Monitoring the Venice Lagoon: an IoT Cloud-Based Sensor Network Approach

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***Abstract*—While the impact of global warming is felt worldwide, coastal and littoral regions bear the brunt more prominently. These areas not only face the threat of rising sea levels but also contend with the escalating occurrence of seaquakes and floods. Additionally, the intricate ecosystems of rivers, seas, and lakes undergo profound transformations due to climate change and pollutants. Thus, monitoring the coastal area, such as the Venice Lagoon (Italy) is of significant importance.**

The aim of this paper is to present the architecture of a novel floating wireless sensor system for the measurement of water-related parameters. The core of the system is the SENSWICH platform, which integrates a set of sensors acquiring parameters like pH, electrical conductivity, turbidity, dissolved oxygen and water level. The platform is provided with LoRaWAN connectivity, which allows the long-range remote collection of data, that is then aggregated in the Amazon Web Service (AWS) cloud environment, and then visualized using Grafana.

While the proposed architecture can be used in any context where a large-scale, diffused monitoring of coastal, lakeside or riverine environments is required, the system was specifically designed for the monitoring of the Venice Lagoon, in Italy. In particular, in this paper we present the results acquired by two different SENSWICH platforms: one deployed in the Piovego river, Padova, which is a tributary of the Venice lagoon, and one in Chioggia, in the lagoon itself. Together with these results, an analysis for a full scale deployment in the whole Venice lagoon is proposed.

The results presented in this paper demonstrate that, while being a very low-cost platform if compared with similar technologies available on the market, SENSWICH allows the pervasive monitoring of large water surfaces, enabling the acquisition of reliable datasets for prolonged periods as well as a significant reduction in human resource requirements. Similarly, the proposed software framework for data aggregation demonstrates its effectiveness for the management of large quantities of data acquired using a LoRaWAN network infrastructure as well as its usability through the proposed graphic tool.

***Index Terms*—WAN, IoT, LoRa, Sensor Networks, Climate Change, Biodiversity**

I. INTRODUCTION

In the contemporary dynamic environment, a paramount challenge confronting us is climate change. The impact of planetary heating is experienced worldwide, with coastal and littoral zones exemplifying prominently its effects. These areas not only are at risk from escalating sea levels but also confront heightened occurrences of seaquakes and floods. Moreover, the complex ecosystems of rivers, seas, and lakes, encompassing crucial biodiversity hotspots such as the Natura 2000 protected areas [1], undergo profound alterations attributable to the repercussions of climate change and pollutants.

Among the promptly discernible outcomes of climate change in coastal regions is the elevation of sea levels, caused primarily by two factors related to global warming: the added water from melting ice sheets and glaciers, and the expansion of seawater as it warms.

This expansion, coupled with the dissolution of glaciers and ice sheets, contributes to heightened sea levels. Coastal communities on a global scale are grappling with the ingress of seawater into their domains, resulting in coastal erosion, land depletion, and the displacement of populations.

The occurrence of underwater earthquakes and floods have been associated with climate change. The warming of ocean waters has the potential to destabilize tectonic plates, increasing the likelihood of seaquakes. Moreover, elevated temperatures can intensify rainfall events and, when combined with rising sea levels, may lead to devastating floods in coastal areas.

Natura 2000 constitutes a network of conservation zones within the European Union, comprising Special Areas of Conservation and Special Protection Areas designated under the Habitats Directive and the Birds Directive, respectively. This network covers both terrestrial and Marine Protected Areas [2]. Encompassing diverse ecosystems, including coastal habitats, these areas face a notable risk to biodiversity from the evolving climate. The elevation of sea levels has the potential to disturb the fragile equilibrium within these ecosystems, posing a threat to various plant and animal species.

The effects of climate change are exacerbated by pollution, as pollutants stemming from human activities, including industrial runoff and agricultural chemicals, enter rivers and oceans. These contaminants adversely affect aquatic life and add additional pressure on the fragile ecosystems of coastal and littoral regions.

Acknowledging the gravity of the circumstance, the European Union has initiated the European Biodiversity Strategy for 2030 [3]. This ambitious endeavor strives to safeguard nature and counteract the deterioration of ecosystems. It endeavors to revive impaired ecosystems, prioritize biodiversity in all policy domains, and tackle primary factors contributing to biodiversity decline, such as climate change.

On a global scale, the United Nations has designated the Decade of Ocean Science for Sustainable Development (2021-2030) [4]. This program tries to enhance global collaboration in advancing scientific research and pioneering technologies that connect ocean science with societal requirements. It represents a crucial advancement in comprehending and tackling the challenges confronted by coastal and littoral regions.

Due to the complex nature and constant changes in coastal systems, efficiently monitoring them poses a significant challenge. Nevertheless, inventive solutions are arising [5]–[7]. Intelligent sensors are being utilized to observe diverse environmental factors in coastal and aquatic ecosystems. These sensors provide real-time data, enabling the anticipation, administration, and alleviation of the impacts of climate change and pollution.

The Venice lagoon in Italy stands as a distinctive and intricate ecosystem that has been a focal point for researchers over an extended period. Illustrated in Figure 1, this brackish and shallow water body features salt marshes and experiences significant changes in tides. Investigating the water parameters within this environment proves to be a challenging undertaking.

Fig. 1: Lagoon of Venice, NASA, Aug 7, 2017.

The main contributions of this paper, which extends [8], are the presentation of the final architecture of a water monitoring platform for littoral areas, and the detailed description of the newly-designed advanced prototype of the sensory system and the cloud infrastructure for collecting the data, making it available to scientists and researchers.

This article explores advancements in networking architectures with a focus on the innovative Surface Node concept named SENSWICH. Beginning with a literature review in Section II, we provide insights into existing research in the field. Section III delves into the core of the contribution, presenting the design principles and theoretical foundations of SENSWICH. The implementation details, specifically the utilization of Amazon Web Services (AWS) Cloud Infrastructure, are discussed in Section IV. Moving on to Section V, we present results and engage in a comprehensive discussion, highlighting the performance metrics and implications of SENSWICH. The article concludes in Section VI by summarizing key contributions and discussing potential future research directions.

II. RELATED WORKS

The examination of the marine ecosystem using smart sensor buoys has a long history that spans several decades. Initially developed for meteorological purposes, these buoys have transformed into essential instruments for investigating various marine factors. In recent years, the implementation of extensive ocean observatory systems in crucial places has brought about important changes in marine research.

Modern smart sensor buoys, as we recognize them today, have their origins in early meteorological research [9]. Originally crafted to gather information on sea atmospheric conditions, these buoys offered valuable insights into weather patterns and climate.

The functionalities of smart sensor buoys also evolved with respect to the progression of technology. Researchers quickly grasped the potential of utilizing these buoys for investigating ocean currents [10]. This represented a noteworthy transition in their use, expanding beyond the realm of meteorology.

The role of ocean currents is pivotal in molding the Earth's climate, redistributing heat worldwide, and impacting weather systems. Gaining insight into these currents has become essential for various purposes, ranging from maritime navigation to research on climate change. Smart sensor buoys were modified to precisely measure the speed, direction, and depth of ocean currents. The information collected aided scientists in constructing detailed maps of currents, enhancing navigation safety for ships, and deepening our comprehension of how currents influence marine ecosystems.

Ocean observatories consist of positioned mooring systems equipped with sensor arrays capable of measuring various water parameters at different depths [11]. These observatories allow scientists to gather data from oceanic regions that were previously inaccessible. Located in crucial areas, these observatories utilize smart sensor buoys fitted with sensors measuring parameters like Conductivity or Temperature, and Depth (CTD) probes, Acoustic Doppler current profilers (ADCPs), fluorometers, and other meteorological sensors. Together, these sensors collect data for the understanding of the oceanic dynamics and for the monitoring of the ecosystems health. CTD probes assess seawater properties such as salinity, temperature, and pressure, while ADCPs precisely measure ocean currents. Furthermore, fluorometers identify chlorophyll levels, aiding in the monitoring of phytoplankton populations. To ensure uninterrupted data collection, the buoys are equipped with solar panels and substantial batteries capable of storing over 30 MJ of energy, crucial for operating industrial-grade PCs onboard and supporting high-power communication systems [11]. In general, maintaining the continuous operation of smart sensor buoys in remote ocean locations poses an operational challenge.

Smart sensor buoys serve not only as tools for data collection but also as essential contributors to environmental impact studies. Researchers leverage the data collected by these buoys to evaluate the health of marine ecosystems, monitor pollution levels, and study the impact of climate change. The increasing concern about the human activities on marine environments is addressed through the continuous data collection by smart sensor buoys, aiding in ongoing environmental impact assessments. Scientists utilize this data to track changes in water quality, temperature, and biodiversity, facilitating the identification and mitigation of the negative effects of pollution and climate change on marine ecosystems. Moreover, it empowers scientists to make knowledgeable choices regarding conservation initiatives and the sustainable management of resources.

The significant costs associated with installing and maintaining smart sensor observatory buoys, each with a price reaching several thousand US dollars, are justified by the advanced technology and extensive sensor arrays integrated into these nodes. Despite the substantial financial commitment required for their intricate design, advanced sensors, and deployment challenges in the ocean environment, this expenditure is justified by the abundant data they generate. This data provides valuable insights into the oceans, playing a crucial role in advancing marine science for the well-being of our planet.

In the field of environmental monitoring, the significance of coastal, river, and lagoon ecosystems cannot be overstated as they play a crucial role in preserving the delicate balance of global biodiversity. However, effectively overseeing these shallow water areas, where the depth rarely exceeds 5 meters, poses distinctive challenges. The complexity of these regions, marked by the convergence of multiple channels, various river mouths, and extensive salt marshes, makes deploying a single large observatory buoy less practical. Furthermore, the high costs associated with deploying and maintaining multiple buoy observatories render it an impractical option. In such situations, opting for a low-cost, easily maintainable monitoring system emerges as a more suitable alternative. Substantial efforts have been directed towards this goal in recent years, aiming to fill the gaps in our understanding of these vital ecosystems.

Furthermore, the work in [12] presents another improvement in shallow-water monitoring with the development of an experimental test referred to as the Internet of Underwater Things (IoUT), as introduced in [13]. The system proposed in this contribution consists of two essential components: an underwater node and a surface node, both equipped with sensing devices. What distinguishes this system is its communication method, which relies on acoustics. The data collected by the underwater unit is transmitted to the surface unit which, in turn, sends it to a shore server using the Long Range Wide Area Network (LoRaWAN) technology. This prototype, utilizing an industrial-grade acoustic modem designed for offshore applications, was primarily designed to illustrate the feasibility of the concept. It is important to note that such IoUT system is not intended for medium- or long-term installations but rather serves as a proof of concept for underwater monitoring in challenging shallow-water environments. Together with the acoustic channel, also LoRaWAN radio communication is being studied for superficial underwater to above water data transmission [14], [15]: while this approach may not be used to convey data from the seabed, it may still be significant for the creation of hybrid radio-acoustic solutions within the IoUT context.

In Europe, many research actions have been performed in the context of IoUT [13], [16]–[18]. The SUNRISE project was a pioneer action that involved the federation of five testbeds comprising underwater communication networks in different locations in Europe to help researchers implement and test innovative network protocol solutions for reliable and efficient underwater multi-hop communication between multiple underwater sensors and vehicles. With more focus on the final use-cases, we find the MarTERA RoboVaaS project [16], where an integrated hybrid underwater and above water network allowed the control of unmanned surface and underwater vehicles to perform robotic-aided services for Smart Ports. The whole infrastructure was controlled through a cloud interface, introducing the concept of Robotic Vessels as-a-Service. Similarly, the SAWRMs project [17] made use of an integrated above water and underwater wireless network to expand the use of underwater and surface vehicles in missions of various nature. This facilitated the conception, planning and execution of maritime and offshore operations and missions, in order to reduce the operational costs and increase the safety of tasks and of involved individuals. Also in the US some actions in the context of IoUT have been performed [19], [20]. The SEANet [19] project, for instance, aims at developing a new generation of programmable platforms and a networking testbed to enable the vision of a programmable IoUT. Both SEANet and the modem in [20] are designed to support data rates at least one order of magnitude higher than existing commercial platforms over short range links. Finally, many studies have been performed in Asia as well [21], [22]. These studies often resulted in technology transfer actions through startup companies, such as SubNero [21], or practical testbeds, like the one in [22] composed by six AquaSeNT OFDM acoustic modems.

Among the other European projects, the SubCULTron initiative, outlined in [18], introduces an array of underwater and surface sensors and vehicles aimed at revolutionizing the understanding and exploration of the underwater environments. Crafted with precision and featuring cost-effective acoustic modems and WiFi modules, these sensor systems have the potential to reshape the landscape of coastal sensor networks. A notable outcome of the SubCULTron project is the establishment of H2ORobotics [23], an innovative startup affiliated with the University of Zagreb. H2ORobotics has successfully brought some of the sensor systems developed in the project to the commercial market. Particularly noteworthy is their introduction of a budget-friendly surface vehicle, marking a significant step forward in making advanced underwater and surface sensors more widely accessible globally.

Other efforts on making low-cost observatories are currently in progress. The Argo floats [24], for instance, aim to collect CTD data around the world. FONDRIEST [25], instead, supplies smart buoys that can simply be equipped with various sensors and wireless communication systems. SOFAR recently developed Spotter [26], a low-cost buoy quite similar to SENSWICH, but less tailored to deployments in the Venice Lagoon due to the higher power consumption and the fact that its eye-catching design may make it prone to vandalism or theft. Similar issues may be faced with the MDM Ulysse line of products that, however, seems to be a valuable alternative in the open sea, also thanks to their low-power surface vessels [27]. Even though all these devices are classified as low cost when compared to large observatories [11], their price per unit is more than two or three times the price of a SENSWICH floater (for instance, the price of a SOFAR Spotter is 6600 USD, more than three times the price of a SENSWICH node).

III. SENSWICH: THE SURFACE NODE

In this section we describe the SENSWICH surface node, designed to measure diverse parameters including pH, electrical conductivity, turbidity, liquid level (with a conscientious consideration of ensuring the dependability of outcomes contingent upon the apt positioning of surface sensors in the aqueous milieu), dissolved oxygen, and temperature. Antecedent examinations of SENSWICH and its inaugural trials in [8] unveiled its efficacy as a cost-effective, real-time monitoring device for climate change. Hence, the relevance of such inquiries extends beyond the efficacy of the apparatus, encompassing the substantive import of extensive data acquisition and protracted analytical scrutiny. Consequently, a decision was made to deposit and scrutinize the amassed data in the Amazon Web Services (AWS) cloud service.

Moreover, the improvements of the main board structure involved a shift from using two Arduino boards to a single Arduino. This change has been made possible by a new circuitry arrangement aimed at ensuring reliable results and energy efficiency. Ensuring electrical isolation among voltage-based sensors was also a key focus in the updated version of SENSWICH. These significant modifications collectively enhance the establishment of a stronger and more effective environmental monitoring system.

A. System Requirement

The peculiarity and heterogeneity of the Venice Lagoon, characterized by several micro-environments due to the convergence of multiple channels and to the presence of various river mouths, and extensive salt marshes, makes the deployment a single large observatory buoy not effective to well characterize such a peculiar environment. In such scenario, the deployment of a low-cost, easy-to-maintain monitoring system emerges as a more suitable alternative. The proposed system is composed of several low-cost low-power floating sensors, named SENSWICH, deployed in the whole lagoon, able to collect and transmit water measurements for several consecutive days with high granularity in time and space. In order to lower the power consumption, the system is kept off most of the time, and switched on every 15 minutes, only for the time needed to acquire the measurements from the sensors and send them to shore. Four samples per hour is indeed considered to be sufficient to characterize the environment. The GPS module of SENSWICH, which is the most power demanding component of the node, is expected to be maintained almost always off: it will be turned on only when specifically required by the operator, that from shore can send a command to get the node position and verify if it is still located in its deployment site. Ideally, the distance between neighbor sensors will be around a few hundred meters, but a more dense deployment is envisioned in hot-spot areas. The high activity of sea life in the lagoon leads to water sensors becoming eventually encrusted with bio-fouling. This calls for periodic maintenance to clean the sensors: during this operation the battery will also be replaced. According to our previous knowledge, maintenance is required every sixty days, hence, we can dimension the battery capacity to provide an autonomy of about two months. We went through this solution instead of solar panels mainly for two reasons:

- extending the battery life for more than the time the sensors can be fully operational will only make the system more complex and expensive without providing any evident benefit;
- given the high number of fishermen, tourists and people moving across the lagoon, the use of floating systems should be as minimal as possible to discourage them them approaching it: the presence of a solar panel would easily attract the attention of people that may dangerously get close to it.

In fact, the floating sensor should be as anonymous as possible, otherwise it will become an easy target for vandalism or theft. Hence, shiny colors, fancy structures and attractive tools like solar panels should be avoided. In addition, to keep the system light and low-cost we cannot equip it with many batteries: this imposes the engineering challenge of making the whole system very low-power, minimizing the number of components and selecting low-power transmission technologies like LoRaWAN instead of more power demanding solutions like 4G.

To ensure extensive connectivity with a low-power transmitter, we opted to integrate a Long Range Wide Area Network (LoRaWAN) transceiver into the sensor. This transceiver enables transmission to a shore gateway situated up to 10-15 km away from the sensor. This approach allows to effectively cover nearly the entire Venice lagoon with just three gateways. (Please, refer to Figure 2 for a visual representation of the coverage area.)

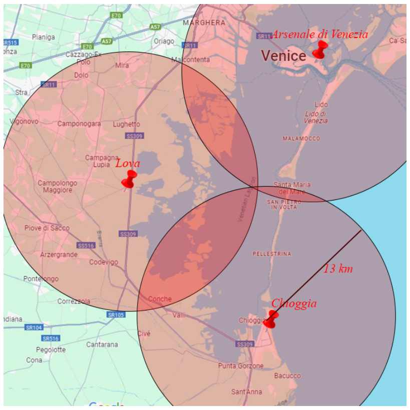


Fig. 2: Expected coverage area of three LoRaWAN gateways.

B. Sensor Selection

The compendium of sensors comprises:

- Analog Industrial pH Sensor/Meter Pro Kit V2 (SEN0169-V2);
- Analog Electrical Conductivity (EC) Sensor/Meter K = 10 (DFR0300-H);
- Analog Turbidity Sensor (SEN0189);
- Waterproof DS18B20 Temperature Sensor Kit (KIT0021);
- Analog Dissolved Oxygen (DO) Sensor / Meter Kit (SEN0237-A);
- Photoelectric High Accuracy Liquid Level Sensor (SEN0205).

To the best of our knowledge, these are among the cheapest liquid sensors available on the market. Moreover, the great documentation and the active forum community allowed us to speed up their integration in our system. Although most of these sensors are laboratory probes not designed for continuous data measurements, their use with the SENSWICH isolation circuit ensures their correct operation for months.

Together with these sensors, the system integrates also a TEL0094 GPS Module with Enclosure. Additionally, there is a shift from the previous model, now utilizing only one Arduino unit in the current setup. This decision is made to balance power conservation and circuit simplification. The chosen Arduino for essential tasks like data acquisition and transmission is the Arduino MKR WAN 1310 board. This device combines a SAMD21 Cortex-M0+ 32-bit low-power ARM MCU with a Murata CMWX1ZZABZ LoRa chip, working across the 433, 868, and 915 MHz frequency bands. The MCU, equipped with 7 Analog input pins and 8 Digital I/O pins, facilitates the efficient connection of all the sensors to a single board.

C. Data Measurement and Transmission Utilizing SENSWICH

In previous studies, we utilized two Arduinos instead of one, as detailed in [8]. To improve the system power consumption and reduce its complexity, we decided to reconfigure SENSWICH removing one of the two Arduino boards used in the previous version of the system. This second Arduino was used to decouple active sensors, like PH and conductivity, whose interference would lead to inaccurate measurements. After conducting electronic investigations, we wanted to be sure that there could be no interference between sensors inside a salty environment which may work as a conductor. To avoid this type of interference, we started to investigate different types of electrical insulators, and ended up developing a tailor-made solution.

To create electrical isolation in the various parts of the circuit, we studied different solutions. Initially, we analyzed existing insulation and assessed their performance based on some features like the manufacturing companies, signal type, zero-load input current, sleep current, and price (Table I).

TABLE I: Commercial solutions for electrical isolation.

Manufacturer	Signal type	Zero load input current	Sleep current	Price
Atlas Scientific	UART, I^2C, SMBus	20 mA	3.8 mA	$24.99
Atlas Scientific	UART, I^2C	22 mA	2.6 mA	$28.99
Atlas Scientific	Analog	15.7 mA	—	$25.99
DFRobot	Analog	75 mA	—	$19.90
DFRobot	I^2C	15 mA	—	$16.00
Our Solution	Analog	≈ 0	≈ 0	$\approx$ $29.40

As a result, we opted against using these power insulators due to the following drawbacks:

1) As indicated in Table I, the existing brands compatible with the SENSWICH circuit exhibited excessive power consumption, which is a critical consideration in our project [8]. Given that even tens of milliamperes are significant in this context, these insulators were deemed unsuitable;
2) Their efficiency did not meet our requirements, considering the high power consumption and the fact that they only separated electrical signals, a task achievable with alternative methods discussed later in this paper;
3) Some insulators consumed power even during sleep mode, which is unfavorable for SENSWICH, as biologists require measurements of various water parameters every few minutes (e.g., every ten or twenty minutes).

Hence, we decided to proceed with low-power relays: their arrangement in the SENSWITCH circuit is presented in Figure 3, and depicted in Figure 4. The circuit employs DPDT single-coil-latching micro-relays, specifically the IM41TS model manufactured by “TE Connectivity”. It is a power efficient relay and, according to its datasheet [28], the coil power consumption during switching is around 140 mW in standard models, 100 mW in high sensitive models, and 50 mW for ultra high sensitive models. As it performs switching in 1-3 ms, we can consider its contribution to the average power consumption as negligible. These components are designed for precise analog signal switching and offer several advantages:

- compact size (10x6 mm), occupying only 60 mm^2 of board space;
- excellent contact stability and long life due to gold-plated PdRu contacts, resulting in a connection resistance of less than 50 mΩ and a minimum electrical endurance

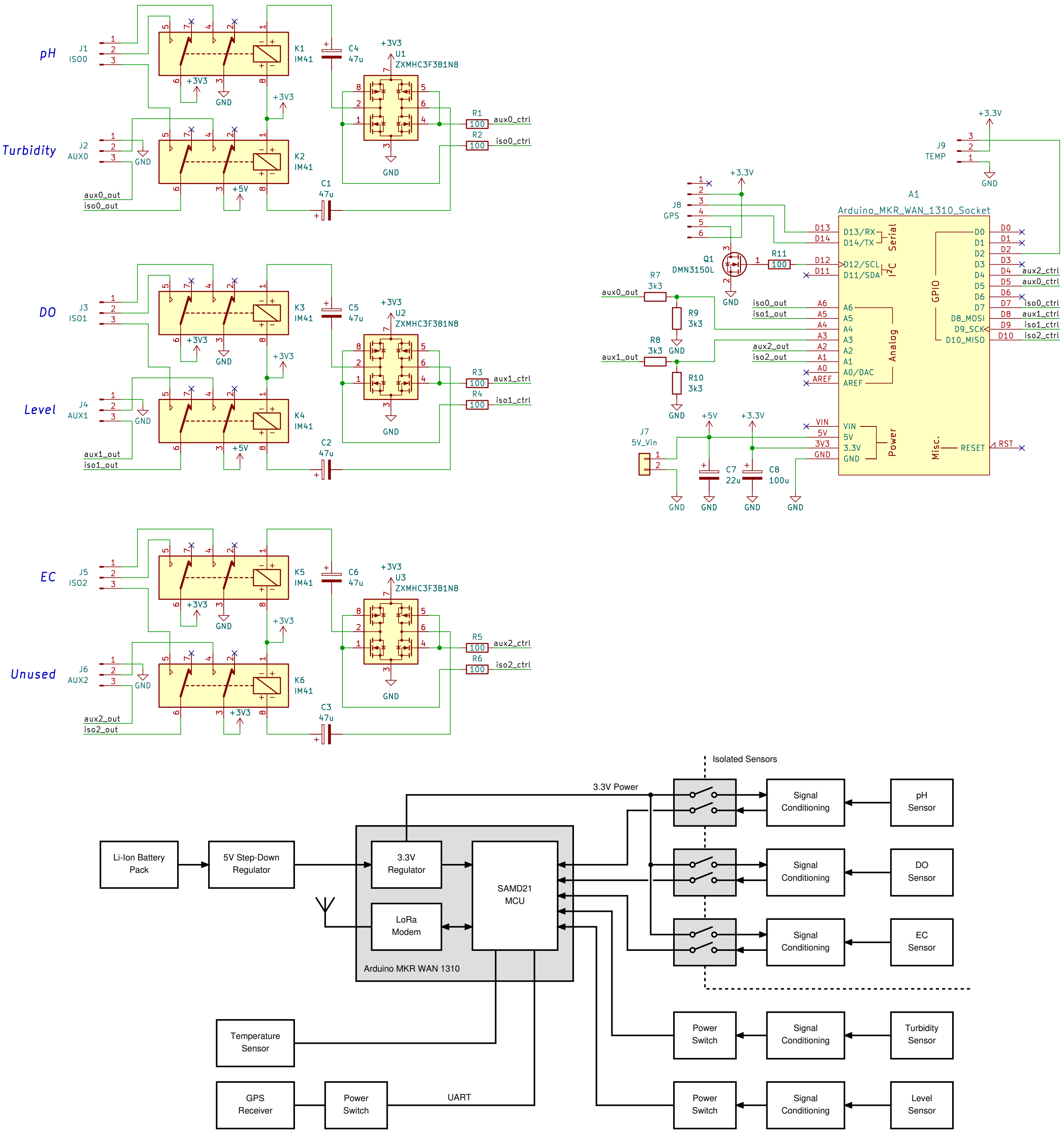


Fig. 3: Schematic and diagram block of SENSWICH with one Arduino (all relays initially are in reset mode).

of approximately 10^6 switching operations, sufficient for the expected operational life of the node;

- low coil excitation voltage of 3 V, eliminating the need for complex voltage translation circuitry;
- hermetically sealed case to prevent performance degradation from moisture and contaminants in the atmosphere;
- affordable, with a cost of around \$3.5 per piece for single quantities.

To generate bidirectional current pulses for the relay coil configuration, we used a discrete MOSFET half-bridge driver with a series capacitor. The selected MOSFETs (U1 through U3 in Figure 3) have a low gate threshold voltage, enabling direct logic-level drive from an Arduino digital output pin. This eliminates the need for an external gate driver, reducing cost, complexity, and power consumption.

For complete electrical isolation of electrochemical sensors (pH, EC, and DO), all three connections from the signal conditioning module (VCC, GND, and analog output) must be

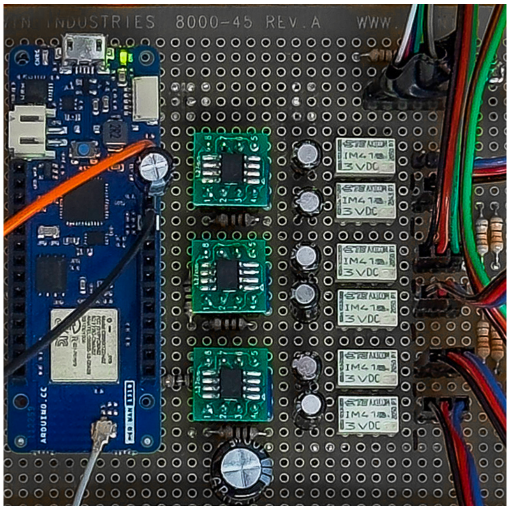


Fig. 4: Circuit of SENSWICH with one Arduino.

interrupted. Thus, two separate relays with three mechanical contacts are utilized. The unused contact in this configuration switches the power terminal to one of the remaining sensors (turbidity and liquid level), which do not require complete electrical isolation since there is no electrical contact with water.

In general, this solution meets the isolation requirements for sensors while preserving signal integrity and consuming virtually zero idle power after the switching transient (which requires a pulse of 10 mA that lasts 1 ms). Additionally, it requires less than four external components per acquired parameter, reducing manufacturing cost and the risk of malfunctions during operation.

We equipped SENSWICH with 8 Li-Ion batteries according to the specifications in Table II. Subsequently, we employed an LM2596 regulator to convert the voltage from nominal voltage 7.4 V to approximately 5.25 V, ensuring a stable power supply for the Arduino. Powering the Arduino at 5.25 V is crucial for optimal sensor functionality, and specifically, the turbidity and liquid level sensors require a 5 V input voltage.

TABLE II: Information of Power Source of Senswich

Parameter	**Value**
Cell capacity (mAh)	3200
Cell energy (Wh)	11.5
Nominal cell voltage (V)	3.7
Number of series cells	2
Number of parallel cells	4

The Arduino is programmed to read the sensor data and send the sampled values via LoRa at regular intervals of 10 minutes, while remaining in the lowest power sleep mode available (called "Standby mode" of the SAMD21 microcontroller) during periods of inactivity. An acquisition cycle is initiated by an interrupt from the Real-Time Clock (RTC) module, which ensures a constant sampling period, after which all the sensor data is read out following a procedure outlined later. Subsequently, the raw values are corrected using calibration constants stored inside the flash memory of microcontroller, organized into a single packet following the CayenneLPP structure. At the end, this single packet is sent to AWS over LoRa, afterwards the Arduino goes back to standby mode.

Because of the relay contact arrangement shown in Figure 3, a specific sequence of operations must be carried out. As an example, in order to read pH and turbidity, firstly relay K1 is switched to the "set" position, powering the pH probe and the associated signal conditioning module. During the subsequent 80-second period required for this sensor to stabilize, the turbidity sensor is kept off to preserve energy. Next, relay K2 is set, simultaneously connecting the pH output to the analog input of the Arduino and powering the turbidity sensor, which will present stable readings after about 10 seconds. At the end, the voltage output from each sensor is read by the ADC, averaging over 256 samples to further reduce noise, and both relays are reset. This procedure is repeated for DO, liquid level, EC and the unused input J6.

Regarding the GPS feature, the activation of the module begins by transmitting a "gps" string in base64 encoding within the AWS Payload segment. It is crucial to note that the GPS sensor stays active for a maximum duration of 5 minutes (if it can find the location in less than that time, it is going to be turned off). After that, it enters a sleep state. If the sensor encounters challenges in determining its location due to unfavorable weather conditions or a displaced device, a new activation request needs to be sent through a designated message.

IV. CLOUD INFRASTRUCTURE

This section presents the Cloud architecture based on AWS used to store and visualize the data collected by SENSWICH. The design of the infrastructure will be discussed, describing the core services involved, from the data acquisition to the final visualization tools.

A. *Design of the Cloud Architecture*

Modern cloud computing platforms offer a wide range of services such as computing power, storage, and databases that can be used to build and deploy various types of applications, including IoT sensor networks. One of the key advantages of using a cloud-based solution for an IoT sensor network is its scalability. Such platform usually allows for the easy addition and removal of resources as needed, which is important for a sensor network that may need to handle varying levels of data traffic. Moreover, a cloud platform also provides a range of security features, such as identity and access management, encryption, and network isolation, which are essential for protecting sensitive IoT sensor data. Additionally, it provides a wide range of services for data storage and management

For instance, AWS [29] offers a variety of services specifically tailored for IoT, such as AWS IoT Core for device connectivity, AWS Greengrass for local device computing, and AWS IoT Analytics for data processing and analysis. Additionally, in terms of data storage and management, AWS includes Amazon Timestream, Amazon S3, Amazon DynamoDB and Amazon Elasticsearch, which can be used to store and analyze large amounts of sensor data.

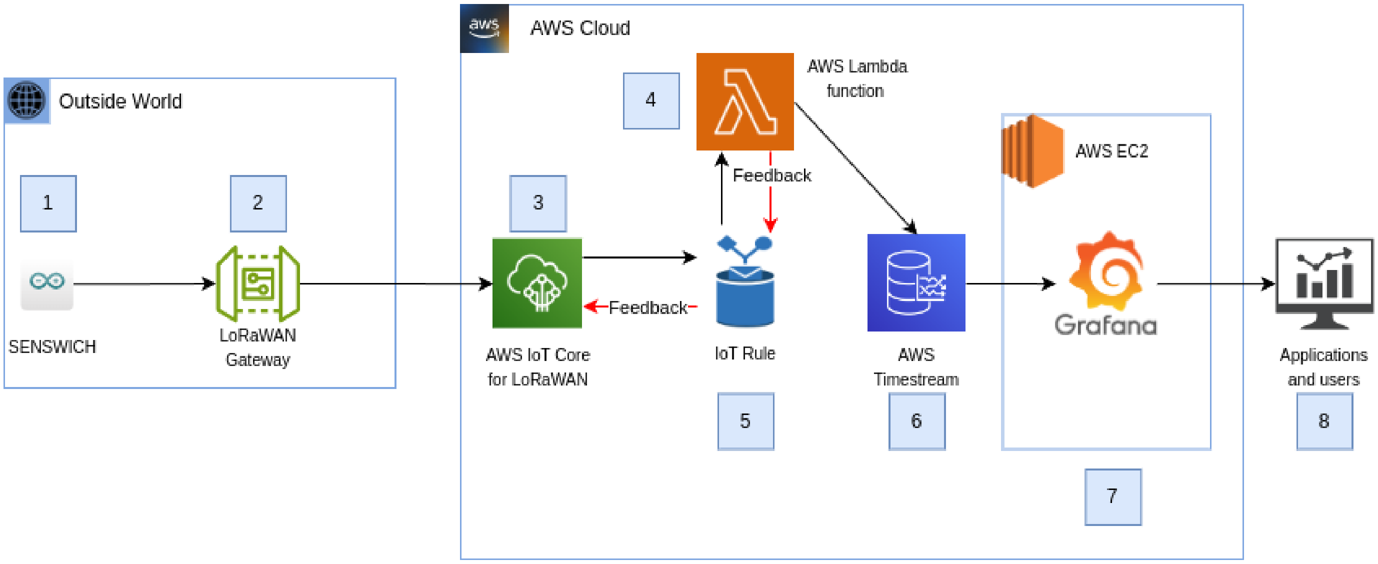


Fig. 5: Cloud architecture used to collect, store, and visualize the data.

The proposed solution for the Cloud architecture and Internet of Things (IoT) sensor network, as illustrated in Figure 5, is composed of two main parts: the Outside world and the AWS cloud [29]. The Outside world includes all the IoT Arduino endpoints and the LoRaWAN gateway, which establishes a secure connection to the AWS IoT Core for LoRaWAN [30] using a double channel and certificate-based authentication. The Arduino then encodes the water data and creates a payload using the CayenneLPP format [31]. This payload is added to the LoRa packet and sent to the gateway.

The AWS cloud is composed of the AWS IoT Core for LoRaWAN, which receives the LoRaWAN packets from the gateway and triggers an AWS rule to handle these packets thanks to a topic in MQTT protocol [32]. A SQL query inside the AWS rule is then used to initiate an AWS Lambda function, which decodes the data received from Base64 to CayenneLPP and then from CayenneLPP to ASCII cleartext. The packets are then modified and augmented with the new decoded data, and finally stored into the Amazon TimestreamDB using Python SDK, making it available for visualization through the Grafana service running on an AWS EC2 virtual machine. AWS Lambda function gives a feedback to the AWS rule on the operation success: if the decoding and storing processes are completed correctly, the packet is republished in *lorawan* MQTT topic, otherwise in *lorawan/error* MQTT topic, allowing the operator to understand what is happening in real-time.

Inside the Grafana service, users can be added with different permissions and groups and each user can use the admin preconfigured dashboard with tables and graphs to visualize quasi real-time data or create their own dashboards and query the Amazon Timestream database to retrieve the data. This allows for flexibility and ease of use in monitoring and analyzing the sensor data.

This is the general operating mechanism for the common water measurements, like temperature, PH, turbidity and the others. The approach is different to retrieve the GPS position of SENSWICH, which is not sent periodically and requires a manual action performed by the operator. In this case, the administrator wanting to get this information has to enqueue a downlink message to the sensor in order to activate GPS and receive the position in next periodic data transmission. This operation can be easily done with the AWS console (Figure 6), where the operator can insert the FPort field of the application and the base64 encoded payload of the packet.

B. *LoRaWAN network server*

Since our sensor is designed to communicate with Long Range (LoRa) modulation and according to the LoRaWAN MAC protocol, we set up a complete LoRaWAN network, which is composed of three main components: the end devices, the gateways, and the LoRaWAN Network Server.

The end devices, such as the Arduino endpoints used in the proposed solution, have sensors that collect data and send it to the gateway. End devices communicate with the gateway using the LoRaWAN protocol and security credentials. In the LoRaWAN network, they are uniquely identified by an Extended Unique Identifier (EUI).

The gateway, also known as the Basic Station Gateway [33], receives the data from the end devices and forwards it to the Network Server; it also receives messages from the Network Server and forwards them to the end devices, allowing the transmission of actuation commands, like the GPS request in our case.

The Network Server is the central component of the LoRaWAN network, and is responsible for managing the communication between the gateways and the end devices, for managing the security, the access control and the device management. Between the two, there are two protocols involved by Network Server to fully control gateways and exchange data: LoRaWAN Network Server (LNS) and Configuration and Update Server (CUPS).

LNS [34] is the underlying protocol (over Web Socket) that allows the gateway to communicate with a Network Server. Different types of messages are exchanged with the gateway to, e.g., configure the gateway physical layer, forward uplink and downlink messages, and keep the gateway synchronized with the Network Server. LNS also provides a secure communication channel between the gateway and the cloud using the Transport Layer Security (TLS) protocol, which ensures that the data is transmitted securely.

CUPS [35] is an optional protocol (over HTTP) used by the Network Server to send to the gateway all the backend configurations, such as credentials for the TLS protocol, along with a generic data segment with arbitrary updates. Although its use is not compulsory, it is commonly used as preliminary connection by the gateway for retrieving LNS endpoint and credentials and then starting the real LoRaWAN traffic through the LNS protocol.

In our scenario, the end devices would be the SENSWICH, the gateway would be any commercial LoRaWAN gateway available on the market (e.g., the MultiTech Conduit® IP67 Base Station) and the LoRaWAN Network Server would be running in the cloud. Specifically, in our setup we used the LoRaWAN Network Server provided by AWS IoT Core for LoRaWAN, part of the more general AWS IoT Core service.

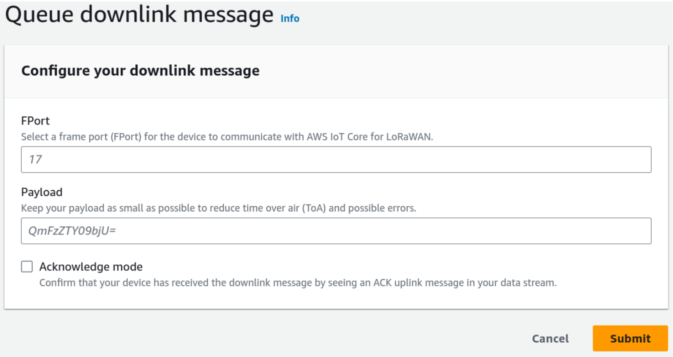
AWS IoT Core [36] is a fully managed platform that enables the connection, management, and processing of data from IoT devices. It provides a set of services to connect and manage devices, including device registration, device provisioning and device management, allowing businesses to focus on creating innovative solutions and applications that leverage the data generated by IoT devices. Additionally, it includes a message broker that allows devices to securely and efficiently send and receive messages.

AWS IoT Core allows for the processing and analysis of data from devices using services such as AWS IoT Analytics and AWS IoT Events. These services enable the creation of complex workflows for data processing, analysis, and triggering of actions. It also enables integration with other AWS services, such as AWS Lambda, Amazon S3, Amazon DynamoDB, and Amazon Kinesis, providing a wide range of options for storing, analyzing, and acting on device generated data. AWS IoT Core also provides a secure communication channel between the base station and the cloud using the Transport Layer Security (TLS) protocol, which ensures that the data is transmitted securely.

In addition, AWS IoT Core also provides security features such as authentication, authorization, and access control to ensure the secure communication between devices and the cloud. It also supports the integration with other security mechanisms such as Virtual Private Cloud (VPC) and PrivateLink.

AWS IoT Core for LoRaWAN [30] is a LoRaWAN Network Server that allows to connect and manage LoRaWAN gateways and end-point devices on AWS. It is part of the AWS IoT Core main service, and is used to securely connect, provision and manage devices. It provides public APIs to register gateways and devices, setting the operating frequency band and performing a first level monitoring of the live traffic. Behind the scenes, it fully implements the procedures and the specifications of the LoRaWAN protocol, freeing the developer from low level tasks.

The service also allows to process and route device data to AWS services and to create IoT applications for LoRaWAN devices.



Queue downlink message Info

Configure your downlink message

FPort

Select a frame port (FPort) for the device to communicate with AWS IoT Core for LoRaWAN.

17

Payload

Keep your payload as small as possible to reduce time over air (ToA) and possible errors.

QmFzZTY09bjU=

☐ Acknowledge mode

Confirm that your device has received the downlink message by seeing an ACK uplink message in your data stream.

Fig. 6: Queue downlink message window.

The connection between the LoRaWAN gateway and AWS IoT Core for LoRaWAN is established using the standard LNS protocol. The gateway connects to the AWS IoT Core for LoRaWAN using its EUI and security credentials, such as a certificate or key. This enables the gateway to securely send and receive data to and from the AWS IoT Core for LoRaWAN service. Once the connection is established, the gateway can send LoRaWAN packets containing sensor data from the Arduino endpoints to the AWS IoT Core for LoRaWAN service. The service then triggers rules that are used to process the data and route it to other AWS services such as AWS Lambda or Amazon TimestreamDB. This allows to create IoT applications that can process and analyze sensor data in real time.

To summarize: the end devices send the data to the Basic Station Gateway which then forwards it to the Network Server managed by AWS IoT Core for LoRaWAN. This allows for secure and efficient communication between the end devices and the network server and enables processing and routing of device data to AWS services for further analysis. In our architecture our data is redirected to AWS IoT Rules, another sub-service of AWS IoT Core.

C. *Data processing and memorization*

AWS IoT Rules [37] is a service included in AWS IoT Core that enables the creation of rules that automatically perform actions on data from IoT devices when specific conditions are met. These rules are used to route, filter, and process data from IoT devices at the edge. They can be applied to all messages or to specific messages based on topic, source, or payload. They can be used to build a wide range of IoT applications and use cases, including smart homes, industrial automation, and predictive maintenance.

AWS IoT Rules allows for the easy creation of rules that perform actions such as sending data to Amazon S3, Amazon DynamoDB, or other services for storage and analysis, triggering an AWS Lambda function, or sending a message to an Amazon SNS topic. Additionally, rules can be used to forward data to other AWS services like AWS Greengrass, AWS Kinesis, AWS Elasticsearch, and more.

Custom actions can also be implemented using AWS Lambda functions in multiple languages.

AWS Lambda [38] is a serverless compute service that runs code in response to events and automatically manages the underlying compute resources. With Lambda, users can run code for virtually any application or backend service, all with zero administration. Users simply upload the code and Lambda takes care of everything required to run and scale their code with high availability. They can set up the code to automatically trigger it from other AWS services or call it directly from any web or mobile app.

AWS Lambda supports multiple programming languages including Java, Python, C#, Go, and Node.js. It can be used to build event-driven applications and microservices, process and analyze data, and run backend services for mobile and web applications. It operates on a pay-per-use basis, with no charge when the code is not running. It also allows for automatic scaling based on incoming requests or other metrics, eliminating the need for provisioning and scaling servers, and integrates with other AWS services.

Integration with other AWS services, such as Amazon S3, Amazon DynamoDB, and Amazon SNS, allows for the building of powerful end-to-end applications. This makes AWS Lambda an attractive option for building event-driven and serverless applications due to its scalability and cost-effectiveness.

Amazon Timestream [39] is a fully managed time series database service that enables users to store, process, and analyze time-stamped data at scale. It is designed to handle high write and query loads, and optimized for storing and analyzing time-stamped data, such as IoT sensor data, application logs, and clickstream data.

Users can create a database and define tables within it, where each table can have multiple dimensions and measures, allowing for easy data modeling and analysis. Timestream also provides a SQL-like query language to easily query and analyze data.

Timestream integrates with other AWS services, such as Amazon CloudWatch, AWS IoT and AWS Lambda, making it easy to collect, store, and analyze time-stamped data from various sources. A retention period can be set to automatically expire data that is older than a certain number of days, reducing storage costs and allowing for better management of data over time.

D. Data access and visualization

AWS Elastic Compute Cloud (EC2) [40] provides a platform to create virtual servers that can be used to run applications as if they were deployed in a local datacenter. The power of this AWS service is its flexibility: it is possible to provision the virtual machines with the hardware needed, equipping it with the required CPU, memory, storage and network interfaces.

When an operator creates an EC2 instance, it first has to choose the type of machine specifically from the use it has to accommodate, for instance there are general purpose machines, storage optimized machines, compute optimized ones and so on. The instance can be prepared with an Operating System (all the most common ones) and applications installing a predefined image or a custom one. Then, the external environment of the machine has to be configured, so the region where it is physically located and the VPC on which it resides, configuring also its network interfaces accordingly. Moreover, the best security options for the specific use-case can be chosen and, finally, there is the possibility to scale the service in order to avoid general failures and manage the different loads.

In our infrastructure (Figure 5) we just deployed one virtual server with Grafana application inside, which is publicly available in the Internet. Grafana [41] is a platform used for live monitoring and visualization of data incoming from different sources, depending on the background solution implemented. As we know, in our specific case data are fetched from an AWS Timestream database hosted in the cloud. Grafana simplifies the setup and management of customizable dashboards and panels used to visualize the information for multiple teams or projects. Alerting and notifications feature allows users to set up alerts and notifications that trigger when specific conditions are met, such as when a metric exceeds a certain threshold. Role-based access control provides granular access controls that allow to specify which users have access to dashboards and panels. Data security is provided by a number of security features, such as encryption, to help protect user data.

V. RESULTS AND DISCUSSION

Fig. 7: Setup of sensors in a bucket.

For testing purposes, we placed all sensors in a bucket filled with saline solution, as shown in Figure 7. The data acquired from the sensors with the Arduino MRK WAN and the SENSWICH circuit was sent through LoRaWAN to the Gateway connected with the AWS cloud infrastructure.

To measure energy consumption, we initially employed a regulator to supply 5.25 V as the input voltage to the Arduino. Table III provides a comprehensive overview of power consumption across distinct sensor phases, aiding in identifying the energy utilization patterns of the Arduino MKRWAN 1310 during various phases.

We can infer that Table IV illustrates power consumption measurements based on information gathered from Table III. The current is measured directly at the battery terminals, thus

TABLE III: Energy Consumption With Using Regulator

Phase	Duration (s)	Current (mA)	Energy (J)
pH	80	18.2	12.37
pH + TB	10	30	2.55
Analog Reading	5.12	39	1.69
DO	80	16.5	11.22
DO + LV	10	26.1	2.21
Analog Reading	5.12	35	1.52
EC	20	24.7	4.19
Analog Reading	5.12	33.9	1.47
LoRa TX	2	41.8	0.71
Standby	382.64	15.7	51.06

the discharge time estimate takes into account the quiescent power consumption of the DC-DC regulator.

TABLE IV: Power Consumption With Using Regulator

Parameter	Value
Idle power (mW)	133.45
Energy/sample (mWh)	24.73
Average current (mA)	17.45
Average power (mW)	148.38
Discharge time (h)	733.20
Discharge time (days)	30.55

This indicates that the device may remain active for one month with a single battery charge.

Table V shows the energy consumption assuming a 100% efficient converter from battery voltage to 5.25 V, and Table VI illustrates power consumption measurements based on information from Table V. These values are estimated by measuring the current at the output of the regulator, which includes only the active currents of the various components, and are thus indicative of the system's minimum possible power consumption.

TABLE V: Estimation of Energy Consumption Without Using Regulator

Phase	Duration (s)	Current (mA)	Energy (J)
PH	80	12.4	5.208
PH+TB	10	26.5	1.39
Analog Reading	5.12	38.2	1.02
DO	80	10.2	4.28
DO+LV	10	21.7	1.13
Analog Reading	5.12	33.2	0.89
EC	20	17	1.78
Analog Reading	5.12	28	0.75
LoRa TX	2	38	0.39
Standby	382.64	9.3	18.68

TABLE VI: Estimation of Power Consumption Without Using Regulator

Idle power (mW)	48.82
Energy/sample (mWh)	9.87
Average current (mA)	11.28
Average power (mW)	59.267
Discharge time (h)	1552.27
Discharge time (days)	64.67

These results suggest that the device may stay operational for up to around 64 days with a single charge, highlighting the fact that the regulator is wasting almost half of the energy, and is then not very efficient. Moreover, the Arduino standby current can be significantly reduced removing the onboard LEDs Arduino uses to signal its correct operation, further extending the battery duration.

Given the effectiveness of the developed prototype, we have recently created the first SENSWICH PCB in order to quickly reproduce more units of the system. The first PCB unit is presented in Figure 9. We further deployed SENSWICH for two weeks in the Piovego Canal (Figure 8a) during the first two weeks of May 2024, and from mid-May for fifty days in Chioggia (Figure 8b) in the Venice Lagoon, in front of the Hydrobiological Station Umberto D'Ancona. The SENSWICH ran out of battery in the second week of July 2024. However, the limitations of the current system are neither related to power consumption nor to the data delivery to the cloud infrastructure through the LoRaWAN network, but rather to the need for periodic cleaning of the sensors (once a week) to obtain reliable data measurements from all sensors due to the high bio-fouling activity during this time of the year. In winter we expect that cleaning will be less frequent (e.g., once a month or even less) as bio-fouling will be drastically reduced because of the cold temperatures. In the meantime, we plan to mitigate the bio-fouling effect by covering the sensor with a copper net, that has the property of being a natural anti-fouling material [42].[1]

(a) Piovego Canal (b) Chioggia

Fig. 8: Deployment in Padova, in the Piovego Canal (a) and in Venice Lagoon, in Chioggia (b).

We utilized Grafana to integrate and display data from various sensors simultaneously, as shown in Figure 10. As an example, in the picture we can observe the data collected from all sensors (and sent through LoRaWAN to the AWS server) over a period spanning from May 6, 2024, to May 10, 2024 in Piovego Canal. To better illustrate the plots, we extracted the .csv files of each sensor, which contain the collected data from that period, from Grafana's panel. We then plotted them using a Python script. From a biological perspective, temperature and DO are related to each other, as illustrated in Figure 11, which shows their correlated results. In our experiments, we anticipated that rising temperatures

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[1] This solution needs to be carefully tested to investigate whether copper impacts on the measurements and on the studied organisms.

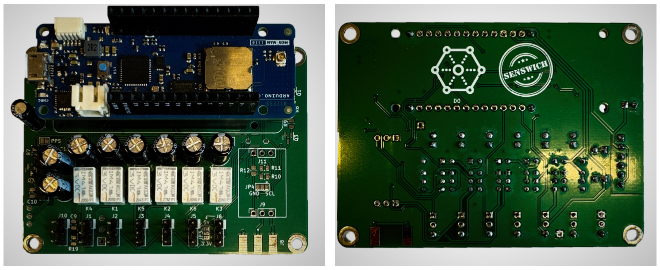
(a) (b)

Fig. 9: Front part (a) and back part (b) of the SENSWICH PCB.

would usually lead to a decrease in DO levels. However, this expectation was not met with respect to the influence of another environmental factor: photosynthesis. During the day, the presence of sunlight activates photosynthesis, which is an instantaneous process [43], and makes the oxygen dissolved in the water increase. This process significantly affects DO levels during daylight hours. Moreover, although DO levels and temperature follow the same trend, we can notice that the increase on temperature is slightly delayed compared to DO. This is because the water temperature rises slower if compared to the rapid response of photosynthesis to sunlight. Regarding the Liquid Level sensor, this digital device indicates whether the SENSWICH was submerged in water during a certain time. If we received data while the Liquid Level sensor showed “false,” it implies that the data from the other sensors (except the GPS sensor, which is not related to water parameters) may not be reliable. To demonstrate the Liquid Level sensor’s results, we also considered a few hours before and after submerging the SENSWICH in water to show the difference between the results inside and outside the water (Figure 12). Figure 13 illustrates the outcomes of the pH sensor, Figure 14 presents data acquired by the Electrical Conductivity Sensor, and Figure 15 relates to Turbidity. The fluctuation in the plot occurred because small particles became lodged between the plastic head of the sensor. Since it is an optical sensor, even minor obstacles can affect the measurements. After these particles were automatically dislodged by the water current over time, the measurements displayed accurate values. As already mentioned, we expect this issue to be mitigated by applying a copper cover to the sensor in the next generation of the SENSWICH platform. Optionally, in Grafana turbidity can also be shown in NTU by converting Volts to NTU units as follows [44]:

$$y = -1120.4x^2 + 5742.3x - 4352.9,$$

where y represents the amount of turbidity in NTU units, and x represents the voltage in volts. Regarding GPS coordinates, after retrieving the payload message from AWS, we obtained accurate latitude and longitude details. Using Grafana, we effectively identified the location of SENSWICH and visually represented it on the map shown in Figure 16.

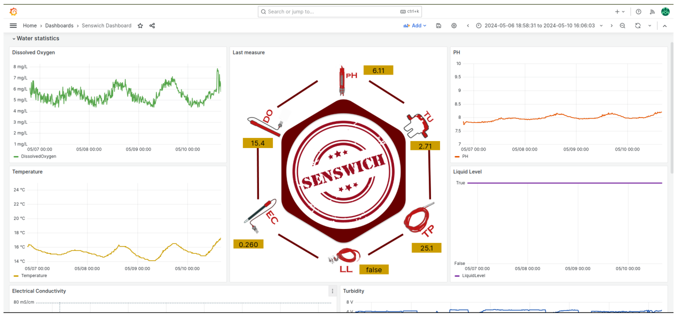

Fig. 10: Visualization in Grafana.

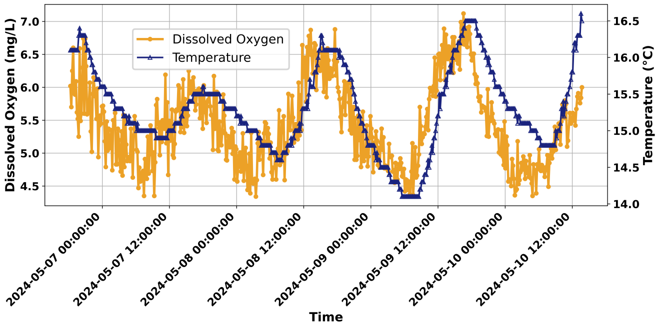

Fig. 11: Comparison of Dissolved Oxygen (DO) and Temperature sensor measurements.

Fig. 16: The location of SENSWICH is mapped using GPS data.

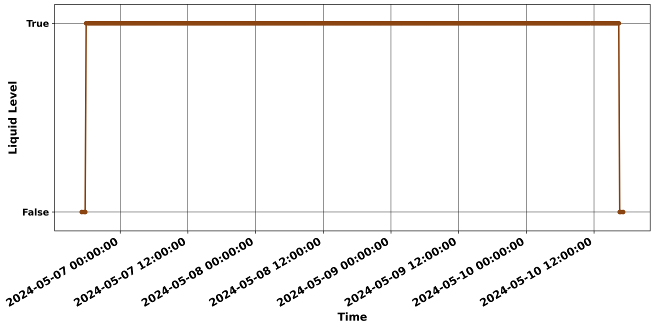

Fig. 12: Results from the Liquid Level sensor measurement experiment.

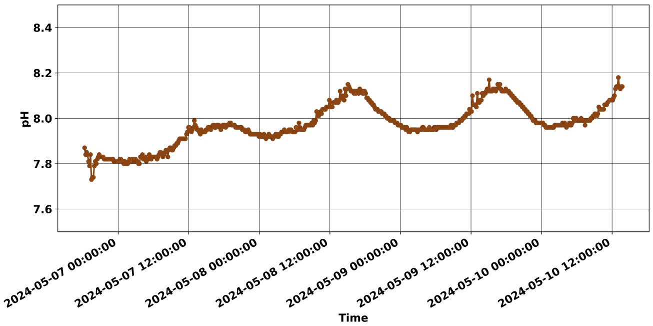

Fig. 13: Results from the pH sensor measurement experiment.

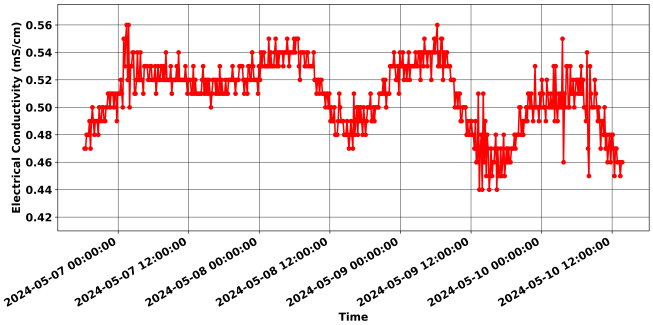

Fig. 14: Results from the Electrical Conductivity (EC) sensor measurement experiment.

VI. CONCLUSION AND FUTURE WORK

In analyzing the results, the combination of AWS and Grafana proves to be a powerful tool, enabling researchers to gain a comprehensive real-time view of data collected from the surface device, SENSWICH. The examination of the data reveals consistent stability in insights obtained from sensors over consecutive days, confirming the choice of the sensors. While considering a future upgrade for certain sensors, such as the electrical conductivity sensor, there is contemplation about replacing it for better outcomes. Another consideration involves the redesign of the SENSWICH floating case, while continuing to use the previous configuration [8] for tests in rivers and the open sea. The goal is to redesign it with an emphasis on stability on the water and resilience against harsh winds and sea storms. Noteworthy is the cost-effectiveness of this device, priced below a thousand US dollars, making it a practical alternative to some similar measuring buoys currently in use. Our attention is directed towards an in-depth investigation and the forthcoming production of additional SENSWICH units. Additionally, future plans include analyzing results in the Venice Lagoon, with further deployments of SENSWICH platforms.

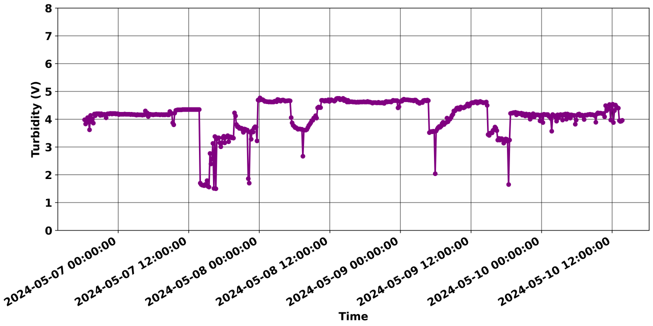

Fig. 15: Results from the Turbidity sensor measurement experiment.

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