Design, Development, and Testing of a Smart Buoy for Underwater Testbeds in Shallow Waters

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***Abstract*—Underwater wireless communication and networking are becoming key enablers of a number of critical marine and underwater applications. Experimentation is underway, in controlled environments as well as at sea, that concerns the deployment of several underwater devices providing wireless communication capabilities to sensors of different nature. Controlling the deployment at sea of these devices, remotely and efficiently, is paramount for enabling expedite testing of hardware and protocol development. To address this need, this paper presents the design, development, and testing of a *Smart Buoy* for real-time remote access to underwater devices and for provision of power and extended computational capabilities. Experimental results are shown concerning the time needed to connect with the Smart Buoy, the power consumption of its operations, and the energy harvesting intake (via solar panels) in time. We also investigate the buoy lifetime when powered by solar panels and supporting acoustic modems over varying traffic scenarios.**

I. INTRODUCTION

With the growing public and commercial interest in the exploration and sustainable exploitation of submerged environments, the field of *underwater wireless communication and networking* becomes fundamental as a key enabler of an increasing number of critical applications. These include monitoring underwater environments for scientific and commercial purposes, pollution control as well as disaster prevention [1]. A flurry of solutions for underwater networking has been proposed, encompassing new hardware and software at all layers of the network protocol stack [2]. Several communication systems, e.g., acoustic modems, are being tested in controlled environments and in the field (e.g., lakes and open oceans) for providing wireless communication capabilities to devices of different nature. In these testbeds, the sensed information is exchanged among the modems along (multi-hop) routes to a data collection point acting as a gateway to users on land.

Given the challenges of deploying and controlling equipment underwater, it is imperative to devise instruments and methodologies that facilitate testbeds monitoring and control for prolonged periods. For instance, in the context of the SEANet project tens of high-speed acoustic modems are built for shorter range underwater communication [3]. Controlling the deployment at sea of these modems, remotely and efficiently, is paramount for enabling expedite testing of hardware and protocol development. The best way to control an underwater device, such as the SEANet modem, is to have a floating device providing real-time connectivity to it. Beyond monitoring the status and operations of the modem, this device could smartly provide further capabilities, including power and extended computational resources. A picture of the SEANet system assisted by such "Smart Buoys" is depicted in Fig. 1.

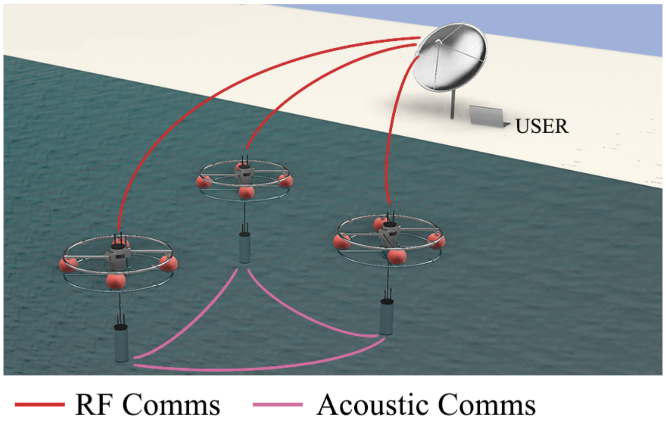

Fig. 1: The SEANet system architecture.

Each device is connected to the Smart Buoy via a cable, making this solution ideal for shallow water deployment. The user onshore can connect with each submerged device via a Radio Frequency (RF) link, enabling direct access to the

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device and real-time control of its functions, including ongoing underwater wireless (e.g., acoustic) communications.

Commercially available equivalents of the described Smart Buoy are expensive, and difficult to deploy because of their size and physical characteristics. Furthermore, they do not provide a flexible interface to a submerged device. For instance, Axis Technologies offers a broad range of floating products for environmental applications [4]. Their "3 Metre Buoy" can be customized with sensors for a variety of measurements like air temperature, barometric pressure, and wave height. The TRIAXYS Directional Wave Buoy is built for accurate measurement of directional waves and equipped with accelerometers, rate gyros, a compass, and proprietary computational hardware. The main purpose of this kind of platforms is the monitoring of meteorological, oceanographic, and water quality parameters. The lightest model among their products weights 60 kg. Fondriest offers a vast range of data buoy, from the small NexSens CB-40 Data Buoy to the large NexSens CB-1250 Data Buoy [5]. They are all specifically built to support NexSens data loggers and require non-trivial modifications to connect and control external devices (e.g., an acoustic modem) to/from them. Besides commercial companies, there are very few examples of smart buoys developed by scientific researchers in support of underwater networking. The "Meduza buoy," developed at Northeastern University in the context of the NU MONET project [6] is equipped with an XBee and a relay board for power management and monitoring, a Bullet M2 for high data rate connection, a BeagleBone Black as a processing unit, a Roland QuadCapture Audio Interface and NiMH batteries. Although the Meduza design was prototyped and tested, this buoy deployment was never extensive, especially for what concerns direct communication with the modem. Busacca et al. present the design and development of a hybrid underwater-terrestrial system for the Internet of Underwater Things [7]. The testbed comprises a floating device that provides the gateway between the underwater acoustic network and the user onshore via a long-distance link implemented through a LoRaWAN connection. Although lightweight and easy to deploy, this buoy only provides low data rate gateway functionalities, does not allow real-time per-modem control, and does not support the submerged devices with extra capabilities.

In this paper, we present the design, development, and testing of a Smart Buoy that flexibly enables the real-time control of the operations of a network of underwater wireless devices in shallow water. Each *Smart Buoy* is designed to support an underwater wireless device directly connected to it (via cable), providing it with the capability of communicating wirelessly with a user on shore, and with additional computational and power resources. Real-time connectivity with the shore is realized via a low power, low data rate radio device that is always powered on, and that, when needed, powers on all other components of the buoy. Actual data exchange with the user on land is instead performed using a high power long-range RF device. A high capacity Lithium-Ion battery provides energy to the buoy and is constantly recharged by an on-board solar panel. The buoy is designed and built to incur low power consumption for a prolonged lifetime. It is also lightweight so that its deployment does not require dedicated machinery.

We tested the time-to-connection of the buoy, namely, the time needed for a user to establish a new high data rate connection with the buoy. We also tested the capability of the buoy to recharge its battery via solar panels, depending on the weather. Finally, we consider a real-life scenario in which the buoy serves as a gateway from a network of underwater acoustic modems to the land. For this scenario, we calculate the lifetime of the buoy depending on solar re-charging and varying traffic.

The rest of the paper is organized as follows. In Section II we describe the mechanical and the electrical designs of the buoy and the realization of a prototype. Section III reports the results of several experiments demonstrating the effectiveness of using the buoy for the SEANet modems. We draw our conclusions in Section IV.

II. BUOY ARCHITECTURE AND PROTOTYPE

The Smart Buoy system is made up of two components. The first is the mechanical structure for the buoy to safely float for as long as necessary. This component includes a cylindrical enclosure that protects the electronics of the buoy. The second is the "smart component," namely the buoy electronics that provide the user onshore with connectivity and information about the status of the buoy and of the device it controls. In the following sections, we describe these two components.

A. Mechanical Design

The Smart Buoy has a mechanical structure designed to stay operational under moderate sea and weather conditions for months. Specifically, it is designed to be (i) mechanically robust against waves and currents; (ii) water and moisture resistant against waves and precipitations, and (iii) UV and heat resistant to cope with the long hours of sun exposure. The mechanical design of the buoy is shown in Fig. 2.

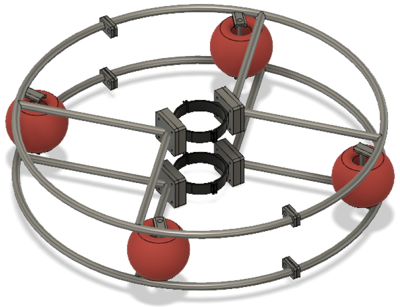


Fig. 2: Mechanical design of the buoy chassis.

The buoy external circular structure is divided into two half circles that are mounted together, allowing a firm holding of the enclosure with the electronics. The outside diameter of the buoy is $0.888\,\mathrm{m}$, offering balance and weight distribution to prevent capsizing. Each layer has four spokes that unite the big circular outside to the part that holds the enclosure with the electronics. These spokes are strategically positioned to enhance structural strength. While one end of each spoke is welded to the outside circle, the other end is welded to a $0.8\,\mathrm{m}$ x $0.7\,\mathrm{m}$ x $0.1\,\mathrm{m}$ structure to which is screwed a $0.8\,\mathrm{m}$ x $0.7\,\mathrm{m}$ x $0.2\,\mathrm{m}$ *adapter*. We call this piece *adapter* because by changing its thickness it gives us the possibility to adapt the whole structure to bigger or smaller enclosures for electronics with bigger or smaller clamps. The clamps that are currently used are from Blue Robotics and have a diameter of $11.5\,\mathrm{cm}$. The entire exterior structure is realized in aluminum; it weighs $3\,\mathrm{kg}$. The floats (the red spheres in Fig. 2) are placed between the two circular layers.

B. Electrical Architecture

The electrical architecture of the Smart Buoy is developed to provide direct remote access to the underwater device as well as power and extended computational capabilities. Its design is structured into four main modules, namely, *processing*, *RF*, *sensor* and *power*, as shown in Fig. 3.

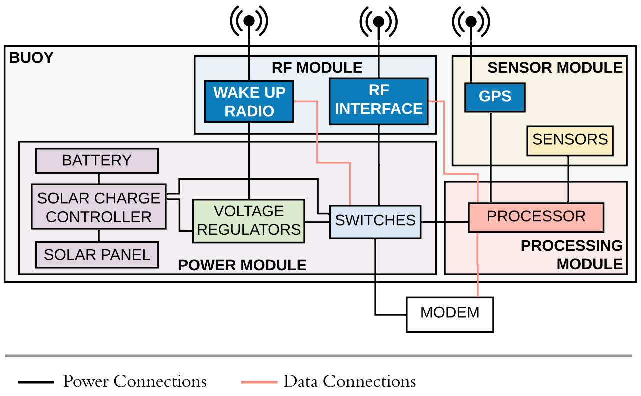


Fig. 3: Smart Buoy schematic.

Processing Module. The Processing Module provides extended computational capabilities through an on-board processor, where operations such as sensor data collection and processing are performed. The processor is also tasked for bridging the high data rate Radio Frequency device to the underwater device, enabling direct remote access to it.

RF Module. The RF Module provides the buoy with the capability to be wirelessly connected and controlled using standard RF technologies. Specifically, the RF module incorporates a long-range, low power device that acts as a wake-up radio, i.e., it is always active and turns on other high power components when needed, and a long-range, high power, high data rate device that allows the Smart Buoy to fast exchange large amounts of data.

Sensor Module. The Sensor Module provides an interface for several different sensors through standard digital interfaces, e.g., Serial Peripheral Interface (SPI), Pulse-Width Modulation (PWM), I2C, and Serial. The module provides real-time information on the state of the buoy, e.g. position, humidity, and also allows easy integration of new sensors.

Power Module. The Power Module houses a central battery unit and a solar panel that together offer the buoy long periods of autonomy while deployed. The module also includes a solar charge controller that prevents over-charging and over-discharging of the battery and voltage regulators and electric switches that power on and off the other components while performing energy-saving when possible.

C. Prototype

The Smart Buoy prototype is shown in Fig. 4. It is built based on the electrical architecture described in Section II-B.

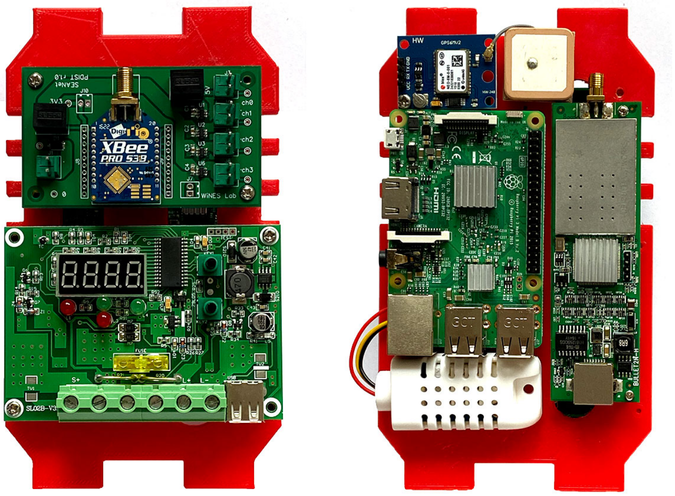


Fig. 4: Buoy electronics.

RF Module. The RF Module incorporates a wake-up radio and an RF interface.

Wake-Up Radio. It is the only constantly available point of contact with the buoy and it is implemented using the compact and low power XBee [8], a long-range RF Module that is able to communicate over $14\,\mathrm{km}$. The XBee controls the switches used to turn on and off the other components of the buoy. To be able to communicate one another, all the XBees must be set on the same channel that represents an operating frequency within the $900\,\mathrm{MHz}$ 802.15.4 band, moreover, they need to have the same Personal Area ID. Each XBee has a role in a network: it can be a Coordinator (one per network), a Router, which is able to forward messages and run functions, or an End Device that can only send messages to a parent device. In our setup, the XBee given to the remote user is a Coordinator while the XBees deployed within the buoys are End Devices.

RF Interface. An M2 Bullet by Ubiquiti Networks performs high data rate transfers [9]. It is a plug-and-play high power device that, depending on the antenna paired with it, can communicate over $50\,\mathrm{km}$. It delivers up to tens of $\mathrm{Mbits/s}$ of real TCP/IP throughput relying on 802.11 b/g/n for the MAC layer. In a network made of Bullet devices, one of them is tasked to operate as a central Access Point while the others are set to function as users directly connected to it. The Bullet devices run on a proprietary operating system called

AirOS that gives the user the possibility to use a TDMA MAC protocol called *airMax* to avoid the hidden node problem.

Processing Module. The Processing Module is based on a Raspberry Pi 3 Model B [10]. Raspberry Pi 3 features a Quad-Core processor, 1 GB of RAM, 1 Ethernet connection, 4 USB connections, 40 GPIO pins, and a Micro SD slot which eases the loading of a custom OS. The Raspberry Pi is connected to the Bullet M2 through an Ethernet cable, obtaining a long-range RF connectivity. It is also connected to various sensors via its GPIO pins. The Raspberry Pi is running on a Raspbian OS paired with a homegrown software. The software runs system diagnostics. Specifically, every 30 seconds it reads from the attached sensors and stores the read information. The Raspberry Pi is connected to the SEANet modem through a USB-to-Ethernet adapter. It acts as a bridge between the Bullet and the underwater modem, allowing the user to open a Secure SHell (SSH) connection with the Raspberry or directly with the interfaced SEANet modem.

Sensor Module. The Sensor Module of the prototype incorporates a set of sensors and a GPS module.

Sensors. The buoy prototype includes an Adafruit AM2302 humidity and temperature sensor, fundamental to control possible leaks and overheating of electronics. The sensor, that has a digital output easily readable with Python libraries, is able to capture $0-100\%$ humidity readings with $2-5\%$ accuracy and $-40\,^{\circ}\mathrm{C}$ to $80\,^{\circ}\mathrm{C}$ temperature readings with $\pm 0.5\,^{\circ}\mathrm{C}$ accuracy.

GPS. A HiLetgo GY-NEO6MV2 NEO-6M GPS module with a ceramic antenna is included for localization. This module allows the buoy to register its location at all times and accordingly offers useful insights in analyzing the results from experiments performed. For instance, the relative Doppler effect due to the current movements or real-time locations of the nodes can be acquired through this module.

Power Module. The Power Module of the buoy houses a set of switches, voltage regulators, and a solar panel.

Switches. Three Load Switches are used for turning on/off the power supply to the Bullet, Raspberry Pi, and modem. Moreover, they offer short-circuit and overload protection with power consumption less than a standard relay. The switches have three input pins (i.e., Voltage In, Control Signal, and Ground) and one output (i.e., Voltage Out) and are operated through control signals generated by the wake-up radio.

Voltage Regulators. The current Smart Buoy prototype houses two Voltage Regulators for regulating (i) the power supply given to the XBee from $14.8\,\mathrm{V}$ of the battery to $3.3\,\mathrm{V}$ that the XBee operates with; (ii) $14.8\,\mathrm{V}$ to $5\,\mathrm{V}$ needed by the Raspberry Pi. The rest of the Smart Buoy components (including the RF interface) and interfaced SEANet modem operate with $14.8\,\mathrm{V}$.

Solar Panel. A $50\,\mathrm{W}$ Kingsolar Solar Panel, able to provide $16\,\mathrm{V}$ and $3.13\,\mathrm{A}$, (not shown in the figure) allows the system to be operational for a long time. The water-resistant panel is made of ETFE material that is able to resist high temperature and corrosion; moreover, it has good weak light sensitivity and an internal blocking diode which prevents reverse current drain at night. Its relatively small dimension ($530\,\mathrm{mm}$ x $539\,\mathrm{mm}$) and slight flexibility allow for a convenient and firm attachment to the buoys' chassis.

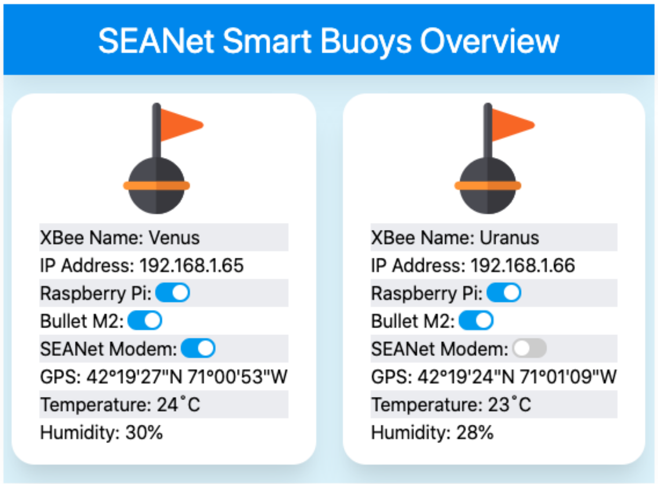
Solar Charge Controller A Wingong Solar Charge Controller for Li-Ion batteries handles the connections between the battery and the solar panel. It prevents over-charge and over-discharge of the battery together with protection over the short circuit and reverse connections.

Battery. The current Smart Buoy prototype houses a $14.8\,\mathrm{V}$ Lithium-Ion battery pack by Blue Robotics that powers the whole buoy. The battery is a rechargeable high capacity custom battery pack, offering a nominal capacity of $18\,\mathrm{Ah}$ and it is composed of Samsung INR18650-30Q $3000\,\mathrm{mAh}$ (Pink) cells. The battery pack physically fits precisely into the buoys' $11.5\,\mathrm{cm}$ enclosure.

III. EXPERIMENTAL EVALUATION

In this section, we report on the results obtained from different sets of experiments focusing on assessing the different performance metrics of the Smart Buoy prototype. Particularly, we first evaluate the connectivity procedures and the power consumption of the buoy prototype. Consequently, we present results and insights from the first real-world deployment of the buoy prototype. Finally, we analyze how the Smart Buoy prototype would perform in a real-life scenario.

User Interface. As a part of the experimental evaluation, we have developed a User Interface that can run on a remote user device allowing each prototype in the deployment to be easily controlled and monitored. As shown in Fig. 5, the developed User Interface is capable of providing sensor information, i.e., internal temperature and humidity of the buoy, GPS position, as well as the name of the smart buoy and their IP address for remote access. It also allows a remote user to be able to power on/off the on-board processor, the RF interface and the interfaced SEANet underwater modem. The developed user interface is used throughout the conducted experiments.



SEANet Smart Buoys Overview

XBee Name: Venus
IP Address: 192.168.1.65
Raspberry Pi: ●
Bullet M2: ●
SEANet Modem: ●
GPS: 42°19'27"N 71°00'53"W
Temperature: 24˚C
Humidity: 30%

XBee Name: Uranus
IP Address: 192.168.1.66
Raspberry Pi: ●
Bullet M2: ●
SEANet Modem: ○
GPS: 42°19'24"N 71°01'09"W
Temperature: 23˚C
Humidity: 28%

Fig. 5: The SEANet Smart Buoy interface.

A. Power Consumption

In this set of experiments, we focus on determining the power consumption of a Smart Buoy prototype when it is operating in different modes. Specifically, we consider three operational modes: *Idle*, *XBee Connection*, and *Experimental*.

In the *Idle* mode, two components that are active, XBee and solar panel controller, are the main source of the power consumption. Particularly, the Smart Buoy drives a constant current of $0.014\,\mathrm{A}$ for the solar panel controller and $9.17\,\mathrm{mA}$ for the XBee which sums up into a total power consumption of:

$$P_{\text{idle}} = VI = 14.8\,\mathrm{V}(0.009\,17\,\mathrm{A} + 0.014\,\mathrm{A}) = 0.375\,\mathrm{W} \quad (1)$$

In the *XBee Connection* mode, the XBee on a Smart Buoy establishes a connection with the XBee on the remote user end for data transfer. In this mode, a remote user can turn on/off a Smart Buoys' on-board modules as well as the interfaced modem. The power consumption, in this case, is $0.380\,\mathrm{W}$.

In the *Experimental* operational mode, the Bullet (RF Interface) on a buoy establishes a high-data-rate RF link with a remote user. In this mode, a remote user can control, monitor, and run underwater acoustic communication experiments with the interfaced modem through an SSH connection. Moreover, a remote user can also operate the on-board processor of the Smart Buoy. This mode, which includes the solar panel controller consumption as well, has a power consumption between $0.768\,\mathrm{A}$ and $0.772\,\mathrm{A}$. Considering the solar panel controller consumption as well, this mode has approximately a total power consumption of $14.600\,\mathrm{W}$

As a part of this set of experiments, we also measure the recharging capacity of the Smart Buoy through its solar panel. To that end, we conducted experiments throughout two days where one of them was a clear sunny day and the other one is a cloudy day. The experiments were conducted in Boston, MA in July where the sun rises around 6 AM in the morning and sets around 9 PM in the evening. The measurement results are illustrated in Fig. 10. As it can be observed, there is substantial solar power generation during the daylight (6 AM to 9 PM), while it is too weak otherwise (9 PM to 6 AM).

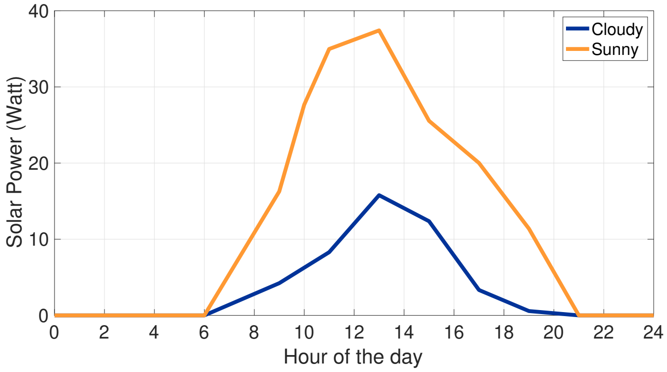


Fig. 6: Solar power through the day.

According to the collected data, the total energy harvested in a sunny day is:

$$E_{\text{sunny}} = \int_{\text{sunrise}}^{\text{sunset}} P_{\text{sunny}}(t)dt = 623.79\,\mathrm{kJ} \quad (2)$$

while in a cloudy day, the total energy is:

$$E_{\text{cloudy}} = \int_{\text{sunrise}}^{\text{sunset}} P_{\text{cloudy}}(t)dt = 183\,\mathrm{kJ} \quad (3)$$

B. Connectivity

In this set of experiments, we focus on evaluating the connectivity procedures. We will focus on the initialization phase, i.e., when the user is disconnected and want to start a new set of experiments.

The first task that the new user needs to perform is to connect the XBee on the shore (XBee$_s$) to the XBee on a buoy (XBee$_b$). To achieve that the XBee$_s$ starts scanning the network with the `start_discovery_process()` python function on a network object provided by the XBee library to discover if there are other XBees. In particular, the XBee transmits a broadcast message to the network, and the nodes that receive it respond with a packet containing their address and other basic information. When a device receives a network discovery message it awaits a random time before sending a reply. We measured the time of the this "scan-and-wait-for-reply" process is measured to take up to $12\,\mathrm{sec}$.

Once XBee$_b$ is attached to XBee$_s$, it is possible to turn on/off the Bullet (RF Interface), the Raspberry Pi, and the SEANet modem through XBee$_b$ pins. Once the Bullet inside the Smart Buoy is active, it is measured to take approximately $67\,\mathrm{sec}$ for it and the interfaced Raspberry Pi and SEANet modem to boot up and be reachable via SSH remotely. Overall, we can conclude that every time we want to start a new set of experiments the initialization phase takes $79\,\mathrm{sec}$.

C. Sea/Ocean Deployment

In this set of experiments, we showcase the first-ever deployment of the Smart Buoy prototypes in the open sea/ocean. Fig. 7 shows the deployment site in the Boston Bay.

Fig. 7: Smart Buoys deployed in the Boston Bay.

We deployed two Smart Buoy prototypes with two SEANet modems (submerged at a depth of $6\ \mathrm{m}$). The buoys were deployed some $50\ \mathrm{m}$ apart from each other. We conducted multiple underwater acoustic communication experiments on the SEANet underwater modems remotely from a boat that is at least $100\,\mathrm{m}$ away from the actual deployment site. Fig. 8 shows the actual GPS position of the buoys during deployment.

Fig. 8: Map of the Boston Bay with the Smart Buoys positions.

Finally, we set to track the position of one of the buoys via the on-board GPS module. The movements over time of one of the buoys are shown in Fig. 9.

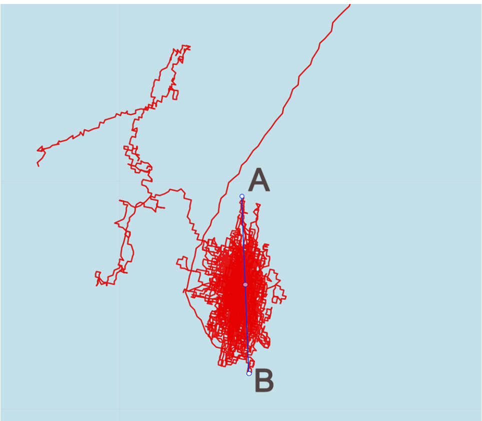


Fig. 9: GPS-based movements of a Smart Buoy.

Even if the Smart Buoy was anchored to the bottom and the sea was fairly calm, the buoy was continuously moving following an elliptic curve (the distance between points A and B in Fig. 9 is $44\,\mathrm{m}$). We observe that the buoy-modem system moves considerably. Consequently: i) The anchoring used in the deployment lacked stability and strength for the specific deployment site currents and conditions, and ii) the underwater acoustic communication results obtained from the SEANet modems throughout the deployment contain substantial Doppler effect due to the constant movement of the nodes.

D. *Real-World Scenario*

In this section, we are investigating how our system would behave in a real-world scenario. Water monitoring is one of the applications to which underwater wireless networks could contribute beneficially, especially enabling the gathering and analysis of data in real-time [3]. We use the application described by Demetillo et al. as an example [11]. We want to determine the working cycle of a modem in an underwater network and the corresponding lifetime of its batteries. We consider a scenario where our buoy acts as a gateway from the underwater network to the shore, measuring the energy needed to collect underwater data with its acoustic modem and to send them to the shore through its RF interface.

The application consists of estimating the water quality measuring Dissolved Oxygen (DO), pH, and temperature. The minimum size of the SEANet modem packet (768 bytes) is suitable to carry the value of pH $\in$ [0,14], DO $\in$ [0,100] mgL^{-1} and temp $\in$ [-200,850].

The network comprises 10 nodes placed statically underwater, each equipped with an acoustic modem, and of one modem attached to the buoy (the *sink*). Each node is at the same distance from the sink. The user onshore starts an *experiment* that behaves as follows. Every time the buoy (namely, the sink) is woken up from the user onshore, it sends 10 (sequential) requests for data to each of the nodes and waits for a reply from each of them, which it forwards to the user. Then, the sink goes back to sleep. Experiments cost is measured based on a 24-hour cycle, staring at 9 PM when the sun goes down. During the night we use battery power since solar energy is not available. Energy is harvested when the sun is up. Each experiment requires $12\,\mathrm{s}$ for XBee initialization, $67\,\mathrm{s}$ for the Bullet and Raspberry initialization, $15\,\mathrm{s}$ to send 10 requests and $15\,\mathrm{s}$ to receive 10 replies (Section III-B). Therefore, the total time of each experiment is $109\,\mathrm{s}$.

Our investigation concerns the maximum number of times per day that the user onshore can access the Smart Buoy/sink to retrieve data from the other underwater nodes. The calculation is performed for a cloudy day and for a sunny day, with the objective of having a fully charged battery at the end of the 24 hour cycle. For self-sufficient operation, the energy generated using solar charging needs to be greater than or equal to the energy consumed during the experiments. Assuming that the battery has enough energy for a day, the following inequality can be stated in terms of duration of experimental activity t in seconds during a cloudy day.

$$\begin{aligned} &\frac{12t}{109}P_{\text{xbee\_conn}} + \frac{67t}{109}P_{\text{bullet\_conn}} + \\ &+\frac{30t}{109}P_{\text{exp}} + (86400 - t)P_{\text{idle}} \leq E_{\text{cloudy}} \end{aligned} \tag{4}$$

Substituting the values of the power consumption from Section III-A we obtain:

$$\begin{aligned} &0.11t\ 0.380\,\mathrm{W} + 0.615t\ 14.6\,\mathrm{W} + \\ &+0.275t\ 14.6\,\mathrm{W} + (86400 - t)0.375\,\mathrm{W} \leq 183\,\mathrm{kJ} \end{aligned} \tag{5}$$

Solving the equation we find that $1.1895 * 10^4$ is the maximum value that t can reach satisfying the constraint of the solar energy. This means that we can do experiments for 3.30 hours. Considering that each experiment needs 109 seconds, the maximum number of experiments that we can perform on a cloudy day is 109, which is approximately 4.5 experiments per hour.

The same procedure that we just performed can be run on a sunny day. Of course, we expect to be able to perform a higher number of experiments since the sun gives more energy. We rewrite the equation solving with E_{sunny} as boundary:

$$\begin{aligned} 0.11t\ 0.380\,\mathrm{W} + 0.615t\ 14.6\,\mathrm{W}+ \\ +0.275t\ 14.6\,\mathrm{W} + (86400 - t)0.375\,\mathrm{W} \leq 623.79\,\mathrm{kJ} \end{aligned} \tag{6}$$

The maximum value that t can reach in this case is 12.97 hours. So in case of a sunny day, we can perform up to 428 experiments, which is roughly four times the number for a cloudy day.

Fig. 10 shows the number of experiments that can be performed in 24 hours with a given amount of solar energy.

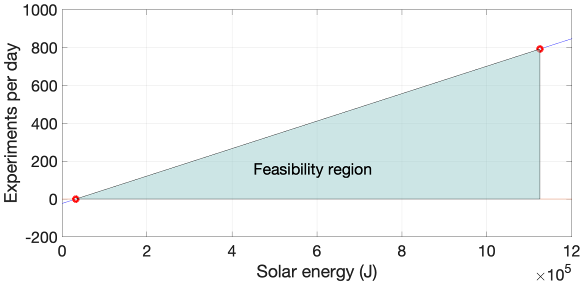


Fig. 10: Solar energy vs. number of experiments.

We notice that the minimum amount of energy affording experiments and self-sufficiency is $32\,\mathrm{kJ}$. The maximum number of experiments, namely, 792, can be performed with $169\,\mathrm{kJ}$ harvested per day.

We finally investigate the worst-case scenario where the sun provides no energy, so that the Smart Buoy/sink can only rely on the battery. We first compute the maximum number of experiments that can be done with the battery. The battery that we use is a $14.8\,\mathrm{V}$ $18\,\mathrm{A\,h}$ battery. As such, the amount of energy stored in the battery is:

$$E_{\text{battery}} = 18 \times 14.8 \times 3600\,\mathrm{J} = 959\,\mathrm{kJ}. \tag{7}$$

For each experiment we need the following total energy:

$$\begin{aligned} E_{\text{exp}} = P_{\text{xbee\_conn}} t_{\text{xbee\_conn}} + P_{\text{bullet\_conn}} t_{\text{bullet\_conn}} + \\ + P_{\text{exp}} t_{\text{exp}} = 1420\,\mathrm{J} \end{aligned} \tag{8}$$

Therefore, the maximum number of consecutive experiments that are afforded by a full battery is

$$n_{\text{exp}} = \frac{E_{\text{battery}}}{E_{\text{exp}}} = 675 \tag{9}$$

for a total of 20 hours of battery life.

Fig. 11 shows how battery life changes as we vary the number of experiments per hour. If we perform only one experiment per hour the battery will last 351 hours. As the number of experiments per hour increases, the battery life decreases reaching its lowest lifetime of 20 hours when performing 33 experiments per hour.

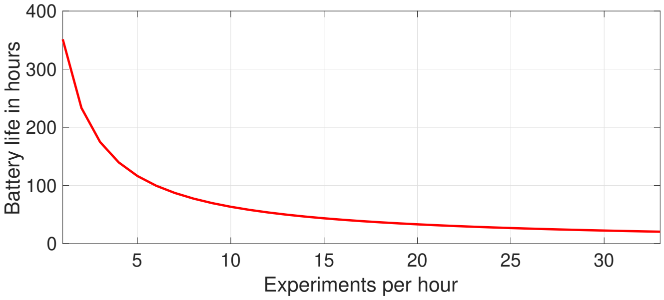


Fig. 11: Battery life given number of experiments per hour.

IV. CONCLUSIONS

In this paper, we presented the Smart Buoy, an instrument for facilitating real-time control of underwater wireless devices. The Smart Buoy allows a user onshore to swiftly connect and control each device of an underwater network. Its mechanical design has been driven to ease usage and deployment while resisting adversarial environmental conditions; its electrical design aims at low power consumption and includes battery recharging via onboard energy harvesters (solar panels). The experimental evaluation of the Smart Buoy at sea demonstrates its effectiveness in supporting per-device, real-time control of underwater networks, aiding long-lived experimental research.

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