducing clutter.

While the Arduino MKR WAN 1310 excels in accommodating various sensors, it is not without its challenges. For instance, integrating sensors like pH sensors alongside electrical conductivity and dissolved oxygen sensors can be complex. These challenges often arise due to differing power requirements and communication protocols. However, innovative solutions are being developed to address these issues, ensuring compatibility and seamless operation.

In some cases, relying solely on a single Arduino unit may not be sufficient to meet the demands of a data acquisition system. To ensure reliability and redundancy, it is possible to employ two separate Arduino units, each serving a specific purpose. This redundancy can help prevent data loss and system downtime.

Efficiency is key in any data acquisition system, especially when operating in remote or energy-constrained environments. To extend the overall lifetime of the node and minimize power consumption, a sleep and wake-up routine can be established for each Arduino unit. This strategy ensures that devices are powered down between data acquisition cycles, conserving energy for extended operation.

The quest for efficiency and reliability in data acquisition and transmission is an ongoing journey. In the final configuration of such systems, it is anticipated that the Arduino boards will be replaced with even lower-power microcontrollers, such as ATTinys. This transition promises a significant reduction in overall energy consumption, making data collection more sustainable and cost-effective. In the world of data acquisition, timing is crucial. To prevent interference and ensure a seamless flow of data, the two MCUs in the system should be synchronized. This synchronization enables sequential operation, reducing the risk of overlapping and data corruption. It paves the way for quasi-simultaneous data collection, improving the overall efficiency of the system.

5.3 OPTIMIZING ARDUINOS FOR DATA COLLECTION

In the realm of data collection and environmental monitoring, precision and efficiency are paramount. Imagine a scenario where we need to gather data about water quality and environmental conditions in remote areas, far from power sources. In such cases, sensor nodes play a pivotal role in acquiring accurate information. In this thesis, we delve into the fascinating world of sensor nodes, specifically focusing on Arduino units that are designed to measure pH value, turbidity, liquid level, dissolved oxygen, GPS coordinates, electrical conductivity, and temperature. We will also explore how energy optimization techniques are employed to ensure these units operate flawlessly.

5.3.1 Two Arduinos for handling all sensors

The first Arduino unit which is shown in Figure 5.10 is equipped with just one sensor to measure only pH value. On the other hand, the second Arduino unit is shown in Figure 5.11 boasts the capability to measure dissolved oxygen, GPS coordinates, electrical conductivity, turbidity,liquid level, and temperature. The reason for this configuration was to eliminate any interference between sensors. We realized that all the sensors could somehow impact the pH reading. Even if the pH sensor shared a common ground cable with other sensors, the issue persisted. In this situation, we had no alternative but to place the pH sensor on one Arduino with separate power sources, while the rest of the sensors were connected to another Arduino. Since we are measuring water parameters based on voltage in saline water, these sensors could potentially influence one another. However, by carefully synchronizing the activation and deactivation of the sensors at the right times, we could mitigate their mutual interference. To ascertain the specific code executed by each Arduino device, reference Appendix B.

pH

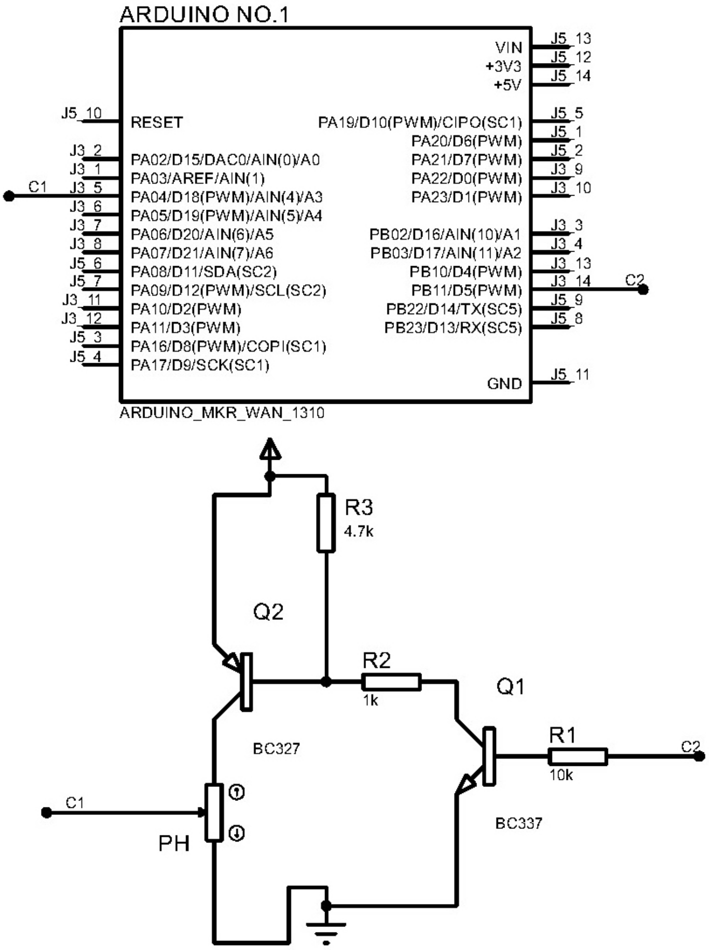


Figure 5.10: First arduino schematic.

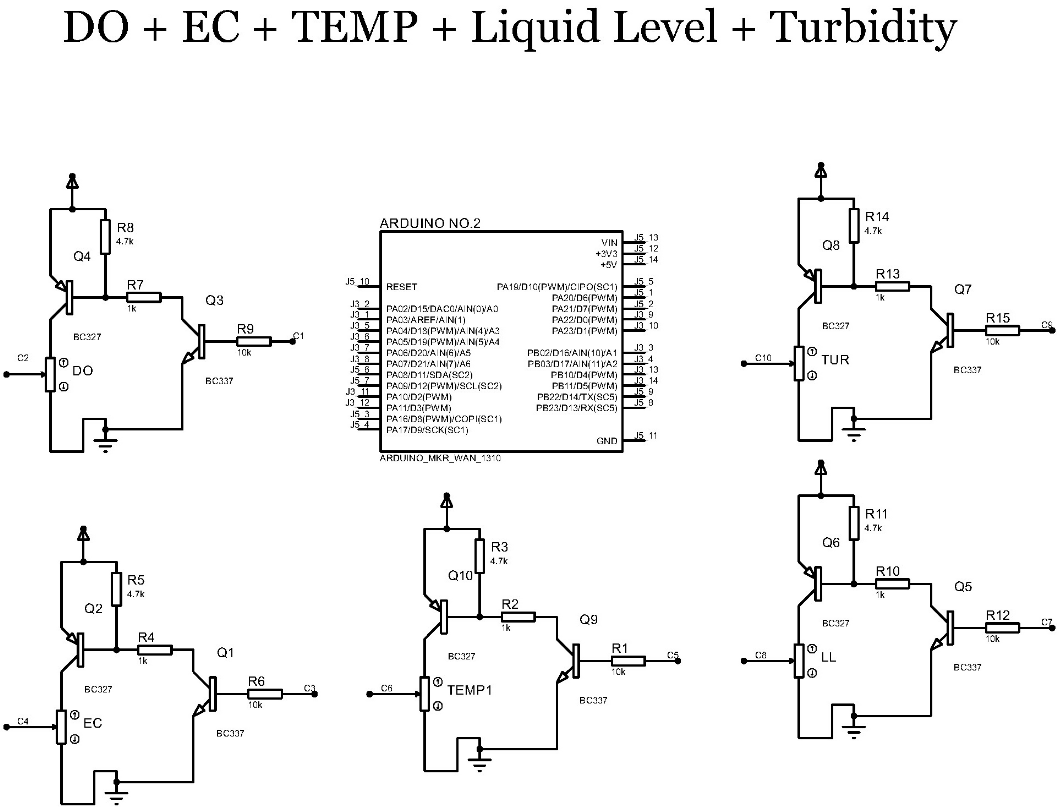


Figure 5.11: Second arduino schematic.

Powering the Arduino Units: Each Arduino unit is powered by eight 3400mAh Lithium-ion (Li-Ion) NCR18650B batteries (Figure 5.12). These batteries are renowned for their reliability and longevity. With a nominal voltage of 3.7 V and a maximum voltage of 4.2 V when fully charged, they provide the necessary energy for our sensor nodes to function effectively. To achieve the required power levels, four batteries are connected in parallel to create a battery set. Subsequently, two of these sets are connected in series, resulting in an 8.4 V 13200 mAh battery pack when fully charged. This ingenious arrangement ensures that each set of four batteries connected in parallel maintains a voltage level of approximately 4.2 V. However, when these two sets are connected in series, the voltage level effectively doubles.

Figure 5.12: NCR18650B 3400mAh Li-Ion battery.

To ensure the Arduino units function optimally, a voltage adjustment is imperative. This is where a DC/DC circuit comes into play. The circuit (Figure 5.13) serves as a transformer, converting the 8.4 V voltage from the battery pack to approximately 5.7 V, a level that aligns perfectly with the Arduino units' requirements. This modification ensures that our sensors receive the correct voltage for precise measurements.

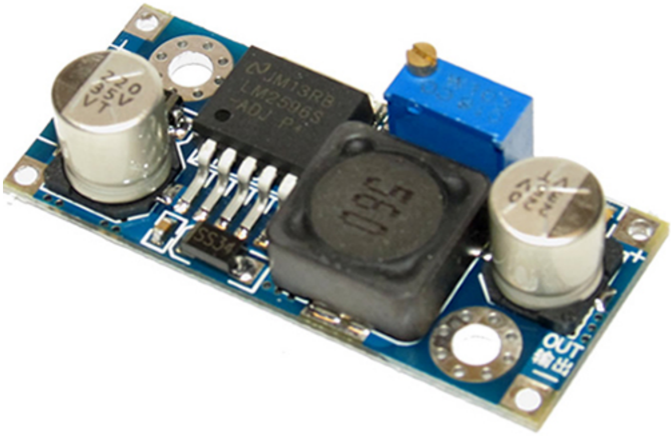


Figure 5.13: DC/DC LM2596S transformer.

5.3.2 Energy Conservation Measures

While these Arduino units are designed for extensive data collection, conserving energy is crucial, especially when operating in remote locations where recharging batteries might be challenging. To tackle this issue, we have implemented a solution involving BJT transistors. Within the confines of our sensor node blueprint, we employ a pair of bipolar junction transistors (BJT) - one bearing the npn classification (BC337), and the other adorned with the pnp categorization (BC327) - meticulously orchestrated as a switch (refer to Figure 5.14). This arrangement affords us the capacity to set our sensors into motion exclusively during measurement operations, adeptly rendering them dormant during interludes of inactivity. This maneuver holds particular eminence in light of the widely recognized energy-intensive disposition exhibited by sensors. Through the discerning allocation of power, we manifest a substantial mitigation in the aggregate energy outlay of our sensor nodes, thereby unequivocally contributing to the elongation of sensor longevity and the enhancement of operational efficiency. The interconnection of this configuration is established at the output pin of the Arduino through the intermediary presence of a 10K Ω resistor (R4), while the sensor undergoes substitution by resistor R3.

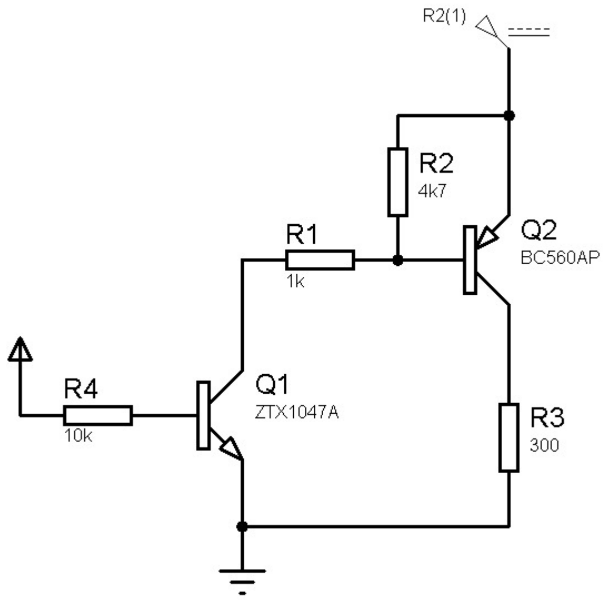


Figure 5.14: Configuration of npn and pnp transistors for switching sensors on and off.

5.4 Setup in the Venice Lagoon

When it comes to deploying sensor networks in unique and challenging environments, few places rival the intricacies of the Venice Lagoon. This picturesque water body, with its intricate network of canals, tidal influences, and diverse ecosystems, demands a well-thought-out deployment setup. In this comprehensive guide, we will explore the nuances of deploying sensors in the Venice Lagoon and how it all comes together to collect critical data for various scientific purposes.

5.4.1 Understanding the Terrain

The Venice Lagoon is a dynamic and complex environment. Before deploying sensors, it is crucial to grasp the lay of the land or, in this case, the water. The distance between nodes in the final deployment setup is expected to average 500 meters. This distance strikes a balance between obtaining finely detailed data and managing economic costs.

In practice, this distance may need fine-tuning based on local conditions. In areas where water parameters are expected to change frequently and unexpectedly, such as where multiple canals intersect with the water flow, decreasing the distance between sensors is advisable. Conversely, in areas where parameters vary slowly and predictably, an increased distance between nodes can be more cost-effective.

5.4.2 SENSOR-SPECIFIC CONSIDERATIONS

Different sensors have varying requirements concerning spatial and time granularity. To optimize energy consumption, it is essential to tailor the data acquisition frequency to each sensor's needs.

The GPS position can be acquired once a day, primarily to verify that the sensor remains anchored in its intended location. Depending on specific requirements, this frequency can be reduced or even switched to an asynchronous reading triggered by downlink messages.

Salinity and temperature tend to change slowly over the course of the day. Consequently, acquiring data once per hour provides adequate granularity for these parameters.

Other parameters, which exhibit faster variability, demand more frequent measurements. It is advisable to collect data for these variables at least once every 15 minutes. Managing acquisition intervals can also play a role in reducing energy consumption, as sensors can be powered off between consecutive readings.

5.4.3 ENERGY EFFICIENCY

Energy efficiency is a critical consideration in sensor deployments. One of the most power-demanding devices in sensor nodes is the GPS. By limiting GPS usage to just five minutes a day (the maximum time needed to acquire a stable GPS position), energy consumption can be drastically reduced.

5.4.4 EXPLORING THE DEPTHS

The Venice Lagoon's unique water stratification makes it of particular interest to biologists and ecologists. They need data not only from the water's surface but also from deeper layers and close to the sea bottom, where sediments can be characterized.

In the future, deploying submerged sensor nodes at various water depths near the seafloor is a promising endeavor. This expansion of the sensor network will provide a more comprehensive understanding of the lagoon's ecological dynamics.

6

SENSWICH

The demand for a cost-effective and intelligent buoy has sparked the birth of SENSWICH, an avant-garde prototype poised to revolutionize the way we gather vital data from submerged water sources. This chapter introduces SENSWICH, examining its design, functionality, and the possibilities it envisions for the future.

6.1 UNDERSTANDING THE NEED

The absence of an economically viable intelligent buoy for deploying internal water sensors has been a persistent challenge for researchers and environmentalists alike. Traditional buoy systems often fall short in terms of cost-effectiveness and efficiency. This prompted the development of SENSWICH, a name derived from "sensing sandwich," owing to its sandwich-like configuration.

6.2 ANATOMY OF SENSWICH'S APPEARANCE

SENSWICH is a buoyant structure designed to meet the demands of modern water sensing applications. Its core components include:

- life Buoy Ring: at its heart, SENSWICH features a life buoy ring with an inner diameter of 40 cm and an outer diameter of 60 cm. This life buoy ring serves as the foundation for the entire system. The choice of a life buoy ring as the base ensures stability and buoyancy, making it suitable for a wide range of water environments.It is not expensive, and also easy to use (Figure 6.1).

Figure 6.1: Life buoy ring of SENSWICH.

- Wooden Panels: two wooden panels, each with an inner diameter of 9 cm and measuring 80 cm x 60 cm, provide structural support and stability to SENSWICH. These panels are strategically placed to maintain balance and keep the buoy upright, even in turbulent waters (Figure 6.2).

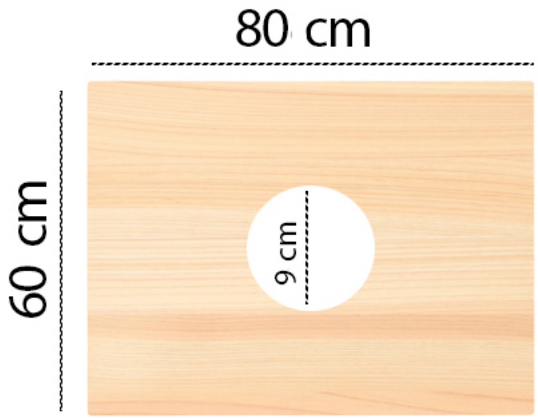


Figure 6.2: Wooden Panel of SENSWICH.

- IP67 Enclosure: an IP67 enclosure with dimensions of 25 cm x 20 cm x 7.5 cm houses critical components, ensuring they remain protected from water damage. The IP67 rating guarantees that the enclosure is dust-tight and can withstand immersion in water up to one meter deep for 30 minutes, making it ideal for water-based deployments (Figure 6.3).

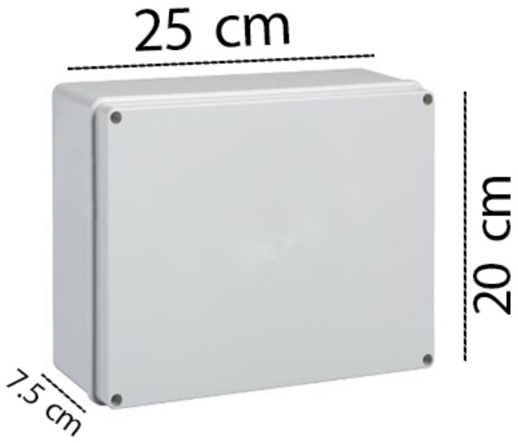


Figure 6.3: IP67 enclosure of SENSWICH.

SENSWICH stands at a height of 15 cm and is designed for easy mooring to poles within water bodies like the Venice lagoon. This mooring system allows SENSWICH to remain stationary while floating, providing a stable platform for sensor deployment.

6.3 Bringing Together All Components in SENSWICH: A Comprehensive Examination of the Structural Elements

As illustrated in Figure 6.4, the experimental setup comprises a distinctive configuration, with a prominent red buoyant safety tube positioned in between two wooden panels, while an IP67-rated enclosure is situated atop the SENSWICH device. Sensors are attached to the lower panel, as indicated in Figure 6.5, and are interconnected with the control unit through the use of specialized IP67 cable glands. The IP67-rated enclosure is securely nestled within the upper panel of the buoyant system, as visualized in Figure 6.6, housing vital components such as batteries, microprocessors, and control circuits. The successful assembly of this prototype serves as compelling evidence of the potential effectiveness of the envisioned system within its designated environmental context.

It is important to note that in future iterations of this research, our strategy includes the incorporation of small-scale solar panels for recharging the system's batteries. Additionally, we plan to explore the substitution of Arduino boards with MCU to enhance energy efficiency. Furthermore, we aim to investigate the implementation of water-jets for periodic sensor cleansing and the prevention of bio-fouling as part of our ongoing efforts to enhance system performance and longevity.

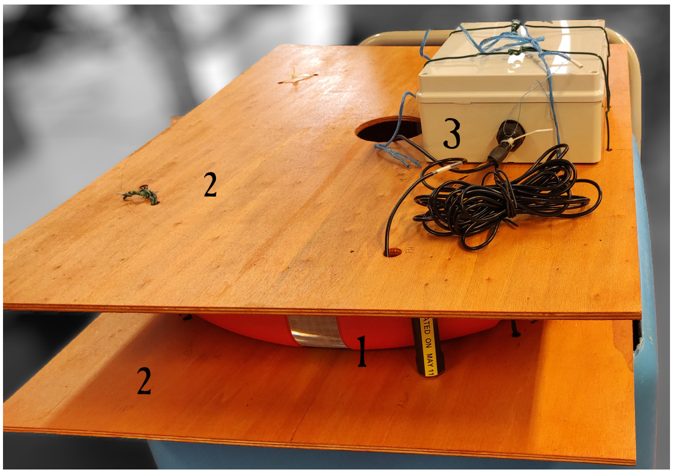


Figure 6.4: Profile view of SENSWICH with: 1. Life bouy ring, 2. Two wooden frames, 3. Closed box with batteries and circuit components.

Figure 6.5: Bottom panel of SENSWICH (top wooden panel removed) with sensors: 1. pH sensor, 2. EC sensor, 3. Turbidity sensor, 4. Temperature sensor, 5. DO sensor, 6. liquid Level Sensor.

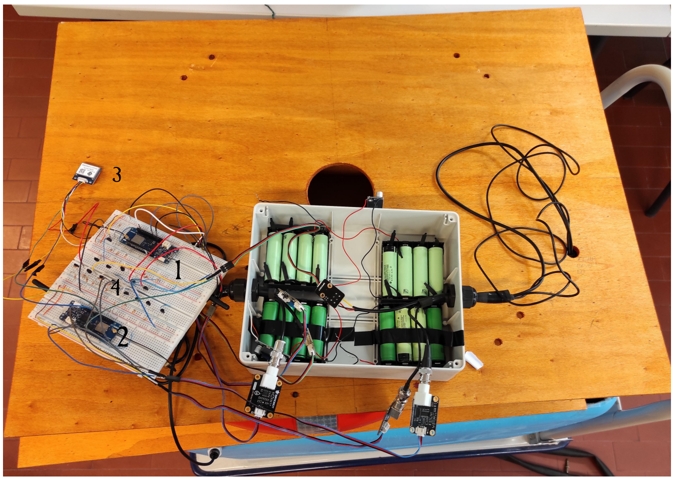


Figure 6.6: Circuit box with components and two packs of 8 batteries: 1. Arduino 1, 2. Arduino 2, 3. GPS module, 4. Circuit components.

6.4 Sensor Integration

SENSWICH's primary function is to house and protect various water sensors. These sensors are strategically affixed to the lower wooden panel, ensuring they can collect data effectively. The sensors are interlinked with the control box through the utilization of IP67 cable glands, guaranteeing secure connections even in wet conditions.

6.5 Control Box

The control box, securely housed within the upper panel of the floating system, plays a pivotal role in ensuring SENSWICH's functionality. It accommodates batteries, microprocessors, and control circuits, enabling seamless data collection and transmission. The control box's placement in the upper panel ensures it remains above the waterline, safeguarding it from potential water damage.

6.6 Proven Feasibility in Real-World Water Sensing

The creation of SENSWICH serves as a testament to the feasibility of the system's functionality in real-world environments. Researchers and engineers have successfully demonstrated its capabilities, marking a significant milestone in the field of water sensing technology. These successful tests have shown that SENSWICH is not just a theoretical concept but a practical solution for gathering vital water data.

6.7 Future Innovations

SENSWICH's upcoming upgrades promise to boost its capabilities significantly. Firstly, the inclusion of small-scale solar panels for battery recharging will make it more eco-friendly, allowing SENSWICH to operate autonomously for extended periods without the hassle of frequent maintenance. Secondly, researchers are exploring the transition from Arduino boards to low-power MCUs to optimize energy efficiency and data processing. This change could substantially enhance SENSWICH's overall efficiency, making it even more reliable for long-term deployments.

In addition to these improvements, researchers are addressing issues like sensor fouling by considering the implementation of water-jets for periodic sensor cleansing. This innovative approach will ensure data accuracy over extended deployment periods, reducing the need for frequent retrieval and maintenance. Overall, these advancements in SENSWICH's design are poised to make it a more sustainable and efficient monitoring system.

7

Preliminary Tests

7.1 LABORATORY TESTS

Embarking on the path to develop an all-encompassing environmental monitoring platform began a sequence of experiments conducted within our state-of-the-art laboratory. These tests were designed to meticulously scrutinize the individual performance of our sensors and their efficacy within a holistic sensing framework. During these laboratory trials, we intentionally refrained from employing SENSWICH, opting instead to place the sensors in close proximity to one another within a small container filled with a salty water.

The first set of tests involved testing the sensors to different environments. Freshwater and saltwater were used to mimic real-world conditions, with the saltwater solution mirroring the average salinity of the Adriatic Sea, approximately 35 mg/L. These tests helped identify how the sensors responded over extended periods. Freshwater environments are common in many terrestrial and aquatic ecosystems, making it essential to understand how sensors function in these conditions. On the other hand, saltwater environments, such as oceans and seas, pose a different set of challenges due to their salinity. Testing the sensors in both environments allowed for a comprehensive assessment of their adaptability. The figure referenced in Figure 7.1 depicts the water sample we utilized in the SIGNET laboratory, containing a salinity of 35 mg/L.

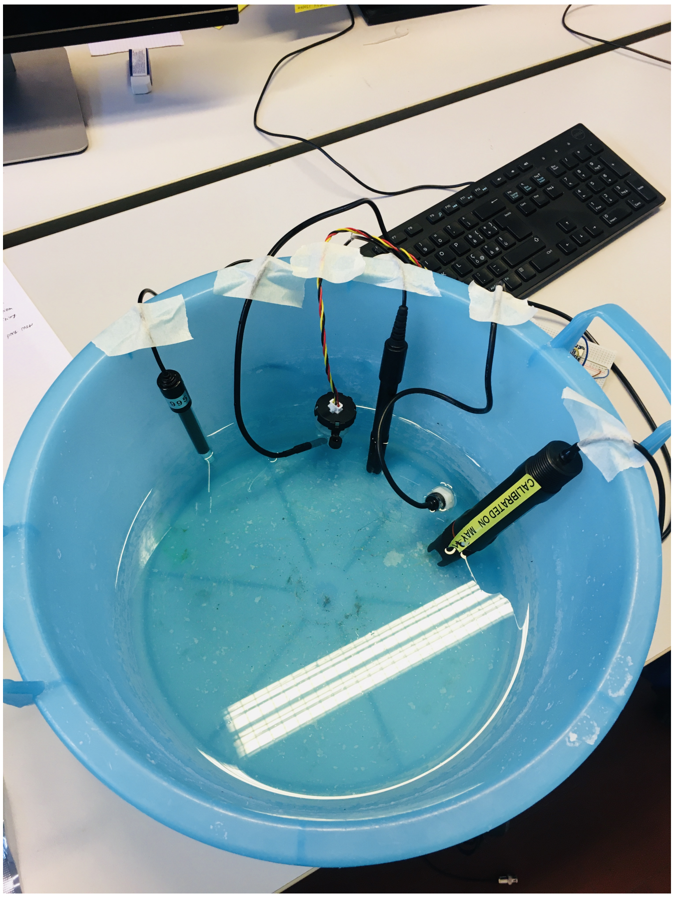
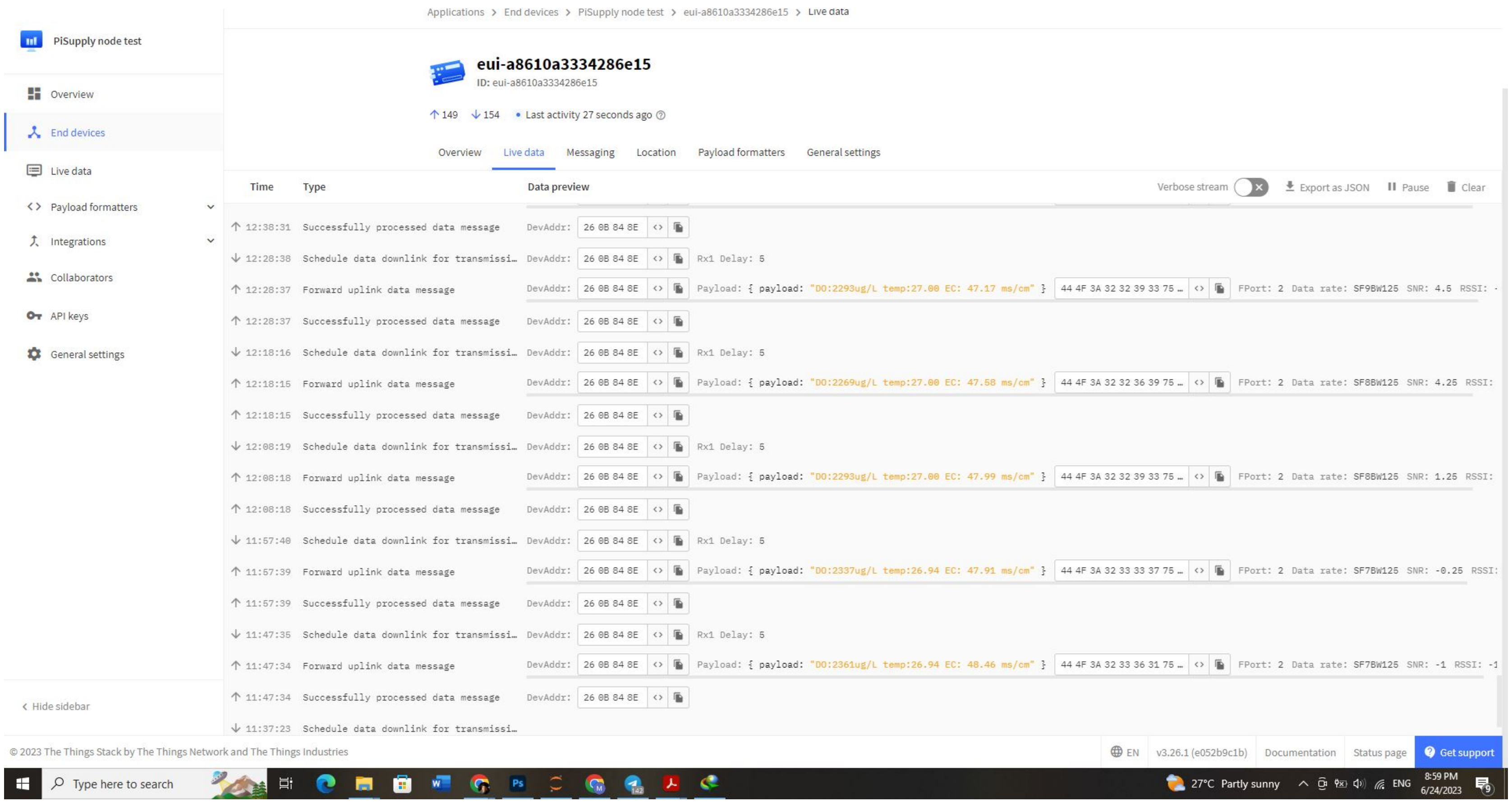


Figure 7.1: Setting up laboratory experiment: salty water container and sensor arrangement.

Stability is paramount when collecting data from environmental sensors. we collected the data, and also whatch the receved data in a real-time with useing TTN (Figure 7.2). After exposing the sensors to varying conditions, the stability of the data acquired was closely examined. The readings needed to remain consistent and reliable over an extended timeframe. The stability of sensor readings is crucial for several reasons. First and foremost, it ensures the accuracy of the data collected. Inaccurate data could lead to incorrect conclusions and misguided environmental decisions. Secondly, stable readings are essential for long-term monitoring projects, where deviations in data could obscure trends or mask critical changes in environmental conditions.



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Time      Type                                    Data preview
↑ 12:38:31 Successfully processed data message    DevAddr: 26 0B 84 8E
↓ 12:28:38 Schedule data downlink for transmissi… DevAddr: 26 0B 84 8E  Rx1 Delay: 5
↑ 12:28:37 Forward uplink data message            DevAddr: 26 0B 84 8E  Payload: { payload: "DO:2293ug/L temp:27.00 EC: 47.17 ms/cm" }  44 4F 3A 32 32 39 33 75 …  FPort: 2  Data rate: SF9BW125  SNR: 4.5  RSSI: -
↑ 12:28:37 Successfully processed data message    DevAddr: 26 0B 84 8E
↓ 12:18:16 Schedule data downlink for transmissi… DevAddr: 26 0B 84 8E  Rx1 Delay: 5
↑ 12:18:15 Forward uplink data message            DevAddr: 26 0B 84 8E  Payload: { payload: "DO:2269ug/L temp:27.00 EC: 47.58 ms/cm" }  44 4F 3A 32 32 36 39 75 …  FPort: 2  Data rate: SF8BW125  SNR: 4.25  RSSI:
↑ 12:18:15 Successfully processed data message    DevAddr: 26 0B 84 8E
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↑ 12:08:18 Forward uplink data message            DevAddr: 26 0B 84 8E  Payload: { payload: "DO:2293ug/L temp:27.00 EC: 47.99 ms/cm" }  44 4F 3A 32 32 39 33 75 …  FPort: 2  Data rate: SF8BW125  SNR: 1.25  RSSI:
↑ 12:08:18 Successfully processed data message    DevAddr: 26 0B 84 8E
↓ 11:57:40 Schedule data downlink for transmissi… DevAddr: 26 0B 84 8E  Rx1 Delay: 5
↑ 11:57:39 Forward uplink data message            DevAddr: 26 0B 84 8E  Payload: { payload: "DO:2337ug/L temp:26.94 EC: 47.91 ms/cm" }  44 4F 3A 32 33 33 37 75 …  FPort: 2  Data rate: SF7BW125  SNR: -0.25  RSSI:
↑ 11:57:39 Successfully processed data message    DevAddr: 26 0B 84 8E
↓ 11:47:35 Schedule data downlink for transmissi… DevAddr: 26 0B 84 8E  Rx1 Delay: 5
↑ 11:47:34 Forward uplink data message            DevAddr: 26 0B 84 8E  Payload: { payload: "DO:2361ug/L temp:26.94 EC: 48.46 ms/cm" }  44 4F 3A 32 33 36 31 75 …  FPort: 2  Data rate: SF7BW125  SNR: -1  RSSI: -1
↑ 11:47:34 Successfully processed data message    DevAddr: 26 0B 84 8E
↓ 11:37:23 Schedule data downlink for transmissi…
```

Figure 7.2: Real-time monitoring in laboratory testing.

7.1.1 Power Consumption

In order to measure power consumption, we assessed the current passing through the Arduino in various scenarios, with a constant voltage of 5.7 V, as shown in Table 7.1 for current measurements and in Table 7.2 for voltage measurements.

Table 7.1: Arduino Power Consumption

Arduino	**Scenario**	**Current [A]**	**Power [W]**
Arduino 1	Sensors off	0.017	0.0969
	Sensors on	0.050	0.285
Arduino 2	Sensors off (without GPS)	0.018	0.1026
	Sensors on (without GPS)	0.035	0.1995
	Sensors off (with GPS)	0.066	0.3762
	Sensors on (with GPS)	0.083	0.4725
Both Arduinos (GPS off)	-	0.038	0.2166
Both Arduinos (GPS on)	-	0.136	0.7752

Table 7.2: Input Voltage

Arduino	**Voltage [V]**
Arduino 1	5.7
Arduino 2	5.7

7.1.2 Integration Challenges

The second set of tests delved into integrating the sensors into a single platform. Initially, a single Arduino board was used to collect data from all the sensors, which were submerged in a common container filled with freshwater. However, a significant challenge surfaced during this phase - the pH sensor's compatibility issues with other sensors, notably temperature, dissolved oxygen (DO), and conductivity sensors. This incompatibility led to inaccurate pH readings when other sensors were present in the same container. Even when the sensors were activated sequentially, the interference persisted.

The integration of environmental sensors into a single platform is essential for creating an efficient and cost-effective monitoring system. Such integration allows for centralized data collection, real-time analysis, and streamlined maintenance. However, as demonstrated by the compatibility issues encountered in these tests, achieving seamless integration can be complex. Understanding the root causes of these issues is vital for future development.

While this phenomenon is intriguing, further investigation is required to understand the root causes. This research will be carried out as part of future work. To expedite the development of the monitoring platform, a pragmatic decision was made. Instead of using a single Arduino, two separate ones were employed. This choice increased energy consumption but was deemed necessary to maintain system integrity. Nonetheless, research efforts are ongoing to eventually achieve the integration of all sensors using a single MCU.

7.1.3 LONG-TERM OPERATION IN SALTWATER

The final set of tests involved an extended period of operation in saltwater conditions. The complete integrated platform, consisting of all the sensors, was submerged in saltwater and monitored continuously in a laboratory setting for two weeks. This phase was crucial for assessing the system's robustness and its ability to function effectively in harsh marine environments.

Saltwater environments present unique challenges for environmental sensors. The corrosive nature of saltwater can affect sensor components and their performance over time. The prolonged testing period aimed to mimic real-world scenarios where sensors would need to endure such conditions without degradation.

7.1.4 RESULTS AND STABILITY

The results of these preliminary tests were promising. Despite the challenges encountered during integration, the sensors demonstrated stability and consistency in their readings over time. In our experimental endeavor, we meticulously gathered data from a triumvirate of sensors specifically, those monitoring pH, temperature, and dissolved oxygenspanning a comprehensive 48-hour timeframe. The resulting insights are eloquently visualized in Figure 7.3, Figure 7.4, and Figure 7.5. Remarkably, even in the absence of any alterations to the aquatic milieu, the sensor data demonstrated unwavering stability. These recorded measurements harmoniously align with the established benchmarks for these parameters in water, thereby substantiating the steadfast reliability of these sensors. The x-axis elegantly delineates each 10-minute interval within this expansive 48-hour window.

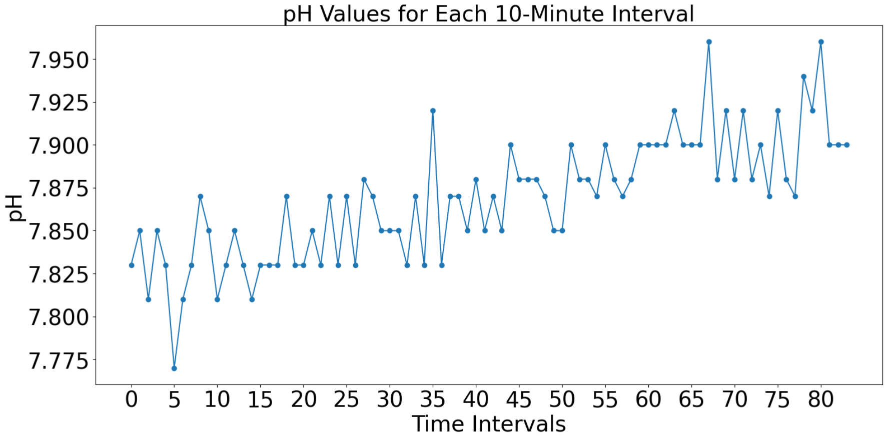

Figure 7.3: pH plot in 48 hours.

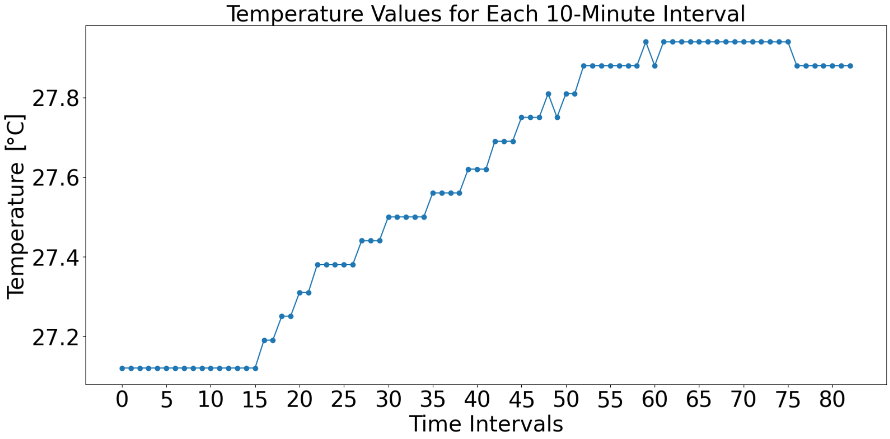

Figure 7.4: Temperature plot in 48 hours.

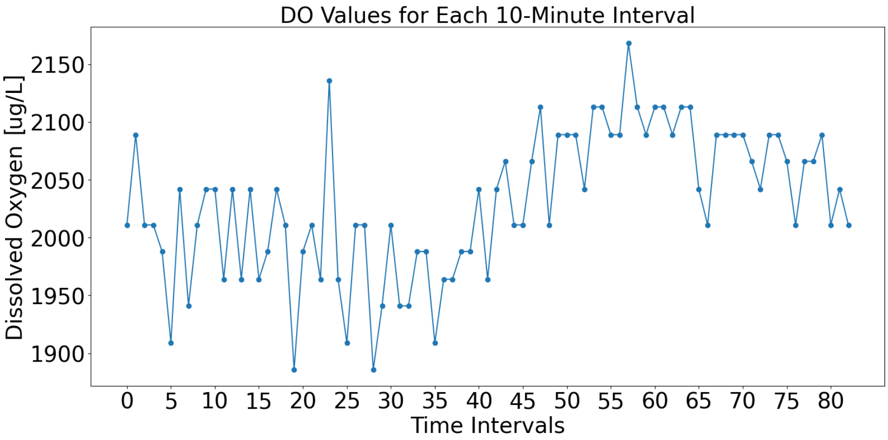

Figure 7.5: DO plot in 48 hours.

7.2 Piovego Canal

The choice of the Piovego canal (Figure 7.6) as the test site was deliberate and strategic. This artificial waterway, which encircles the historic city walls of Padova, Italy, offers a unique blend of conditions that mimic both urban and natural aquatic environments. Moreover, it serves as a tributary to the Brenta river, eventually leading to the iconic Venice Lagoon. Testing the SENSWICH system in such a location allows us to assess its adaptability to a wide range of aquatic settings, from serene canals to more turbulent open waters.

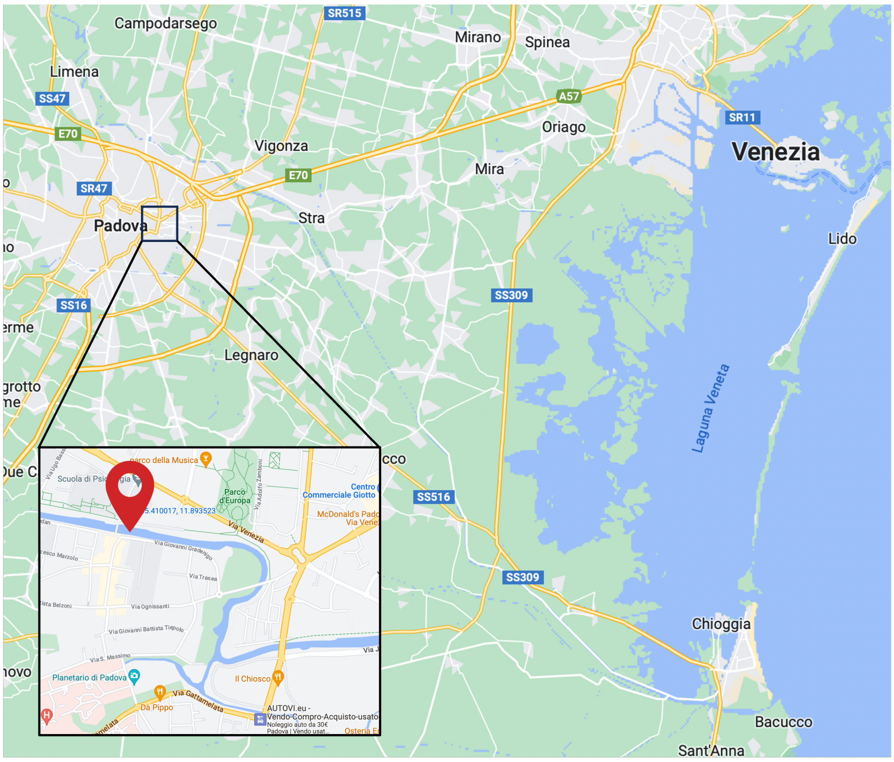

Figure 7.6: Location of Piovego Canal.

7.2.1 The Deployment Setup

A key aspect of the field test was the deployment setup, which played a pivotal role in the system's performance evaluation. The SENSWICH platform was securely fastened to a sturdy pole within the Piovego canal. This precaution was taken to ensure that the device remained in its intended testing location throughout the experiment, unaffected by the flow of the water. Stability during deployment is crucial as it guarantees the accuracy of the data collected (Figure 7.7).

Figure 7.7: SENSWICH stability.

Simultaneously, a LoRaWAN gateway was strategically positioned in the main building of the Department of Information Engineering at the University of Padova, approximately 200 meters away from the deployment site. This gateway served as the communication hub, enabling seamless data transmission between the SENSWICH system and the data collection and analysis infrastructure. The choice of LoRaWAN technology allowed for efficient, low-power, and long-range communication, ensuring that data was reliably relayed for subsequent analysis.

7.2.2 Buoyancy and Stability

During the one-hour immersion in the Piovego canal, the buoyancy and stability of the SENSWICH system were thoroughly evaluated. The results were not only encouraging but also highlighted the system's robust design.

As mentioned earlier, the device floated gracefully on the water's surface. Its slight imbalance, with approximately 5 cm of the structure submerged, was an anticipated outcome due to the uneven distribution of weight within the platform (Figure 7.8).

Notably, this imbalance did not adversely affect the system's functionality in any way. The buoyancy and stability of SENSWICH were not only visually validated but also crucially confirmed during the experiment (Figure 7.9). This outcome holds significant promise for the system's potential deployment in more challenging aquatic environments, such as the Venice Lagoon, where it may encounter stronger currents and turbulence.

Figure 7.8: Real-time monitoring of SENSWICH functionality.

Figure 7.9: SENSWICH inside Piovego Canal.

7.2.3 Sensor Precision and Reliability

The core of the SENSWICH system lies in its array of sensors, each designed to fulfill a specific role in aquatic data collection. These sensors are not just state-of-the-art; they demonstrated remarkable precision and reliability during the field test. In the following items, we will discuss several applications where SENSWICH assisted us:

- water Quality Sensors: the water quality sensors, responsible for measuring critical parameters such as pH levels, turbidity, dissolved oxygen, and temperature, exceeded expectations. The accuracy and consistency of their measurements were particularly noteworthy. For instance, pH levels consistently fell within the expected range for freshwater bodies, underlining the system's potential for applications in water quality monitoring, aquatic research, and environmental conservation.

- Environmental Sensors: the environmental sensors, tasked with capturing data on air temperature, humidity, and light intensity, provided invaluable context to the aquatic environment. Their exceptional performance allowed us to gain a holistic understanding of the conditions surrounding the SENSWICH system during the test. Such data is indispensable in various domains, including weather forecasting, ecosystem analysis, and climate research.

- Water Level Sensors: water level sensors, crucial for monitoring changes in water levels over time, played a pivotal role in the experiment. They demonstrated precision in measuring even the slightest variations in water levels. This capability is particularly significant for flood prediction and management, where accurate data can be a lifesaver.

7.2.4 A Path Forward

In conclusion, the preliminary field test of the SENSWICH integrated system in the Piovego canal showcased its capabilities. The device's buoyancy, stability, and sensor performance were not only validated but exceeded our expectations. This success paves the way for more extensive and demanding trials in the future, particularly within the dynamic and challenging environment of the Venice Lagoon.

As we continue to push the boundaries of aquatic sensor technology, the SENSWICH system stands as a testament to innovation and engineering excellence in the realm of aquatic data collection. Its potential applications are vast, ranging from environmental monitoring and research to disaster management and urban planning.

8

MetroSea 2023

The world's oceans had always held a special place in the hearts of humanity. Being the cradle of life on planet Earth, the sea had been a constant presence since the dawn of time. It had facilitated global travel, served as a vital source of food, and remained a critical component of our existence. However, as our world faced the challenges of global warming, the health of the sea had become a pressing concern. It was more crucial than ever to understand and monitor the state of our oceans. This was where the 2023 IEEE International Workshop on Metrology for the Sea (MetroSea 2023) stepped in.

The conference was hosted at the University of Malta's Valletta Campus, situated within the historic Old University Building. This campus had a storied history dating back to 1592 when it was founded as the Collegium Melitense.

The organization of MetroSea 2023 was a joint effort, with IEEE Italy Section and IEEE Malta Section working together. Here are several chapters were actively involved in making this event a success:

- IEEE Italy OES Chapter;
- IEEE Italy Instrumentation and Measurement Chapter;
- IEEE System Council Italy Chapter;
- IEEE Sensors Council Italy Chapter;
- IEEE Women in Engineering Italy Section Affinity Group;
- IEEE Italy Section Young Professional.

This collaboration signified the importance of the event and showcased the dedication of these IEEE sections to the cause of understanding and preserving our oceans.

Furthermore, a notable milestone for MetroSea 2023 was the sponsorship by the IEEE Oceanic Engineering Society[18].

I had the honor of serving as the representative for the University of Padova at the MetroSea 2023 conference, where I presented our project titled *"A LoRaWAN Network for Real-Time Monitoring of the Venice Lagoon: Preliminary Tests."* This project showcased the efforts and accomplishments of our work over the past few months at the SIGNET lab of the University of Padova. The moment when the project was presented in Malta on October 6, 2023, was captured in the images in Figure 8.1a and Figure 8.1b.

(a)

(b)

Figure 8.2: MetroSea 2023, Malta, 6 October 2023.

9

Conclusions

This section summarizes the key findings and implications of my thesis, focusing on the transformative impact of an innovative LoRaWAN-based sensor node architecture on environmental monitoring, particularly in the context of safeguarding ecosystems such as the Venice Lagoon.

The study introduced a pioneering approach to environmental monitoring through the implementation of a novel LoRaWAN-based sensor node architecture. The potential of this technology to comprehensively evaluate water quality in the Venice Lagoon has the capacity to revolutionize the preservation of fragile ecosystems. Beyond theoretical considerations, this research serves as a testament to its practicality. Rigorous preliminary testing has not only validated the theoretical framework but has also established a solid basis for real-world applications in environmental monitoring.

Laboratory validation procedures meticulously scrutinized each individual component and confirmed the seamless integration of the system within controlled laboratory settings, highlighting the robustness of the sensor node technology. This validation ensures its reliability for extended deployment.

The field test, conducted in a genuine environmental setting, played a critical role in assessing the mechanical resilience of the system. Its successful execution reaffirms the technology's suitability for challenging environmental conditions. Furthermore, this research has a pragmatic dimension beyond technological innovation. The pursuit of optimization not only enhances operational efficiency but also reduces production costs, which is pivotal for fostering the widespread adoption of this transformative technology. The vision of a network of sensor nodes intricately woven across the Venice Lagoon paves the way for a comprehensive monitoring network. This network promises to amass a wealth of ecological data, effectively transforming each sensor node into a vigilant environmental sentinel. As this network accumulates an extensive reservoir of data, it unveils previously concealed ecological insights. These insights, akin to a treasure trove of knowledge, promise to illuminate the intricate rhythms and patterns of the Venice Lagoon's ecosystem.

Going beyond data collection, this research endeavors to decipher the complex language of the Venice Lagoon ecosystem through the power of machine learning algorithms. This journey towards understanding facilitates the development of predictive models for proactive environmental management. This study transcends the boundaries of academic inquiry and stands as a testament to innovation and environmental stewardship. It exemplifies how technology can be harnessed for the betterment of delicate ecosystems, moving beyond the realm of mere theoretical discourse.

The positive outcomes of preliminary testing, coupled with ongoing optimization and mass deployment efforts, paint a promising picture for our planet's ecosystems. This research aspires to create a future where technology plays a pivotal role in the preservation and sustainable coexistence with precious environments like the Venice Lagoon.

In conclusion, the research highlights the transformative potential of this innovative sensor node architecture, redefining environmental monitoring, and paving the way for cost-effective, widespread adoption. It serves as a beacon of innovation and environmental responsibility, promising a brighter future for our planet's ecosystems.

References

[1] Fabio Busacca et al. "An experimental testbed of an Internet of Underwater Things". In: *Proc. ACM WiNTECH*. London, UK, Sept. 2020.

[2] F. Campagnaro et al. "A Network Infrastructure for Monitoring Coastal Environments and Study Climate Changes in Marine Systems". In: *Proc. IEEE/MTS OCEANS*. Hampton Roads, US, Oct. 2023.

[3] P. S. Cheong et al. "Comparison of LoRaWAN Classes and Their Power Consumption". In: *2017 IEEE Symposium on Communications and Vehicular Technology (SCVT)*. Leuven, Belgium, 2017, pp. 1–6. DOI: `10.1109/SCVT.2017.8240313`.

[4] Cisco. "Embracing the Internet of Everything". In: 2016. URL: `https://www.cisco.com`.

[5] DFRobot. *Gravity: Analog Dissolved Oxygen Sensor / Meter Kit for Arduino*. DFRobot Product Page. `https://www.dfrobot.com/product-1628.html`.

[6] DFRobot. *Gravity: Analog Electrical Conductivity Sensor / Meter (K=10)*. DFRobot Product Page. `https://www.dfrobot.com/product-1797.html`.

[7] DFRobot. *Gravity: Analog Industrial pH Sensor / Meter Pro Kit V2*. DFRobot Product Page. `https://www.dfrobot.com/product-2069.html`.

[8] DFRobot. *Gravity: Analog Turbidity Sensor for Arduino*. DFRobot Product Page. `https://www.dfrobot.com/product-1394.html`.

[9] DFRobot. *Gravity: Photoelectric High Accuracy Liquid Level Sensor for Arduino*. DFRobot Product Page. `https://www.dfrobot.com/product-1470.html`.

[10] DFRobot. *Gravity: Waterproof DS18B20 Temperature Sensor Kit*. DFRobot Product Page. `https://www.dfrobot.com/product-1354.html`.

[11] R. Diamant et al. “THEMO: The Texas A&M - University of Haifa - Eastern Mediterranean Observatory”. In: *Proc. IEEE/MTS OCEANS*. Kobe, Japan, May 2018.

[12] *Euorpean Environment Agency - The Natura 2000 protected areas network*. Last time accessed: June 2023. URL: `https://www.eea.europa.eu/themes/biodiversity/natura-2000`.

[13] E. Garcia. “A Smart Low-Power Meteorological System”. In: *Proc. IEEE/MTS OCEANS*. Washington DC, US, Sept. 1986.

[14] H2ORobotics. *H2ORobotics Website*. URL: `https://h2o-robotics.com/`.

[15] L. Hanschke, J. Heitmann, and C. Renner. “On the Feasibility of WiFi-Enabled and Solar-Powered Sensors for Smart Ports”. In: *GI/ITG KuVS Fachgesprach Sensornetze, FGSN*. Augsburg, Germany, Sept. 2016.

[16] Alexandru Lavric and Valentin Popa. “A LoRaWAN: Long Range Wide Area Networks Study”. In: *2017 International Conference on Electromechanical and Power Systems (SIELMEN)*. 2017.

[17] Kais Mekki et al. “A Comparative Study of LPWAN Technologies for Large-Scale IoT Deployment”. In: *Research Centre for Automatic Control of Nancy, Campus Sciences* BP 70239, Vandoeuvre (Mar. 2018).

[18] MetroSea. *MetroSea 2023*. URL: `https://metrosea.org/`.

[19] N. L. Guinasso et al. “Observing and forecasting coastal currents: Texas Automated Buoy System (TABS)”. In: *Proc. IEEE/MTS OCEANS*. Honolulu, HI, USA, Nov. 2001.

[20] *RESEARCHITALY - Biodiversity: national research centre established under the coordination of the CNR*. Last time accessed: June 2023. URL: `https://www.researchitaly.mur.gov.it/en/2022/07/26/biodiversity-national-research-centre-established-under-the-coordination-of-the-cnr/`.

[21] B. Reynders and W. Meert. “Range and Coexistence Analysis of Long-Range Unlicensed Communication”. In: *23rd Conference on Telecommunications*. Thessaloniki, Greece, May 2016.

[22] Other (STAR RIVER). *GPS Module with Enclosure*. DFRobot Product Page. `https://www.dfrobot.com/product-1302.html`.

[23] J. de Carvalho Silva et al. “LoRaWAN A Low Power WAN Protocol for Internet of Things: A Review and Opportunities”. In: *2017 2nd International Multidisciplinary Conference on Computer and Energy Science (SpliTech)*. Split, Croatia, 2017, pp. 1–6.

[24] *subCULTron - Submarine Cultures Perform Long-term Robotic Exploration of Unconventional Environmental Niches*. Last time accessed: June 2023. URL: `https://labust.fer.hr/labust/research/projects/subcultron`.

[25] The Things Network. *What is the The Things Network?* URL: `https://www.thethingsindustries.com/docs/reference/ttn/`.

[26] Benny Vejlgaard et al. “Interference Impact on Coverage and Capacity for Low Power Wide Area IoT Networks”. In: *Wireless Communications and Networking Conference (WCNC) 2017 IEEE*. 2017, pp. 1–6.

A

Appendix A

A.1 Arduino MKRWAN 1310 Structure

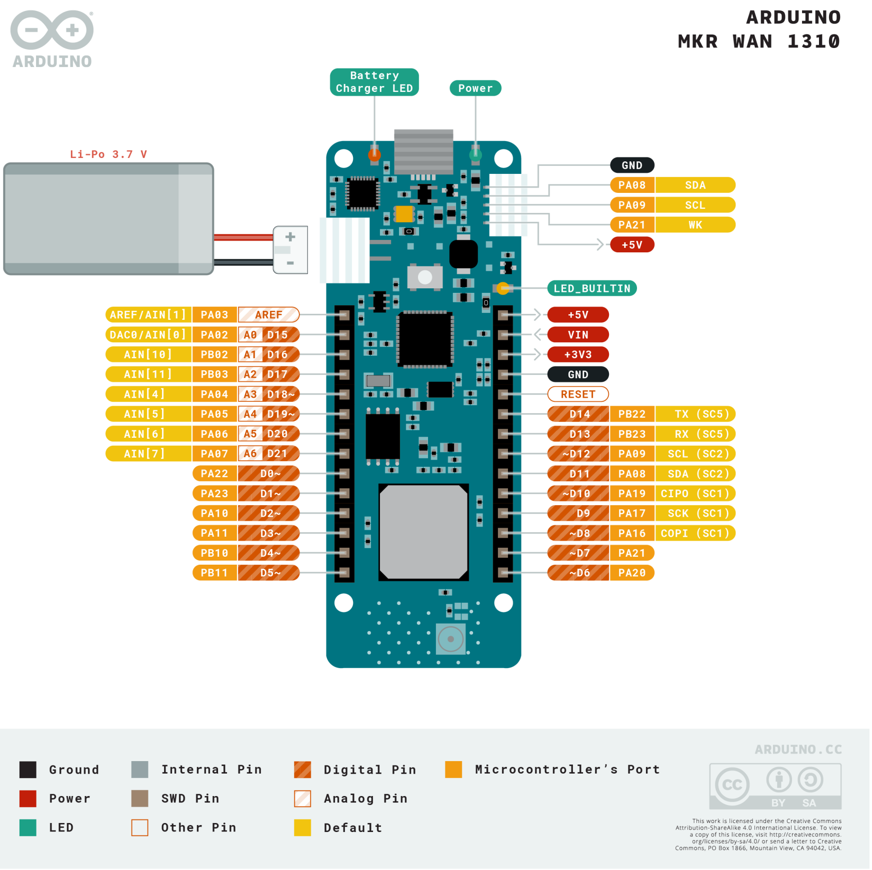

Figure A.1: Pinout Diagram.

B

Appendix B

B.1 First Arduino Code

```
// Libraries
#include <OneWire.h>
#include <FlashAsEEPROM.h>
#include "DFRobot_PH.h"
#include <MKRWAN.h>
#include <CayenneLPP.h>
#include "TinyGPS.h"
#include "ArduinoLowPower.h"
#include <LoRa.h>

// Init Values
float voltage;

#define PH_PIN A3
#define PH_CONTROL_PIN 6

#define DELAY_BASED_ON_BIOLOGICAL_MEASUREMENT 4 * 60000

#define VREF 3300       // VREF (mV)
#define ADC_RES 1024.0  // ADC Resolution

// pH Sensor
float phValue;
DFRobot_PH ph;
```

```

// pH Sensor Calibration Initial Values (2 Point Calibration)
float acidVoltage = 2060;
float naturalVoltage = 1559;

// LoRa Setting
LoRaModem modem;
String appEui = "A8610A3535387D0C";
String appKey = "3F3B76EC9C5758096F03BDD10AEAA702";

void setup() {
  Serial.begin(9600);
  Serial1.begin(9600);

  if (!modem.begin(EU868)) {
    Serial.println("Failed to start module");
    while (1) {}
  }

  int connected = modem.joinOTAA(appEui, appKey);
  while (!connected) {
    if (!modem.joinOTAA(appEui, appKey)) {
      // Failed to join, retry
    } else {
      break;
    }
  }

  pinMode(PH_PIN, INPUT);
  pinMode(PH_CONTROL_PIN, OUTPUT);
  digitalWrite(PH_CONTROL_PIN, LOW);
  delay(2000);
  modem.minPollInterval(60);
}

void loop() {
  digitalWrite(PH_CONTROL_PIN, HIGH);
  delay(2000);
  readpH();
  digitalWrite(PH_CONTROL_PIN, LOW);

  modem.beginPacket();
  modem.print("pH:" + String(phValue));
```

```

  int err = modem.endPacket(true);
  if (err > 0) {
    Serial.print("Message sent correctly!");
  } else {
    Serial.print("Error sending message :(");
    Serial.print("(You may send a limited amount of messages per
   minute, depending on the signal strength");
    Serial.print("It may vary from 1 message every couple of seconds
   to 1 message every minute)");
  }

  LowPower.deepSleep(DELAY_BASED_ON_BIOLOGICAL_MEASUREMENT);
}

float readpH() {
  voltage = (analogRead(PH_PIN) / 1024.0) * 3300;
  float slope = (7.0 - 4.0) / ((naturalVoltage - 1500) / 3.0 - (
   acidVoltage - 1500) / 3.0);
  float intercept = 7.0 - slope * (naturalVoltage - 1500) / 3.0;

  phValue = slope * (voltage - 1500) / 3.0 + intercept;
  return phValue;
}
```

Code B.1: Code for Managing pH Sensors with the First Arduino.

B.2 SECOND ARDUINO CODE

```
#include "DFRobot_EC10.h"
#include <FlashAsEEPROM.h>
#include <MKRWAN.h>
#include <CayenneLPP.h>
#include "ArduinoLowPower.h"
#include <LoRa.h>
#include <OneWire.h>
#include <DS18B20.h>

#define ONE_WIRE_BUS 2

OneWire oneWire(ONE_WIRE_BUS);
DS18B20 sensor(&oneWire);
```

```

float volt;
float ntu;
int Liquid_level = 0;
#define MAX_ITERATION 100

TinyGPS gps;

#define DO_PIN A3
#define TURBIDITY_READ A2
#define EC_PIN A1
#define LIQUID_LEVEL 3

// Control
#define CONDUCTIVITY_CONTROL_PIN 4
#define DO_CONTROL_PIN 5
#define TEMP_CONTROL_PIN 6
#define LIQUID_LEVEL_CONTROL_PIN 7
#define TURBIDITY_CONTROL_PIN 8

#define DELAY_BASED_ON_BIOLOGICAL_MEASUREMENT 6 * 60000

float voltage, ecValue, temperature = 25;
DFRobot_EC10 ec;

// Dissolved Oxygen
#define VREF 3300     //VREF (mv)
#define ADC_RES 1024  //ADC Resolution

#define TWO_POINT_CALIBRATION 0

#define READ_TEMP (25)

#define CAL1_V (970)  //mv
#define CAL1_T (25)   //
#define CAL2_V (1300)  //mv
#define CAL2_T (15)    //

const uint16_t DO_Table[41] = {
  14460, 14220, 13820, 13440, 13090, 12740, 12420, 12110, 11810,
    11530,
  11260, 11010, 10770, 10530, 10300, 10080, 9860, 9660, 9460, 9270,
  9080, 8900, 8730, 8570, 8410, 8250, 8110, 7960, 7820, 7690,
```

```
  7560, 7430, 7300, 7180, 7070, 6950, 6840, 6730, 6630, 6530, 6410
};

uint8_t Temperaturet;
uint16_t ADC_Raw;
uint16_t ADC_Voltage;
uint16_t DO;

int16_t readDO(uint32_t voltage_mv, uint8_t temperature_c) {
#if TWO_POINT_CALIBRATION == 0
  uint16_t V_saturation = (uint32_t)CAL1_V + (uint32_t)35 *
    temperature_c - (uint32_t)CAL1_T * 35;
  return (voltage_mv * DO_Table[temperature_c] / V_saturation);
#else
  uint16_t V_saturation = (int16_t)((int8_t)temperature_c - CAL2_T) *
     ((uint16_t)CAL1_V - CAL2_V) / ((uint8_t)CAL1_T - CAL2_T) + CAL2_V
    ;
  return (voltage_mv * DO_Table[temperature_c] / V_saturation);
#endif
}

void setup() {
  Serial.begin(9600);
  Serial1.begin(9600);
  ec.begin();
  sensor.begin();
  if (!modem.begin(EU868)) {
    while (1)
      ;
  };

  int connected = modem.joinOTAA(appEui, appKey);
  while (!connected) {
    if (!modem.joinOTAA(appEui, appKey)) {
    } else {
      break;
    }
  };

  pinMode(CONDUCTIVITY_CONTROL_PIN, OUTPUT);
  pinMode(DO_CONTROL_PIN, OUTPUT);
  pinMode(TEMP_CONTROL_PIN, OUTPUT);
  pinMode(LIQUID_LEVEL_CONTROL_PIN, OUTPUT);
```

```
  pinMode(TURBIDITY_CONTROL_PIN, OUTPUT);
  pinMode(GPSEN_PIN, OUTPUT);

  pinMode(GPS_CONTROL_PIN, OUTPUT);
  digitalWrite(GPS_CONTROL_PIN, LOW);
  digitalWrite(GPSEN_PIN, HIGH);
  digitalWrite(CONDUCTIVITY_CONTROL_PIN, LOW);
  digitalWrite(DO_CONTROL_PIN, LOW);
  digitalWrite(TEMP_CONTROL_PIN, LOW);
  digitalWrite(LIQUID_LEVEL_CONTROL_PIN, LOW);
  digitalWrite(TURBIDITY_CONTROL_PIN, LOW);
  delay(2000);
}

long lat, lon;
unsigned long fix_age, time, date, speed, course;
unsigned long chars;
unsigned short sentences, failed_checksum;

int DEG;
int MIN1;
int MIN2;

String latString;
String lonString;

void LON() {
  DEG = lon / 1000000;
  MIN1 = (lon / 10000) % 100;
  MIN2 = lon % 10000;

  lonString = "LON:" + String(DEG) + String(MIN1) + "." + String(MIN2
    ) + "'   ";
}

void LAT() {
  DEG = lat / 1000000;
  MIN1 = (lat / 10000) % 100;
  MIN2 = lat % 10000;

  latString = "LAT:" + String(DEG) + String(MIN1) + "." + String(MIN2
    ) + "'   ";
}
```

```

int p = 0;
int m = 0;

void loop() {
  digitalWrite(DO_CONTROL_PIN, LOW);
  digitalWrite(TEMP_CONTROL_PIN, LOW);
  digitalWrite(CONDUCTIVITY_CONTROL_PIN, LOW);
  digitalWrite(TURBIDITY_CONTROL_PIN, LOW);
  digitalWrite(LIQUID_LEVEL_CONTROL_PIN, LOW);

  digitalWrite(TEMP_CONTROL_PIN, HIGH);
  sensor.requestTemperatures();
  unsigned long startTime = millis();
  while (!sensor.isConversionComplete() && millis() - startTime < 2*60000)
    ;

  if (sensor.isConversionComplete()) {
    Serial.print("Temp: ");
    Serial.println(sensor.getTempC());
  } else {
    Serial.println("Conversion timed out!");
  }
  temperature = sensor.getTempC();
  digitalWrite(TEMP_CONTROL_PIN, LOW);
  delay(10000);

  unsigned long startTime = millis();
  while (p == 0 || p == MAX_ITERATION) {
    digitalWrite(GPS_CONTROL_PIN, HIGH);
    digitalWrite(GPSEN_PIN, HIGH);

    while (!Serial1.available() && (millis() - startTime < 60000)) {
    }

    if (Serial1.available()) {
      int c = Serial1.read();
      if (gps.encode(c)) {
        gps.get_position(&lat, &lon, &fix_age);
        gps.get_datetime(&date, &time, &fix_age);
        LAT();
        LON();
```

```
        digitalWrite(GPS_CONTROL_PIN, LOW);
        digitalWrite(GPSEN_PIN, LOW);

        modem.beginPacket();
        modem.print("lat: " + String(latString));
        modem.print("lon: " + String(lonString));
        int err;
        err = modem.endPacket(true);
        if (err > 0) {
          Serial.print("Message sent correctly!");
        } else {
          Serial.print("Error sending message :(");
          Serial.print("(You may send a limited amount of messages per minute, depending on the signal strength.");
          Serial.print("It may vary from 1 message every couple of seconds to 1 message every minute.)");
        }
        p++;
        break;
      }
    } else {
      digitalWrite(GPS_CONTROL_PIN, LOW);
      digitalWrite(GPSEN_PIN, LOW);
      p = MAX_ITERATION / 2;
      break;
    }
  }
  p++;

  digitalWrite(CONDUCTIVITY_CONTROL_PIN, HIGH);
  float ecValue = readElectricalConductivity();
  digitalWrite(CONDUCTIVITY_CONTROL_PIN, LOW);

  digitalWrite(DO_CONTROL_PIN, HIGH);
  Temperaturet = (uint8_t)temperature;
  ADC_Raw = analogRead(DO_PIN);
  ADC_Voltage = uint32_t(VREF) * ADC_Raw / ADC_RES;
  DO = readDO(ADC_Voltage, Temperaturet);
  digitalWrite(DO_CONTROL_PIN, LOW);

  digitalWrite(TURBIDITY_CONTROL_PIN, HIGH);
  digitalWrite(LIQUID_LEVEL_CONTROL_PIN, HIGH);
  float turbidity = readTurbidity();
```

```
  uint32_t Liquid_level = digitalRead(LIQUID_LEVEL);

  Serial.println("temperature: " + String(temperature));
  Serial.println("electricalConductivity: " + String(ecValue));
  Serial.println("DO:\t" + String(readDO(ADC_Voltage, Temperaturet))
    + "\t");
  Serial.println("Turbidity:" + String(turbidity));
  Serial.println(String(Liquid_level));

  // Transmit the data using LoRa
  modem.beginPacket();
  modem.print("DO:" + String(DO) + "TMP:" + String(temperature) + "EC
    :" + String(ecValue) + "LIQ:" + String(Liquid_level) + "TRB:" +
    String(turbidity));

  int err;
  err = modem.endPacket(true);
  if (err > 0) {
    Serial.print("Message sent correctly!");
  } else {
    Serial.print("Error sending message :(");
    Serial.print("(You may send a limited amount of messages per
  minute, depending on the signal strength.");
    Serial.print("It may vary from 1 message every couple of seconds
   to 1 message every minute.)");
  }

  LowPower.deepSleep(DELAY_BASED_ON_BIOLOGICAL_MEASUREMENT);
}

float readElectricalConductivity() {
  voltage = analogRead(EC_PIN) / 1024.0 * 3300;
  ecValue = ec.readEC(voltage, temperature);
  ec.calibration(voltage, temperature);
  delay(2000);
  return ecValue;
}

float readTurbidity() {
  volt = 0;
  for (int i = 0; i < 800; i++) {
    volt += ((float)analogRead(TURBIDITY_READ) / 1024.0) * 5;
  }
```

```
  volt = volt / 800;
  volt = round_to_dp(volt, 2);
  if (volt < 1.65) {
    ntu = 3000;
  } else {
    ntu = -2572.2 * sqrt(volt) + 8700.5 * volt - 4352.9;
  }
  Serial.print("Voltage: ");
  Serial.print(volt);
  Serial.print(" V   ");
  Serial.print("NTU: ");
  Serial.print(ntu);
  Serial.println(" NTU");
  return ntu;
  delay(1000);
}

float round_to_dp(float in_value, int decimal_place) {
  float multiplier = powf(10.0f, decimal_place);
  in_value = roundf(in_value * multiplier) / multiplier;
  return in_value;
}
```

Code B.2: Code for Managing Multiple Sensors with the Second Arduino.

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