HydroNode: a Low Cost, Energy Efficient, Multi Purpose Node for Underwater Sensor Networks

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***Abstract*—The research of underwater sensor networks (UWSNs) is gaining attention due to its possible applications in many scenarios, such as ecosystem preservation, disaster prevention, oil and gas exploration and freshwater reservoirs management. The main elements of a UWSN are underwater sensor nodes (UWNs). In this paper we present HydroNode: a low cost, energy efficient, multi-purpose underwater sensor network node (UWN). Nowadays, to the best of our knowledge, there is no UWNs that is simultaneously low cost, low power, able to couple diverse types of sensors and educationally available. Thus, the objective of this paper is to fill this gap by describing the design of HydroNode, an underwater sensor node that fulfill all these requirements and can be used in various UWSNs applications. We used only commercial off-the-shelf components to build our underwater sensor node. Compared to commercial UWN, HydroNode is 5 to 10 times cheaper. Furthermore, it achieves up to 150 days autonomy due to the data acquisition and transmission operations schedule we implemented. Finally, we also present an underwater sensor network architecture that can reduce costs for large deployments. Due to its multi-purpose design, HydroNode can be used in different UWSNs, therefore aiding the research of UWSN system protocols, configurations and applications.**

I. Introduction

Underwater sensor networks (UWSNs) is an important research area that is attracting increasing interest both from the research community and also from the industry. Oceans, rivers and lakes are critical to the life on our planet and monitoring these environments is a hard and costly task. Thus, there is a large number of applications where UWSNs are important, such as ecosystem preservation, disaster prevention, oil/gas exploration, and freshwater reservoirs management [2], [16].

In oceanography, for example, UWSNs can perform sampling of the coastal relief as a way of obtaining information to infer and predict specific characteristics of this environment. Data collected can also be used to avoid possible risks to navigation, assisting its execution [1]. Moreover, in military, UWSNs may be applied to recognize submarines and prevent eventual bouts [10]. It can also aid in the localization of underwater mines. UWSNs can also benefit the industrial area by helping in the control and monitoring of undersea pipes and fishing machinery [9]. Finally UWSNs may be used as a new measurement system in the energy sector. For instance, UWSN can monitor and detect the the golden mussel, a Chinese clam, that infects Brazilian hydroelectric barrages and causes more than US$ 1 million loss daily [4].

An underwater sensor network is formed by many autonomous sensor nodes. An underwater sensor node (UWN) can sense the environment, collect data, as well route data in the network. One of the main challenges of deploying such a network is the sensor node development, including its high cost when compared to terrestrial sensor nodes. Most hardware architectures of sensor network nodes aimed at very specific applications, lacking in generality, and researchers lacked a unified platform to test practical performance of network protocols.

In this paper we present HydroNode: a low cost, energy efficient, multi-purpose underwater sensor network node (UWN). HydroNode design objective is to fill the gap the underwater sensor network area where, to the best of our knowledge, there is no UWN that is simultaneously low cost, low power, able to couple diverse types of sensors and educationally available. The sensor node we propose has a set of interchangeable modules: energy, acquisition, processing and communication units [17]. These units can be easily applicable in a diverse number of UWSN architectures and scenarios.

Our underwater sensor node is built up using only off-the-shelf components. This construction approach reduces the sensor node costs and, compared to commercial UWN, HydroNode is 5 to 10 times cheaper. In addition, it achieves up to 150 days autonomy due to the data acquisition and transmission operations schedule algorithms implemented.

We also present an underwater sensor network architecture that can reduce costs for large deployments. With a multipurpose design, HydroNode can be used in different UWSNs, therefore aiding the research of UWSN system protocols, configurations and applications. For instance, in this paper we also discuss a real world *e-limnology* application, which is a science that studies the biological dynamics of freshwater reservoirs [19] with the aid of electronic devices.

The main contributions of this paper are:

1) We provide a complete description of a low power, low cost, multi-purpose underwater sensor node for real application.
2) We develop a complete sensor station, including a buoy that allows sensor node mobility in vertical axis.
3) We present, in each basic node unit, how a real world application in the field of *e-limnology* affected the hardware design.
4) We discuss the UWSN architecture and we show benefits of using sensor nodes in an underwater communication environment.

The remainder of this paper is organized as follows. In Section II we describe the related work. In Section III, we present HydroNode and its basic units. In Section IV, we introduce the floating platform gateway used in the *e-limnology* application. In Section V, we present results related to the node's cost and energy consumption, as well as our designed UWSN architecture. Finally, in Section VI, we conclude this paper and describe future work.

II. Related Work

During the last two decades, research on preservation of aquatic environments has attracted scientific community attention. The importance of water, being essential to life, stimulated the interest in advances of mapping, monitoring, and surveillance techniques. In this section we describe current underwater sensor networks, especially the issues related to the design of underwater sensor nodes. The inherent aspects of UWSN's design are widely discussed by [10]. Akyildiz *et al.* [1] outline protocol design challenges in each network layer. A classification model for UWSN's and a study about the particularities of the physical layer and MAC protocols in underwater environments are presented by [13]. However, despite the valuable contributions to the study of UWSN's, none of the mentioned works focuses on the design of sensor nodes.

Most recently, Wen-Yaw et al. [18] present a system for in water quality monitoring. Nevertheless, the communication is carried on through the air, with radio-frequency modules. In this case, only the sensing elements are in contact with water. In other words, its processing, energy and communication units are not immersed. This characteristic implies in restrictions to the sensor operating depth, due to signal propagation limitations via cable.

In [5], an architecture of sensor nodes for surveillance systems is described. In this application the sensors are immersed and all collected data is sent through cables to a buoy that has a wireless communication module. That work focused mainly on how the nodes distribution affected the network performance.

Yang *et al.* [20] present an underwater sensor node prototype. The node supports only one sensor type, restraining its use in other UWSNs applications. Yang *et al.* [21] present a complete underwater sensor node, providing data acquisition and underwater communication. The data transmission is carried during fixed data sample intervals and the node sleeps during the remaining time. Unfortunately the system is not tested with real sensors, the data transfer rate is not specified, and the signal propagation and attenuation results are not discussed, not allowing communication analysis.

An effort to build a low cost aquatic sensor node is presented by [8]. The node uses two different MAC protocols and alternative transducers, different from conventional hydrophones. They obtain an 8 bps data rate, but the range, depth and energy efficiency values are not presented. The node is designed to use only voltage output analog sensors, and it is suitable for small testbeds.

Lu *et al.* [12] present a node design with no consideration to range and data transfer implications. Their objective is to analyze the feasibility of acoustic communications in aquatic environments. The node's low cost and low power characteristics allow around 3 meter communication range making it unsuitable for real world applications.

Vasilescu *et al.* [14] publish one of the most complete studies related to underwater sensor node prototyping. The design includes two different communication strategies. The first, using optical modems, is intended to low range, real time data transfer, up to 100 meters under ideal conditions and 10 meters in real applications. The second, using acoustic modems, allows further communication distances. Although the node can couple eight sensors, the tests are performed using only two sensors: pH and temperature. The node uses several proprietary components. Unfortunately, the node is not commercially or educationally available. High energy consumption is also a problem.

To the best of our knowledge, HydroNode is the first UWSN that offers the following characteristics: low cost and energy efficient; multi-purpose; able to couple different analog and digital sensors; long underwater communication range; open design platform.

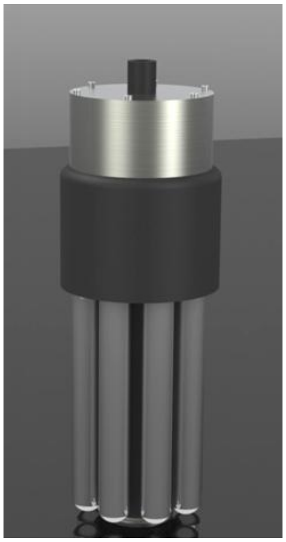
III. Underwater Sensor Node

In this section, we describe HydroNode hardware. We present the HydroNode 5 main units: enclosure, power supply and battery management unit, sensing unit, processing unit and communication unit. We discuss each of these units and show how they adapt to hardware and applications constraints. We also discuss how HydroNode units works in an e-limnology application.

A. Enclosure Design

Figure 1 presents the underwater sensor node enclosure prototype. The external module of the node enclosure, shown in Fig. 1a, allows to easily attach new sensors to the node, whereas the internal compartments, shown in Fig. 1b, keeps the node architecture components isolated from water.

We place the circuit boards components on the top of the UWSN. In the opposite way, we place the batteries on the



(a) External view of HydroNode

(b) Internal view of Hydronode

Fig. 1: Hydronode

lower portion of the node. Finally, we place sensors and modem on the outer edge of the node enclosure, as shown in Fig. 1a. This component distribution helps to maintain the node stability as we place heavier components, as batteries and sensors, in the lower portion of the node.

All inner sensor node components are hermetically sealed. To access these components, we just have to unattach the outer part of the node enclose, unscrewing it from the main enclosure body. This sensor node enclosure model allows us to easily change the sensors and safely handle the internal components, especially batteries.

B. Power Supply and Battery Management Unit

We used a combo of 2300 mAh Ni-MH AA batteries where we obtain an equivalent 14.4v and 6.9Ah battery. We choose this battery setup because it is easy and cheap to buy 2300 mAh Ni-MH AA batteries. Moreover, AA batteries are well know from almost all people. Anyone could easily change nodes batteries or recharge them if necessary. We may also use batteries with better capacity, as Li-FeS_2, in applications that require longer lifetime.

We also have included a battery management module in the sensor node design. This enables the development of energy-aware protocols. We use a mathematical model of the battery discharge curve to predict the battery lifetime, in terms of its voltage and current. More precisely, this mathematical model translate the battery voltage and current into a look-up table. Then, we compare the battery current values of voltage and current with the look-up table, to obtain a good estimative of the battery's state of charge (SOC). The estimative of the SOC allows the design of duty cycle protocols, used in MAC layer protocols, as well as routing algorithms that can adapt to link loss and nodes energy state.

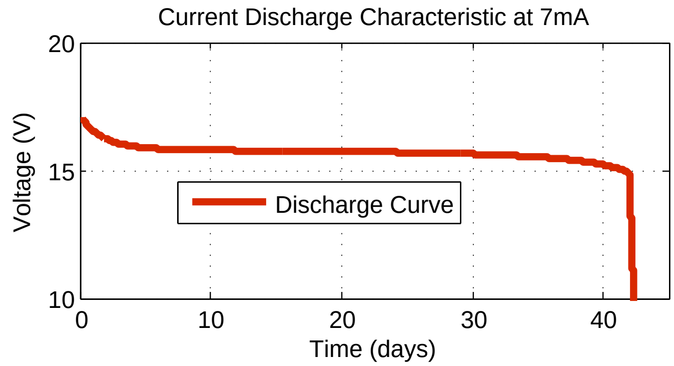


Fig. 2: Discharge rate model

Figure 2 shows a Ni-MH battery combo discharge model where the system consumes 7 mA over time. The curve in this figure presents an approximate value of the node's current consumption with sampling and commutation being executed four times per hour.

We have also implemented a scheduler procedure for data acquisition and transmission, in order to minimize UWSN energy consumption. We turn on the modem and sensors only when they are needed, according to a node execution regimen that can be configured. The scheduling configuration can be changed any time to suit the best UWSN configuration, in terms of energy and data sampling rate.

This energy saving approach is very useful for event-driven and periodic applications, where we don't need to perform measurements and communicate continuously. We can execute these functions sparsely during long periods. As natural consequence, underwater sensor nodes can work for a longer period, which reduces maintenance costs and increases the network lifetime.

C. Sensing Unit

HydroNode can physically couple up to 7 sensors. Our hardware offers an interface for both, analog and digital sensors. Moreover, the enclosure design allows coupling a variety number of sensor due to its adjustable straps.

In the case of analog sensors, Hydronode operates with both voltage and current outputs. It samples the analog sensors and pre-processes its data (e.g. analog signal amplification or gain adjustment). Later, it uses its microcontroller analog-to-digital converters to get the previous pre-processed data in a digital format. For digital sensors, Hydronode implements most common IC data transfer protocols, such as serial RS-232, HART, I2C and SPI.

In the *e-limnology* application, we have equipped HydroNode with water quality related sensors as temperature, dissolved oxygen, conductivity, pH, chlorophyll and turbidity. Since the sensing unit is versatile, it can be used in other research fields by simply adding sensors according to the parameters we need to measure.

D. Processing Unit

The HydroNode uses MSP430F2274 microcontrollers to carry out processing. These devices present very low consumption, with four standby modes and a large number of peripherals. We use 3 microcontrollers in our design: the first is used to perform data pre-processing and acquisition; the second is used to handle acoustic communications; the third is used to control the node operations, as well as to store data and monitor battery SOC.

To synchronize all these functions, we use a real-time clock (RTC). Using a RTC, we can put each module to sleep and thus, save energy. Modules may be wake up using interruptions. These interruptions can be generated via serial or I2C communication. The RTC also provides timestamps useful to build network packets, storage data, aiding in the development of underwater protocols.

Electronic devices communicate with each other using I2C, a master-slave protocol that can be easily implemented with microcontrollers. The I2C protocol only requires 2 buses for a complete communication.

The Hydronode sensor node stores the data it collects in a non-volatile memory (EEPROM) This way, each node can buffer the data until the proper moment to transmit. Moreover, as nodes can store data, they can increase its redundancy, which in turn, increases the network resistance to data loss.

E. Communication Unit

HydroNode can use any modem with a serial interface, or any modem that operates with I2C and SPI protocols. In our application, we used a SAM-1 acoustic modem [6]. SAM-1 is one of the cheapest acoustic commercial modems available. Its communication ranges from 250 m to 1000 m and it can operate up to 300 m depths.

The modem can achieve up to 20 bps data transfer rate. This data rate is enough for the *e-limnology* application, as we only need to send small amounts of data periodically. In applications where higher data rates are required, HydroNode can use any available acoustic modem that achieves better rates.

We can establish multi-hop network with HydroNode using nodes point-to-point communication. We can implement routing algorithms into HydroNode's communication unit. It can act as a router, storing and transmitting data thought the network they form. In this work we do not focus on routing algorithm, and in this way, we may implement any available routing algorithm in the literature, such as Pressure Routing [11] and Pherotrail [15].

IV. Floating Gateway Platform

In order to facilitate remote access, the floating gateway platform centralizes the data generated by the nodes. Each node uses an acoustic modem to transmit data to the node installed on the floating platform. The floating platform node communicates with a datalogger board that stores the information sent by all the nodes. The datalogger is implemented with a MSP430 microcontroller and a SMD card.

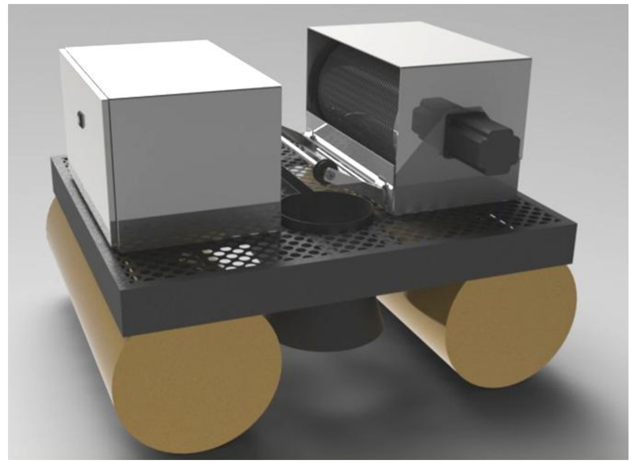


Fig. 3: Floating platform layout

The floating platform includes a gateway that links the UWSN to a remote computer providing data remote access. Data are indexed by the node identifier and organized using the sample timestamp, so that one can easily access the data from a specific node or the entire network, as well as follow data evolution over time. The gateway can use any of the most common wireless technologies, such as bluetooth for ranges up to of 10 m, ZibGee for ranges up to 100 m, Wi-Fi for ranges around 300 m or even GPRS (cellular networks).

The platform's layout is depicted in Fig. 3. There are two waterproof compartments, one to store the electronic devices and one for a controlled motor. A HydroNode can be attached to a cable and that cable is connected to the motor. The electronic device controls the motor, enabling Hydronode to dive and make measurements at desired depths. The floating gateway platforms lets the user configure the depth and also the amount of time it should stay at that depth to make measurements. In the *e-limnology* application, this is vary valuable, as it allowed the automation of data sampling at different depths. For our specific scenario, the cable was limited to 30 m but longer cables are available, enabling the formation of 3D networks.

V. Results

A. Energy Consumption

Table I presents HydroNode average power consumption. Data are obtained as follows. In each hour the node performs data acquisition once every 15 minutes, requiring the sensors to remain active for 30 seconds each time. After the acquisition, data is transferred in 2 minutes. The node remains active for a total time of 5 minutes, time considered to calculate the consumption due to processing and other peripherals usage.

HydroNode is energy efficient. The average power consumption is 86.1 mWh. It is importante to note that the consumption can be decreased, depending on how many

TABLE I: HydroNode average consumption in one hour

Operation	Current (mA)	Voltage (V)	Time executed (sec)	Consumption (mW)
Data acquisition	80	14.4	120	38.4
Data processing	2	3.3	600	1.1
Data transmission	20	14.4	240	19.2
Data receiving	21	14.4	240	20.2
Other	3	14.4	600	7.2

TABLE II: HydroNode cost

Component	Price US$
Waterproof case	250
Electronic components	180
Acoustic modem	1,000
Sensors	900
Total	2,330

times data acquisition and transfer are executed. Using the default configuration, HydroNode can operate ininterruptly for about 48 days. If data transferring operation is performed only one time each hour, battery lifetime is extended to 73 days. Moreover, if we perform data acquisition operation one time each hour battery lifetime reaches 150 days. Acquiring data once each hour is sufficient for many applications.

B. HydroNode Cost

Typical prices for commercial underwater sensor nodes range from US$ 3,000, not considering the sensing elements or supporting hardware [13], to US$ 10,000 [7] for a complete node. We have developed a low cost node, as shown in Table II. The total price includes the components of a complete node, waterproof case, acoustic modem, and sensors.

Hydronode communication unit can use any commercial or educational acoustic modem, ranging from US$ 600 to US$ 10,000 [3]. Cheaper sensors can also be used, decreasing the total cost to approximately US$ 1,100. Our platform is flexible, multi-purpose and able to cover different applications communication requirements.

C. UWSN Architecture

We designed the architecture presented in Figure 4 for the *e-limnology* application. Each multi-purpose Hydronode can be configured as sensors, routers or gateways. Acting as a sensor, HydroNode collects environment sensed data. Data are stored and transmitted via the acoustic modem according. The router receives the transmitted data, forwarding the packets to other routers or to the gateway, whichever presents the lower transmission cost calculated in terms of distance and energy consumption. When the data packets arrive in the gateway, it can be either permanently stored in the datalogger

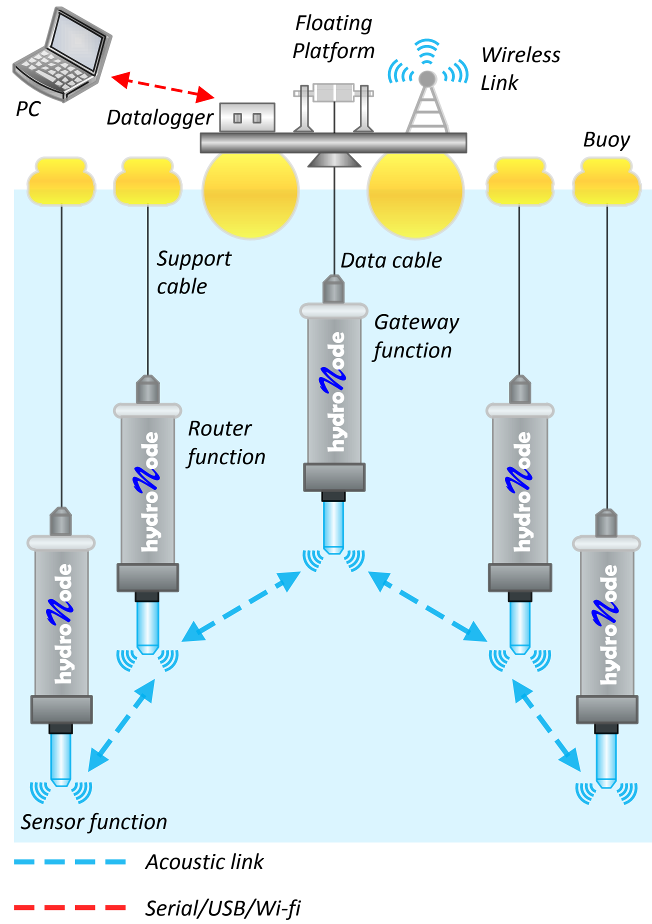
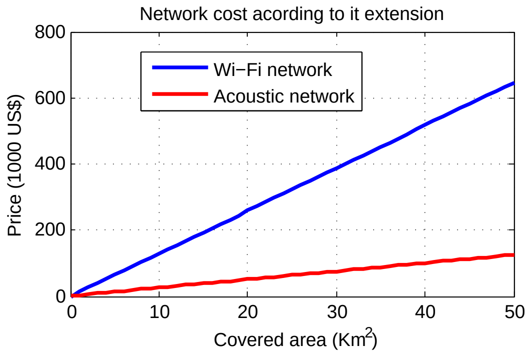


Fig. 4: Water quality monitoring case study architecture

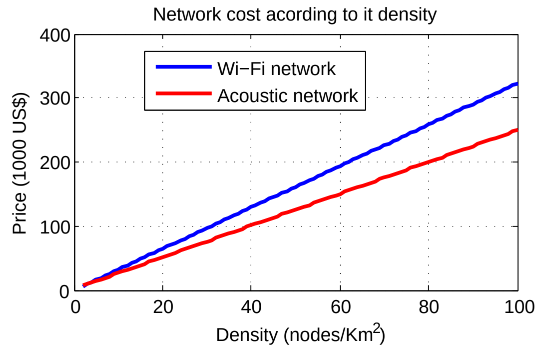
or transmitted through wireless communication. In our case study, the stored data is available to a personal computer over a wireless interface.

The traditional approach to measure water quality parameters is to use many sensing units, each of them connected to the surface through a cable, without underwater communication. Wi-Fi can connect the surface gateways. Using an UWSN to measure water quality parameters has many technical and economic advantages:

1) Acoustic modems can operate in depths up to 6,700 m. In the traditional approach, the data should be sent to the platform using a cable. Unfortunately electrical signals suffer high attenuation in distances greater than 100 m;
2) Only one platform is needed to monitor a wide area. Platforms are much more expensive than nodes, so reducing its number greatly reduces the network cost;
3) The cable used to send data to the platform is expensive, about US$ 1,200 for 25 m cable. Therefore, as the acoustic communication reduces cable usage, the cost of the network is reduced;
4) Wi-Fi technologies have ranges up to 300 m (over the air), while acoustic modems present ranges typically 3 to 10 times higher in an underwater environment. Thus,



(a) Network comparison considering coverage area.



(b) Network comparison considering data sampling resolution.

Fig. 5: Comparison of underwater networks and solely Wi-Fi networks for water quality monitoring

using Wi-Fi to perform the communications would be impracticable, considering that the aquatic nodes are typically more sparse.

Using a UWSN enables great depths operation and higher communication ranges. Figure 5 compares the cost of a water quality monitoring network using our UWSN architecture and using a Wi-Fi network. The use our architecture is also less costly.

Figure 5a shows the relation between price and area for a network. As acoustic communication presents higher ranges than Wi-Fi, typically 3 times higher, the UWSN needs less nodes to cover the same area, resulting in cost reduction In Figure 5b we considered the relation between price and nodes density. By increasing the node density we can improve our data sensing resolution. When Wi-Fi networks are used, we need to introduce one floating platform and use a data cable for each node. Therefore, as the price of an acoustic modem is lower than the combined prices of the cable and platform, the use of an UWSN is more cost effective.

VI. Conclusion and Future Work

In this paper, we presented HydroNode, a multi-purpose node for underwater sensor networks. We described the design of the node, detailing its basic units, as well as a floating platform gateway that can link a UWSN formed by HydroNodes to other wireless communication forms. We described its use in *e-limnology* application forming a UWSN of HydroNodes, and showed how they can be reconfigured in order to applied in other UWSNs. We showed that HydroNode has a total cost of only US$ 2330, and that this value can be lowered to US$ 1100, a value that is lower than what is presented in the literature. We also showed that HydroNode is energy efficient, with a lifetime that can go from 48 to 150 days, depending on how frequent sampling and data transfers occur. We finally concluded that, in the *e-limnology* application, our UWSN architecture is a better solution than a solely Wi-Fi network, considering both range (coverage area) and density (data resolution) cases.

Future work are related to improving HydroNode's cost and energy efficiency, as well as the development of new UWSNs protocols and applications. Examples include the development of MAC, routing and transport protocols, considering duty cycle, new applications of UWSNs (mainly oil, gas, hydropower monitoring and agriculture) and battery management improvements. We also plan to investigate data link quality metrics for protocol improvement and develop data fusion techniques.

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