Long Lasting Underwater Wireless Sensors Network for Water Quality Monitoring in Fish Farms

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***Abstract*—This paper concerns the implementation of an efficient underwater acoustic network suitable for long lasting environmental monitoring in fish farming. Several hardware and software solutions have been designed and implemented to extend the network lifetime and to make the system autonomous and suitable for such an application scenario. The proposed system is composed of different components. The SUNSET Software Defined Communication Stack (SDCS) is used to provide networking capabilities to underwater nodes communicating acoustically through AppliCon SeaModem modems. The Hydrolab Series 5 probes are used to monitor the water quality. Lifetime of underwater nodes is extended through the use of a novel device that allows to harvest energy from underwater water currents via suitable propellers. In addition, novel sleep and wake up mechanisms have been designed and implemented into the underwater nodes to minimize the energy consumption of the system during the idle periods. The performance of the proposed system has been extensively evaluated in field by monitoring the water quality in three fish farming cages located in the Mediterranean Sea, Italy. The system has been connected to the Internet infrastructure allowing the users to easy interact with the underwater system in real-time. Our results confirm that the proposed system is suitable for long term monitoring providing a reliable and robust data collection scheme with an extended network life time.**

***Index Terms*—Underwater wireless sensor networks, long lasting environmental monitoring, SUNSET, S-SDCS, SeaModem, sea current propeller.**

I. Introduction

In the last years underwater exploration and monitoring has emerged as a vital part of the economy of many countries. Aquaculture, monitoring of oil industry deployments, pollution and climate control, search missions and preservation of cultural heritage are just a few of the many applications that will be enabled by exploration and sustainable exploitation of the underwater world [1].

Among them, fish farming, as part of marine aquaculture monitoring, is a vital problem and has increasingly attracted a great deal of research and development attention. Ocean products, particularly fish, are a major source of food for major parts of the world. Although aquaculture is rapidly expanding, several challenges have to be considered to significantly improve worldwide supplies of food. The fish farms require a healthy environment that implies a continuously monitor and check of its environmental parameters.

Traditional fish farms are till now mostly manually operated and their management requires the farmers to pay attention to a lot of factors for success, without having full control over the environment. Being usually placed several miles offshore at suitable depths their management can be critical in certain sea and weather conditions. The same holds true for the required environmental control, that it is usually accomplished manually by collecting samples of water at different depths on a periodic basis to be later analyzed in chemical labs. However, too sparse measurements can lead to either (or both) environment pollution or loss of profit. It is also worth remarking that the growing global demand for seafood will lead the marine aquaculture to expand and move further offshore, into deeper ocean waters, where the demand for sophisticated monitoring and automation systems for their management will be more considerable.

Different approaches have been proposed in literature to tackle these issues. Traditional approaches, such as [2], rely on cabled network infrastructure for aquaculture monitoring. However, using such solutions, the size of the monitored area is limited due to the elevated costs for network deployment and maintenance. Other approaches, such as [3], use wireless communication between the surface sensor nodes and the onshore control system limiting the applicability of the system only to surface nodes.

Recently, Underwater Wireless Sensor Networks (UWSNs) have been considered as potentially promising alternatives for enabling such applications due to the number of advantages they offer, such as unmanned operation, real-time monitoring, easy deployment, etc. The unique features of these networks, such as the variable link quality, limited battery capacity and high power consumption, pose many challenges for ensuring a reliable and long term data delivery.

In this paper we demonstrate the feasibility of using acoustic communication and networking underwater technologies to enable long term environmental monitoring of water quality for underwater fish farms. The proposed approach is based on the SeaModem, a low-cost underwater acoustic modem [4], leveraging on the networking capabilities provided by the SUNSET Software Defined Communication Stack (SDCS) framework [5]. The SUNSET SDCS (S-SDCS) framework, running on each node, has been extended to support the Hydrolab multi-sensor probe [6] in order to provide real-time monitoring of the physical and chemical variables related to the water quality of the farm, that include: Ph, Conductibility, Dissolved Oxygen, Water Temperature, Chlorophyll, Ammonia and other Nitrogen compounds. The system has been then connected to the Internet infrastructure allowing the final users to remotely control and interact in real-time with the underwater nodes and sensors deployed. A particular effort has been put in designing hardware and software solutions able to extend the network life-time and to make the network autonomous and suitable for long term environmental monitoring. In particular, two different approaches have been considered: 1) Harvesting the energy from the environment using a dedicated sea-current propeller; 2) reducing as much as possible the energy consumption of the underwater nodes by disabling the hardware not needed on demand.

A long term in-field experiment has been carried out to validate the proposed system. A network composed of 3 nodes has been deployed at three fish farming cages owned by the Italian company APRIMAR [7] located in the Mediterranean Sea (Italy). Each node, deployed at a suitable depth in the fish farm, was equipped with the SeaModem [4] and with the multi-parametric probe [6] used to sense the physical and chemical variables of interest. A fourth node located on a floating buoy on the sea surface acted as a data collecting central station and as a gateway between the underwater network and the Internet infrastructure. In particular, it was equipped with an 3G/4G modem so as to establish a wireless Internet connection to the sensors network allowing remote interrogation and data exchange with a webserver database, which is populated with the sensed data and used for consultation and further elaborations. The achieved results confirm that the proposed approach can enable several application scenarios where long lasting monitoring is a key requirement.

The rest of the paper is organized as follows. In Section II we describe the system architecture by deeply detailing its components. The results of in-field experiments are reported in Section III. Finally, Section IV concludes the paper.

II. System Architecture

In the following section we describe in details the components that underpin our system architecture. We start by describing the two types of multi parametric probes we have used to monitor the water quality. Then, we describe the design of the sea-current propeller and its harvesting capabilities, the AppliCon SeaModem and related hardware integration. Finally we present the new SUNSET SDCS architecture and the new modules developed for the system integration and to handle the hardware sleep/wake-up mechanism during inactive periods.

A. Hydrolab Multi Parametric Probe

The Hydrolab Series 5 (DS5) multi-parameter water quality instruments [6] are the premier family of Hydrolab probes for monitoring several water quality parameters simultaneously in situ. The DS5 probe has a unique body of cylindrical shape with a diameter of 8.9 cm on which the necessary sensors for the requested measures are mounted. It is made of resistant plastic to avoid corrosion, it is submersible to a maximum depth of 200 meters and can be exposed to a maximum temperature of $55\,^{\circ}\mathrm{C}$ (the maximum depth depends, also, on the sensors dive characteristic limit). The probe is equipped with a serial port through which can be easily interfaced to a personal computer. It uses the serial protocols RS232, RS485 and SDI-12. The multi-parameter probe Hydrolab DS5 performs the simultaneous reading of all sensors and the automatic compensation of the measurements. The probe sends the data, with the configured serial protocol, after a user request or continuously.

Two different types of the probe, named A and B in the following, have been considered (Figure 1). The Type A probes measure the following water parameters: Temperature, Conductibility, Ph, Redox, Dissolved Oxygen, Depth, Chlorophyll A and Turbidity. The probes of Type B instead measure: Water Temperature, Conductibility, Ph, Dissolved Oxygen, Salinity and Depth.

(a) Type A. (b) Type B.

Figure 1: Hydrolab multi parametric probes.

B. Sea-current Propeller

A novel energy harvesting device, able to convert the sea currents into electrical energy, has been designed and developed to power and charge the batteries of the underwater nodes.

First, a preliminary analysis on the current velocity in the sea area of the fish farm was performed. On the basis of this data a set of design parameters were defined and used to build a preliminary CAD model of the blades and turbine. Finite elements simulations of turbine blades were conducted to check their resistance to the force effect of the fluid current. After the structural analysis, fluid dynamic simulations were performed to compute the torque and the stresses generated by the turbine at different water speeds and to determine the rotation speed maximizing the transmitted torque. After the blade design also the turbine nacelle was designed, including rotating support and sealed shaft. The nacelle parts were built up with anodized aluminum and assembled with stainless screws. Blade, nose and hub were built up with PA2200. Blades were reinforced with carbon fibers. All joints and shaft were sealed with suitable O-rings that make the assembly water proof up to 60 meters.

In parallel with the blade and rotor design, the electronic control board for sea-current propeller has been designed and developed. The board integrates a microcontroller, a Real Time Clock (RTC) and all other electronic components needed for powering and interfacing with sensors and switches, such as Pulse Width Modulation (PWM) outputs, analogue input and UART interfaces. The energy harvesting device can be divided into four sections:

- The supply section: it provides power to the system by a Lithium battery pack and converts its voltage using high efficiency switching DC/DC converter.
- The battery charger section: it converts the voltage provided by the generator and charges the Lithium batteries.
- The processing and control unit: it controls and manages battery charging, turbine starting, data logging and communication with a host.
- The energy generation section: it includes an electric generator, a starting driver and one electronic switch.

An external host, via UART interface, can request by means of suitable commands a series of data to the turbine, such as the battery level, the rotor RPM and the system status.

Figure 2: Sea-current propeller harvester.

Sea-propeller, shown is Figure 2, is capable to generate a power of about 4 Watt at about 42 RPM achieved with the current speed of about 1 knot.

Other details have been omitted because the patenting process for the system has been started.

C. *Acoustic Modem*

SeaModem [4] is a low cost MFSK underwater acoustic modem developed by AppliCon s.r.l. for shallow water communications, currently working in the $25-40$ KHz frequency band.

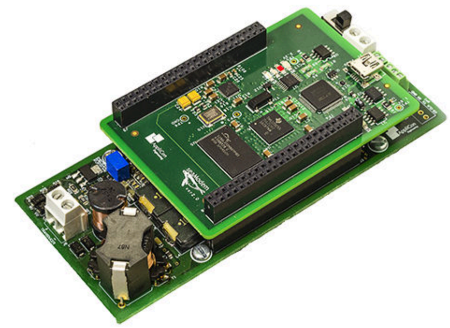


Figure 3: SeaModem acoustic modem.

MFSK modulation protocols provide two-, four- or eight-tone selectable via suitable commands to achieve a transmission data rate of 750, 1500 and 2250 bits per second, respectively. A 16 bit CRC error detection mechanism is implemented. Furthermore, a Forward Error Correction schema utilizing Convolutional Codes and the Viterbi algorithm can be enabled. Four different transmission power levels from 5W up to 40W can be selected on-line. An Automatic Gain Control (AGC) device is also present in the input channel.

The SeaModem (shown in Figure 3) is equipped with two header connectors, allowing the stacking of expansion board(s) on top of it such as the Linux embedded platform “BeagleBone”. BeagleBone [8] is a low-cost, open source, community-supported development platform based on ARM Cortex-A8 processor. It runs Debian GNU/Linux with the support for many other Linux distributions and operating systems (i.e., Ubuntu, Android, Fedora). In this way, new high-level functionalities that use the modem as a communication device can be easily developed by exploiting the power and flexibility provided by a stand-alone system with a Linux OS. This approach has been used to integrate in the SeaModem the SUNSET networking framework and the JANUS modulation scheme [9]

D. *The SUNSET SDCS Architecture*

The Sapienza University Networking framework for underwater Simulation Emulation and real-life Testing framework [5] (SUNSET) is a framework that provides networking and communication capabilities to underwater nodes. It has been designed to allow an easy implementation of novel protocols and algorithms and to easily integrate external hardware, such as sensors, modems and mobile platforms. The same code can be used in simulation, in lab emulation and in field experiments without any code rewriting. SUNSET supports also the innovative concept of the Software Defined Communication Stack (SDCS) [10] being therefore able to run different protocol stacks and modems that can be dynamically and adaptively selected and tuned according to the application scenarios and/or environmental conditions. All the solutions and features of SUNSET SDCS are currently commercialized by WSENSE srl [11].

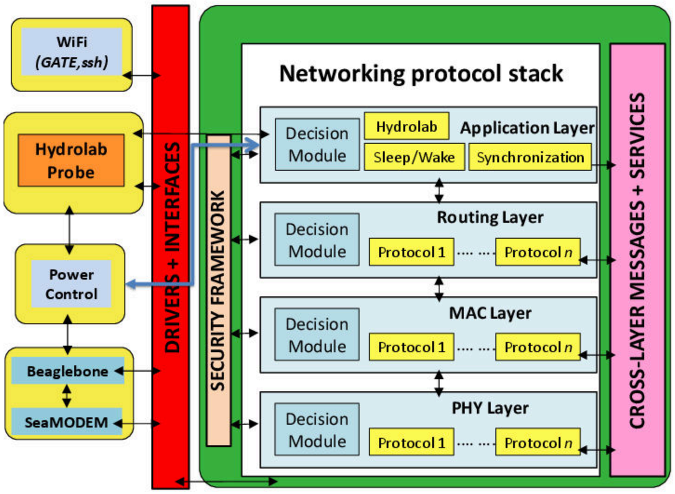


Figure 4: S-SDCS architecture.

Several novel modules and drivers have been developed to: 1) Integrate the Hydrolab probes and the propeller; 2) allow for a correct sleep and wake-up mechanism in order to reduce the energy consumption. Such modules are described in what follows.

Hydrolab probe and sea-current propeller integration. Two new modules that allow the integration with the Hydrolab probes and the sea-current propeller have been designed and implemented in SUNSET SDCS. The first one is used to read water quality data from the multi-parametric probes. The second module provides the remote control and monitoring of internal parameters of the sea-current propeller. Both the modules have been designed to allow the users to interact remotely and in real-time with the devices by defining frequency and alarm thresholds for data reporting.

Sleep and wake-up mechanism. A new sleep and wake-up mechanism has been designed to further increase the network life time. Using such a system, the hardware that is not needed during the idle periods (i.e., when no network activities are present) is temporarily switched off for energy saving. In addition, the remaining active component of the system, i.e., the Beaglebone where SUNSET SDCS runs, is put into a sleep mode to further reduce the energy consumption. This greatly decreases the power consumption as the system only accounts for the Real Time Clock (RTC) module of the Beaglebone. Once the different components wake up, the system is able to compensate for the clock drift, if it is needed, by using the synchronization protocol proposed and tested in [12]. A specific board has been designed and interfaced with the Beaglebone allowing to switch on/off the hardware on demand. A new module has been implemented in SUNSET SDCS that allows a proper shutdown of the system (comprising modem and probe power) and a precise scheduled wake-up after which the system becomes active. The system can be easily programmed locally or remotely, exploiting the acoustic links, to perform a synchronized shutdown with a user defined interval of sleeping/power-off time.

Figure 4 shows a schematic description of the new modules implemented in SUNSET SDCS and their interaction with the external hardware.

III. Experimental Evaluation

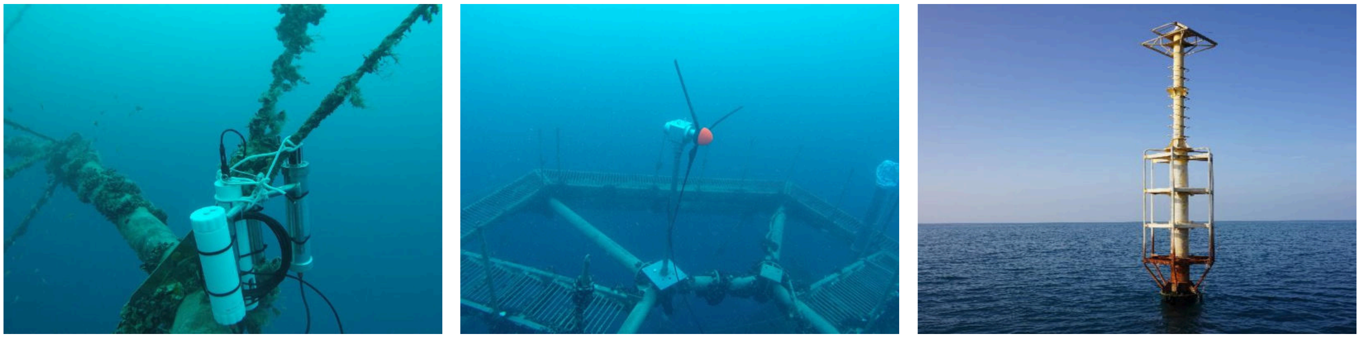
The performance of the proposed system have been evaluated in a network composed of 3 nodes deployed in three fish farming cages, owned by the Italian company APRIMAR [7], located in the the Mediterranean Sea, off the coast of Corigliano Calabro (Calabria, Italy). The cages used by APRIMAR are installed at a depth of 45 meters on average, at a distance from the coast of about one nautical mile, and all of them are fully immersed in water. They are covered by nets made by high tenacity nylon that is well anchored to the bearing structure with a capacity of about four thousand cubic meters ($4500/5500$ m^3) each. One of such a cages is shown in Figure 6. It can be noted that the upper-part of the cage is not fully immersed in water because the cage can emerge by inflating air inside the pipes of the metallic structure.

Three underwater nodes, with IDs 1,2 and 3, have been deployed at each cage at different depths, of 16, 25 and 40 meters respectively. A schematic design of the deployed network topology is presented in Figure 7. Each underwater node has been equipped with a SeaModem modem and the Hydrolab probe. They were connected to the WSENSE underwater node, which contains the battery pack and runs the S-SDCS framework (see Figure 5a). Node with ID 1 was equipped with the Type A probe, while nodes with ID 2 and 3 were equipped with the Type B. In addition the node with ID 1 was connected with the sea-current propeller that was installed in the upper part of the cage (see Figure 5b). The node with ID 4, positioned at the center of the network, acted as the data collection point (sink). It was deployed at 6 meters of depth connected to a floating surface buoy (shown in Figure 5c). It was also equipped with a 3G/4G router acting as a gateway for remote control and real-time data reporting from/to the on-shore control station.

The network experiment was carried out for 6 days. In order to test the system feasibility for long term environmental monitoring each node was remotely configured to report few measurements during the day. In particular we considered several time periods for reporting the environmental data during the day. Each time period lasted 30 minutes in which the collected measurements were reported every 60 seconds. At the end of each time period, the nodes were configured to be temporarily turned off into the sleeping mode for about 5 hours.[1] In addition to the probe measurements, the node 1 was configured to report also the data related to the status of the propeller, such as the energy harvested, voltage, Revolutions Per Minutes (RPMs), etc.[2] The networking capabilities of the S-SDCS framework ensured a reliable data delivery during the active period of the network.

[1] Except the sink node that was always powered by batteries and solar panels of the buoy.

[2] Please note that the results concerning the energy harvested from the propeller have been omitted due to the ongoing patenting process.



(a) Underwater node (WSENSE node on the left, Hydrolab probe in the middle and SeaModem on the right).

(b) Sea current propeller.

(c) Surface buoy.

Figure 5: Deployed assets.

Figure 6: One of the APRIMAR fish farm cages.

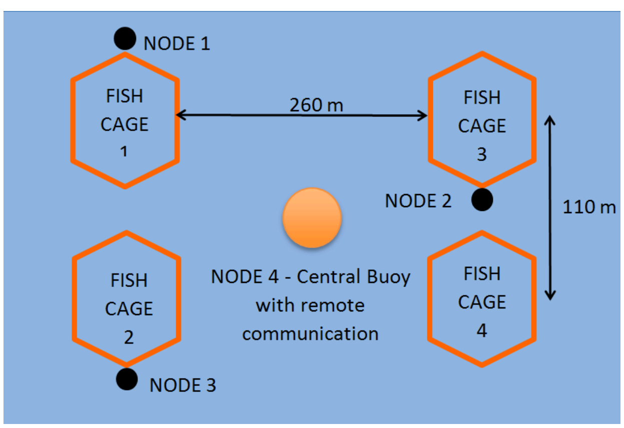


Figure 7: Deployed topology.

In Figure 8 we report a subset of the collected environmental data that includes water quality parameters such as: Potential of hydrogen (pH), Luminescent Dissolved Oxygen (LDO), Temperature, Oxidation Reduction Potential (ORP), Specific Conductance (SpCond) and Salinity (SAL). Different types of environmental data have been reported by the nodes according to the type of probes they were equipped with. E.g., the ORP was reported only by node 1 equipped with the Type A probe, whereas the salinity was measured only by nodes 2 and 3 using the Type B probe. It can be noticed that the collected data during different reporting periods are equally time spaced of about 5 hours. This demonstrates that the system was able to perform a correct shutdown and wake-up ensuring a longer lifetime of the network.

IV. Conclusions

In this paper we have investigated the performance of a complete system to enable the use of underwater wireless sensor networks for long lasting monitoring underwater. The architecture is composed of different components that allow the nodes to communicate underwater, monitor the water quality and minimize the energy consumption. A novel sea current propeller has been also designed and built to harvest the energy from the environment allowing to increase the network lifetime. The proposed system has been validated at sea by monitoring the water quality in three fish farming cages. The achieved results confirm that the proposed approach is suitable for long lasting environmental monitoring and allows to enable several application scenarios where long network lifetime is a key issue.

Acknowledgments

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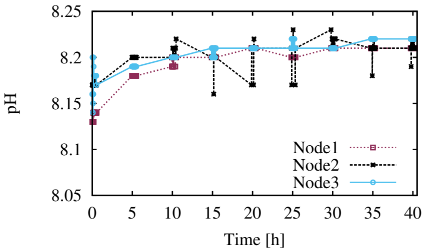
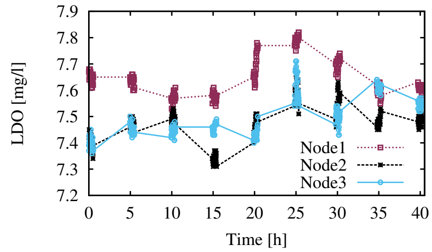
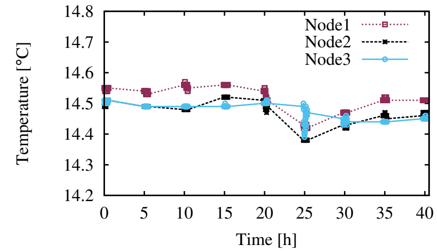


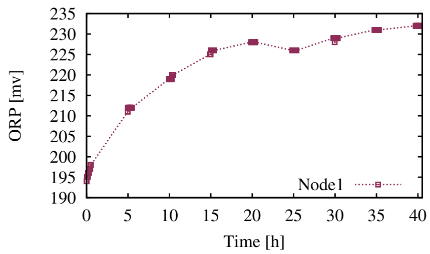
(a) Potential of hydrogen (pH).



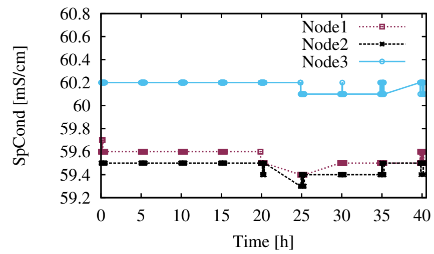
(b) Luminescent Dissolved Oxygen (LDO).



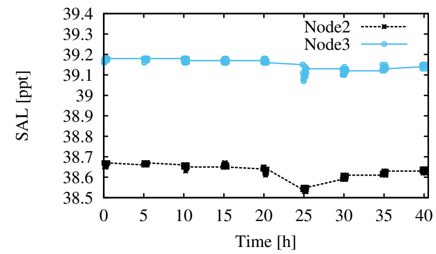
(c) Temperature.



(d) Oxidation Reduction Potential (ORP).



(e) Specific Conductance (SpCond).



(f) Salinity (SAL).

Figure 8: Data related to 40 hours of water quality monitoring.

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