An Acoustically Powered Battery-less Internet of Underwater Things Platform

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***Abstract*—The Internet of Underwater Things (IoUT) is a promising approach to future military, scientific, and commercial applications at sea. Vital components of the IoUT are underwater wireless sensor networks (UWSNs) and autonomous underwater vehicles (AUVs). Powering of these systems in deep water still remains one of the main challenges, since UWSN nodes and AUVs are typically powered by batteries that need to be replaced or recharged through expensive and difficult operations.**

This article presents the design of the first batteryless underwater sensor node that can be wirelessly recharged through ultrasonic waves from longer distances than allowed by current inductive and magnetic technologies. First, the architecture of an underwater platform capable of extracting electrical energy from ultrasonic waves is introduced. We then illustrate how to interface this system with an underwater digital communication unit. We discuss the design of a prototype of the proposed architecture where the storage unit is realized with a batch of supercapacitors. We show through experiments that the harvested energy stored in the supercapacitors is sufficient to provide an underwater sensor node with the power necessary to perform a sensing operation and power an acoustic modem for ultrasonic communications.

We evaluate the system performance in terms of wireless power transfer efficiency (PTE). Our system is characterized by a lower electrical-to-radiated power conversion efficiency when compared to other technologies. However, given the reduced attenuation of ultrasonic waves in water, we were able to show that our approach can cover longer distances with less transmission power. Last, we evaluate the operating efficiency that we define as the maximum achievable digital data rate relative to the charging and transmission times.

I. Introduction

Underwater networking technologies have been a key enabler for many military, commercial, and scientific applications, including (i) tactical/coastal surveillance; (ii) control and monitoring systems for the oil and gas industry; (iii) climate change monitoring, pollution control and tracking; and (iv) commercial exploitation of the aquatic environment, among others [1], [2]. We envision that the increasing number of applications will eventually lead to a vast deployment of underwater objects and realization of the Internet of Underwater Things (IoUT) on a larger scale.

The architecture of underwater objects (e.g., underwater wireless sensor network nodes (UWSNs) and autonomous underwater vehicles (AUVs)) is increasingly becoming more complex. These systems will encompass multiple sensors, wireless communication systems, actuators, and rotors or propulsors which will inevitably increase the total power requirement. Typically, an underwater sensor node requires about 30 W to provide power for non-propulsion related functions (communication, processing, and sensing), on top

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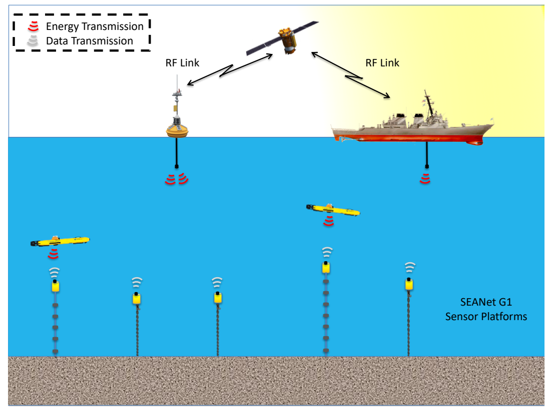

Fig. 1. An application scenario enabled by the battery-less IoUT platforms.

of which another 15–110 W are needed if the device includes propellers or other mechanical components [3]. Supplying these levels of power to underwater sensor nodes and vehicles deployed deep in the sea over long periods of time still remains an open problem.

Batteries are the most common solution to power underwater devices. However, a remotely operated vehicle with the support of a vessel is generally required to recharge or replace these batteries. These operations are very expensive and non-scalable [4]. Moreover, given the inaccessibility and dynamic movement of the nodes, the charging operations are often difficult and inefficient, as precision alignment is often required [5]. For example, some recharging solutions for AUVs have been limited in their usage, as they call for wet mate connectors that are prone to failure, and docking methods that are too complex. Energy harvesting, successfully applied to traditional wireless sensor networks (WSNs), is challenging in the underwater environment because natural sources, such as solar or wind energy, are unavailable or inefficient. In recent years, research has investigated wireless power transfer (WPT) technologies to remotely power underwater sensors. The most investigated methods are based on electromagnetic (EM) propagation in the near field region, namely inductive and magnetic coupling (see Table I). Even though the majority of prototypes have shown efficiency values above 65%, the maximum operative distances are limited to few centimeters with inductive coupling and one order of magnitude higher with magnetic coupling. Additionally, a very good alignment between the transmitting and the receiving coil is often necessary.

Given their better propagation characteristics, namely lower attenuation, in aqueous media, acoustic waves are a promising alternative to EM induction for realizing WPT in underwater systems. Acoustic propagation in water can cover longer

TABLE I
COMPARISON BETWEEN WPT TECHNIQUES IN UNDERWATER

Ref.	Type	Distance [cm]	Tx/Rx power	Eff. (%)
[8]	Inductive coupling	4 7	Tx=-25 dBm Tx=-3 dBm	50
[9]	Inductive coupling	-	Rx=10 kW	91
[4]	Inductive coupling	5	-	60–75
[6]	Inductive coupling (simul.)	8–13	-	65–80
[10]	Eddy current propagation	10 5	- -	60 50
[11]	Magnetic coupling	0.2	-	90
[7]	Magnetic coupling	15 (simul.) 26 (exper.)	Rx=3 kW -	~80% ~65%
[12]	Ultrasonic WPT	100	Rx=~mW	-

The values reported in the table are for experimental results if not differently indicated.

distances while losing less power when compared to EM-based methods. This means that ultrasonic WPT technologies for remote recharging operations are feasible because the charger and the submerged nodes can be placed further apart. In this article, we present the architecture of a platform equipped with ultrasonic connectivity for IoUT that can be remotely charged via acoustic waves, eliminating the need for large batteries. Ultrasonic communications have been extensively investigated in UWSN applications, but the literature about ultrasonic WPT in underwater environments is more sparse. Thus, in this article, a batteryless underwater sensor node that can be powered through ultrasonic energy transfer is demonstrated for the first time.

The system includes a set of supercapacitors that can be recharged with about 1 W of power at a distance of approximately 1 m in less than 5 min. A study on the acoustic underwater wireless link is conducted showing that longer distances than state-of-art technologies can be covered. Furthermore, based on the energy requirements of the IoUT system, a specific design is proposed to overcome the challenges arising from interfacing the power module with the communication unit. A practical implementation of an ultrasonically rechargeable UWSN node is demonstrated, showing that enough energy for sensing and data transmission can be transferred and stored. Finally, the prototype performance and efficiency are experimentally evaluated.

II. Related Work

Multiple studies compare coil-based to spiral-based inductive coupling. Generally, WPT by means of spiral inductors provides better performance. This is confirmed by both simulation and experimental results [4], [6]. The work in [4] reports experimental efficiency values higher than 60% and 75% for coil and spiral-based inductors, respectively, at a distance of 5 cm. Similarly, simulation results of inductive coupling in seawater show an approximately constant efficiency of the range of 65–80% in the overcoupled region up to 8 cm for a coil and up to 13 cm for a spiral [6]. A white paper released by WiTricity [7] reports the simulation results of a WPT method based on magnetic coupling as showing an efficiency of about 80%. A practical implementation of the system offers efficiency values of 15% less than the simulated results.

In [8] a study is conducted on radio frequency-based communications and inductive energy transfer in underwater environments. Experimental results demonstrate the feasibility of underwater communications at 2.4 GHz up to 4 cm with -25 dBm of transferred power and up to 7 cm with -3 dBm. The wireless power transfer efficiency of the system is approximately 50%.

Ultrasonic WPT was demonstrated in [12] where power values on the order of milliwatts were measured over a distance of 1 m. The feasibility of a system able to wirelessly power underwater sensors from an acoustic source was proven through an analytical model in [13]. However, to the best of our knowledge, no other study has further investigated the possibility of using ultrasonic waves for underwater WPT through a practical implementation. An alternative to WPT is harvesting energy from the environment surrounding the nodes. The best energy sources in seas and oceans are (i) kinetic energy in form of underwater currents and vibrations and (ii) solar energy for superficial applications [14]. Underwater harvesters can reach powers from the order of milliwatts to few watts by means of turbines and piezoelectric transducers. An example of energy harvesting from underwater vibrations is reported in [15].

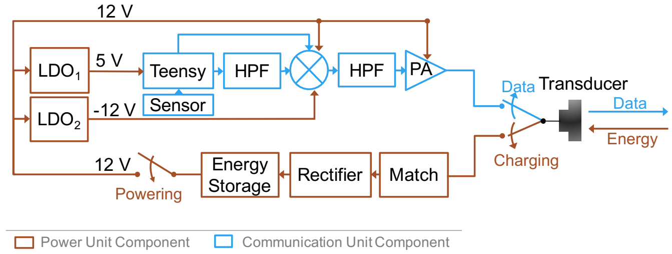

Fig. 2. Block diagram of the ultrasonically rechargeable IoT platform. SEANet components in blue, power management elements in brown.

III. System Architecture

Figure 1 shows an application scenario enabled by the battery-less IoUT platforms. A set of battery-less IoUT platforms equipped with different sensors is deployed in the ocean/sea. These platforms are wirelessly powered through acoustic waves either by surface objects, such as ships or buoys, or submerged objects, such as remotely operated vehicles (ROVs) or unmanned underwater vehicles (UUVs), to perform sensing operations and transmit their sensed data back to the charging objects. The data collected by the charging objects can eventually be globally accessible through an RF link.

A. Architecture and operating principle

The general architecture of the batteryless underwater IoT platform is shown in Figure 2. The system includes two main modules, namely a SEANet node, which serves as an underwater communication and sensing platform, [16] and a power unit (also called energy management module).

The core building block of the communication unit is a Teensy board that receives and processes the data from a sensor. Later it generates waveforms containing the processed data based on the Zero-Padded Orthogonal Frequency-Division-Multiplexing (ZP-OFDM) communication scheme. The ZP-OFDM scheme occupies a bandwidth of 11.025kHz at a center frequency of 22.050 kHz. A high pass filter (HPF) connects the Teensy with a mixer and removes the DC offset from the waveforms. The mixer shifts the waveforms with a signal of 27.950 kHz and producing waveforms at 50 kHz that are high-pass filtered again and amplified before being transmitted by means of an ultrasonic transducer.

The energy management unit includes a traditional full wave rectifier connected to the transducer through a matching network to increase the unit's wireless power efficiency (WPE), or power transfer efficiency (PTE). The output of the rectifier is a DC waveform that is sent to the energy storage element. Two low drop out (LDOs) regulators provide different components with their required supply voltage.

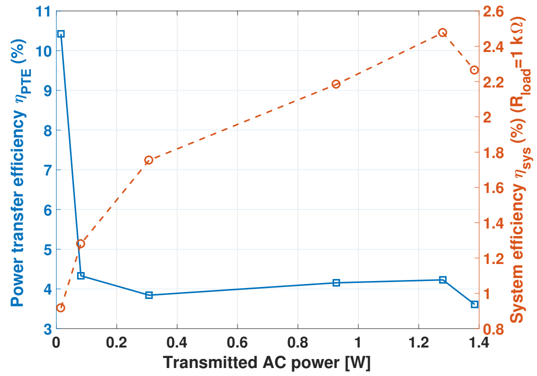

Fig. 3. Wireless link efficiency and system efficiency vs. transmitted electrical power.

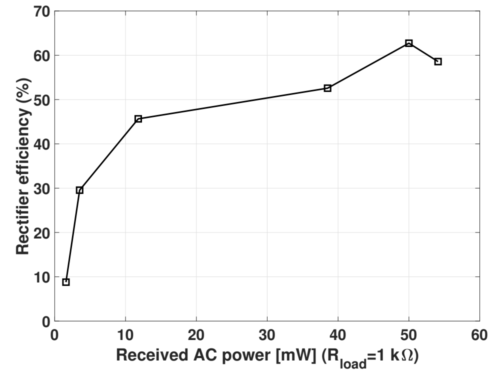

Fig. 4. Rectifier efficiency η_{rect} vs. the received AC power with a 1 kΩ load.

The system encompasses two MOSFET/ADC-based switches that connect the transducer to the energy management unit, or allow power to the data communication unit and activate the transmission once enough energy has been received.

The operation of the system can be divided into two phases. Initially the energy storage component is completely or partially depleted. Therefore a remote charger must send energy to the system via ultrasonic radiation so the node can be recharged. The system enters the second phase after receiving enough energy, which is used to power the SEANet node for sensing and data transmission operations.

B. System Design

Design challenges and requirements: A detailed description of the design of SEANet communication and sensing platform is reported in [16]. We briefly report the most important design requirements. The SEANet node can perform sensing and communication operations in 1.2 s including 5 ms for a powering-up period, 800 ms for sensing and processing data from its temperature sensor, and 310 ms for transmission operations that can send one ZP-OFDM packet including eight ZP-OFDM symbols carrying 6144 bits of data. To perform these operations, it requires a voltage of 12 V and 140 mA of current. Hence, the required power amounts to 1.68 W consuming 2.02 J of energy. However, not all components of the communication unit require the same supply voltage. Specifically, the Teensy is powered with 5 V, the mixer needs two "supply rails" (± 12 V) and the power amplifier can only work with 12 V positive.

The design challenges relative to the energy management module are due to the received low power levels caused by the attenuation in water and conversion losses of the transmitting and receiving transducer. Furthermore, it is difficult to design a small energy storage component that can be quickly recharged, for the following reasons: (i) the charging voltage across the supercapacitor has an asymptotic behavior when approaching full capacity; (ii) the maximum voltage rating of the storage component is typically lower than the voltage requirements of the communication circuit; (iii) the internal equivalent series resistance (ESR) can be too large to provide the current needed by the load; (iv) as seen above, different parts of SEANet have different power and voltage needs.

Component design: From these the capacity needed to store the minimum amount of energy to activate the communication module can be calculated. The SEANet system needs 25 mF to be powered-up, and to sense and transmit one packet of data. It can be challenging or time consuming to charge a single capacitive element up to 12 V. Therefore, we use a bank of supercapacitors that are connected in parallel during the charging phase and, during the powering phase, in a configuration such that the voltage across the equivalent capacitor matches the load requirements. In this way it is easier and faster to charge the whole set of supercapacitors and, at the same time, a 12 V voltage can be provided to the SEANet components. Switching between the two phases is realized with a MOSFET and an ADC circuit. Different components of the communication circuit have different power requirements. Therefore, we include two low drop out (LDOs) regulators to adjust the storage supplied voltage and match the values required by the communication unit (Figure 2).

Evaluation metrics: The system performance was evaluated as follows. The *charging efficiency*, defined as the ratio between the energy accumulated into the super-capacitors bank (E_s) and the total energy needed to charge it (E_{tx}), can be expressed as

$$\eta_c = \frac{E_s}{E_{tx}} \times 100. \tag{1}$$

The *effective data rate* η_d is defined in (2) and accounts for the total amount of data d_m (in *bits*) that can be sent with the harvested energy with respect to the time (T_c) needed to charge the system and the time to complete the transmission (T_{tx}), given by

$$\eta_d = \frac{d_m}{T_c + T_{tx}}. \tag{2}$$

To assess the source of loss for varying transmission power levels, the *power transfer efficiency* (PTE) of the wireless link can be measured as

$$\eta_{PTE} = \frac{P_{rx}}{P_{tx}} \times 100, \tag{3}$$

where P_{rx} is the received AC electrical power before the rectifier and P_{tx} is the transmitted AC electrical power. PTE will quantify the power loss due to the combined effect of the transducer electro-acoustic and acousto-electric conversion losses and the attenuation in water. Moreover, to evaluate the loss caused by the rectifier, we can measure the *rectifier efficiency* as the ratio between the DC rectified power and the received AC electrical power, given a certain load, which can be expressed as

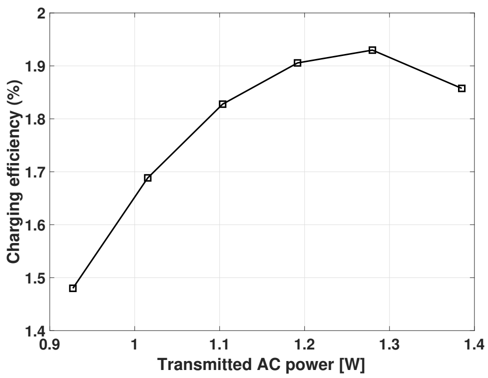

Fig. 5. System charging efficiency for different values of the transmitted electrical power.

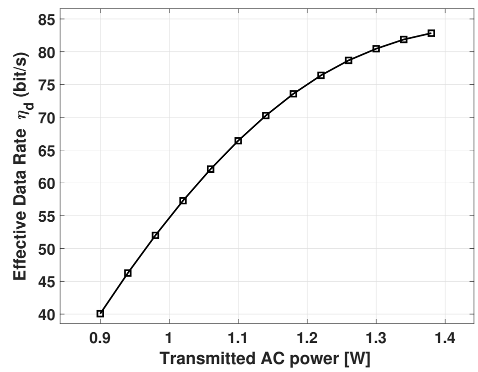

Fig. 6. System effective data rate η_d for different values of the transmitted electrical power.

$$\eta_{rect} = \frac{P_{dc}}{P_{rx}} \times 100. \tag{4}$$

Finally, we define the global *system efficiency* as the ratio between the DC rectified power and the transmitted AC electrical power, given by

$$\eta_{sys} = \frac{P_{dc}}{P_{tx}} \times 100. \tag{5}$$

IV. System Prototype

The experimental setup consists of an underwater sensor node based on the architectural model reported in Section III and a charging station. The latter is a USRP-based underwater modem [17]–[20] including a Microcircuits LZY-22+ high power amplifier, and an Airmar P58 transducer. The IoUT platform uses the same type of Airmar transducer for both energy reception and data transmission. The matching network is a passive lumped element circuit and the rectifier is a traditional full wave AC-to-DC converter based on BAT54 diodes. As for the storage, we used six 5.5 V off-the-shelf supercapacitors, four with $100\,\mathrm{mF}$ of capacity and two $47\,\mathrm{mF}$. During the charging phase the capacitors are connected in parallel so that the equivalent capacity seen from the rectifier is 494 mF. During the powering phase two sets of $100\,\mathrm{mF}$, $100\,\mathrm{mF}$ and $47\,\mathrm{mF}$ series-connected supercapacitors are connected in parallel so that the total equivalent capacity is $48.45\,\mathrm{mF}$ and the voltage across this equivalent capacity is $15\,\mathrm{V}$, namely the sum of the voltages across each capacitor in one of the two series. This is the minimum capacity needed to transmit one packet (one ZP-OFDM packet including eight ZP-OFDM symbols carrying 6144 bits of data) and perform sensor readings for 800 ms. Finally, two LDOs are included in the powering module to regulate the voltage supplied from the storage to the communication components. Specifically, a 12 V-to-5 V LDO provides a 5 V voltage to the Teensy and a $12\,\mathrm{V}$-to-$(-12\,\mathrm{V})$ LDO converts the voltage for the negative rail of the mixer.

V. Experimental Results

In this section, we present two sets of preliminary experiments to showcase the feasibility of the wireless acoustic charging over a distance of 1 m and the battery-less IoUT platforms.

We first measured the *power transfer efficiency* to estimate transfer efficiency of the wireless acoustic link. Figure 3 showcases that the *power transfer efficiency* is around 4% for transmission power levels larger than $0.1\,\mathrm{W}$. After quantifying the link loss including the loss due to non-ideal electro-acoustic and acoustic-electric conversions, we measured the loss due to the rectifier by connecting the output of the rectifier to a $1\,\mathrm{k\Omega}$ load. Figure 4 shows the rectifier efficiency (η_{rect}) for varying received AC electrical power levels. The results prove that with at least 30 mW of AC electrical power, the rectifier can work with an efficiency of more than 50%. As a final experiment in this set, we measured the efficiency of the whole system (η_{sys}) as illustrated in Figure 3. As expected, the combined effect of η_{pte} and η_{rect} leads to a system efficiency of 2% for a transmission power level of 1 W.

The second set of experiments focuses on the charging efficiency and the actual amount of data that can be transmitted with the received energy. To this end, as explained in Section IV, we charged a set of supercapacitors. Experimental results for the charging efficiency (η_c) are shown in Figure 5. Since E_s is constant, and we observed that the charging times become shorter with an increase in transmitted power, the decrease of η_c is due to the decrease of the PTE η_{PTE} around 1.3 W (compare Figure 3 with Figure 5).

Finally, we measure the effective data rate. Once the supercapacitors are charged up to 5 V, their configuration is changed to provide an initial voltage of 15 V to power the IoUT system. Figure 6 shows that the effective data rate, as defined in (2), increases relative to the transmitted power. This can be explained by the fact that higher transmitted power levels reduce the charging time which will eventually lead to higher effective data rates.

VI. Conclusions

Powering of systems deployed in deep waters remains one of the core challenges toward the long-term deployment of untethered underwater systems. In this article, we presented the first ultrasonically rechargeable underwater sensor node. The system is batteryless and powered by supercapacitors whose charge can be restored by means of WPT realized over distances longer than current inductive and magnetic technologies. We reported on the architectural model of an underwater platform capable of extracting electrical energy from ultrasonic waves and using it to power an ultrasonic communication system. We realized a prototype based on the proposed architecture. Experimental results proved that the collected energy is sufficient to perform a sensing operation and power an acoustic modem for ultrasonic communications.

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