A Study of Applications, Challenges, and Channel Models on the Internet of Underwater Things

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Abstract

The Internet of Underwater Things (IoUT) is a novel class of Internet of Things (IoT), and one of the emerging technologies toward smart city. To support the concept of IoUT, Underwater Wireless Sensor Networks (UWSNs) have emerged as a promising system. In this paper, we survey the potential IoUT applications, point out the challenges and differences between UWSNs and traditional sensor networks, and investigate the channel models. We validated the models by simulations.

Key words: Internet of Things (IoT), smart city, underwater wireless sensor networks, and wireless sensor networks (WSN)

Introduction

In recent years, there has been a growing trend toward the smart city. One of the most important techniques to be used is the Internet of things, the so-called IoT. IoT is defined as "the infrastructure of the information society" [1]. To the best of our knowledge, the concept of IoT was invented in 1985 [2]; then, in 2012, the Internet of Underwater Things (IoUT) was first discussed in [3]. IoUT is defined as "the network of smart interconnected underwater objects". IoUT is a new class of IoT, and an important part of smart city evolution.

In the literature, there have been increasing attempts [3][4][5] to emphasize the importance of IoUT. We provide three main reasons. First, more than 70% of the area on earth is covered by water, and the majority of the underwater areas are still unexplored. Second, IoUT is expected to enable numerous applications, which would be applied in smart cities. Third, the underwater communication and equipment waterproofing technologies have been at a more mature stage. Accordingly, this is an appropriate time to do research on IoUT.

For IoUT, Underwater Wireless Sensor Networks (UWSNs) have emerged as a promising network system. Fig. 1 (a) shows the network architecture of UWSN. Figs. 1 (b) and (c) show the equipment used in the real-world projects [6][7]. UWSNs usually consist of several components. Sensors are the main components. Sensors are the nodes with acoustic modems, and distributed in the shallow or deep water. Each sensor node can sense, relay, and forward data. The data should be transferred to the essential component(s) on the surface of the water, called sink(s). Sinks are the nodes with both acoustic and radio modems. When data arrive at sinks (through acoustic channels), the sinks will forward data to the remote monitoring center (through radio channels). The monitoring center is often on the sea-shore, and responsible for monitoring the water areas. Specifically, the monitoring center collects, analyzes, and deals with the information from the water areas.

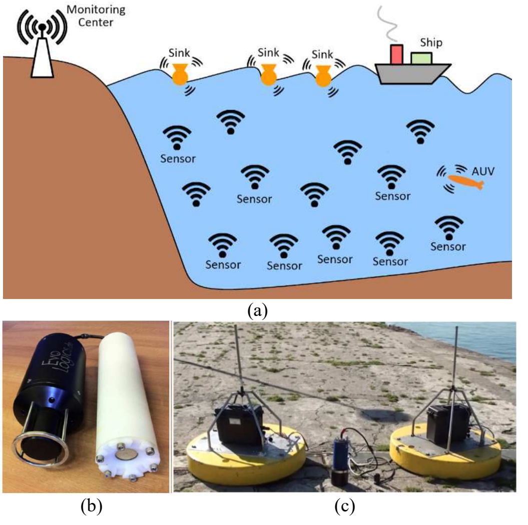

Fig. 1 (a) The network architecture of UWSN; (b) the photo of a sensor (CO_2 probe with acoustic modem); (c) the photo of sinks.

UWSNs are expected to enable a diverse range of practical applications, such as environmental monitoring, underwater exploration, disaster prevention, and military applications. However, UWSNs are different from the traditional Territorial Wireless Sensor Networks (TWSNs), and have several unique properties, such as long propagation delay, narrow bandwidth, high mobility, and low reliability. The unique properties would be great challenges for UWSNs. In the literature, while many studies concentrated on the problems of the end-to-end delay, lack of bandwidth, and dynamic topology, few studies looked at the more fundamental problem of reliability. Note that low reliability would lead to frequent data retransmission, which would eventually result in longer delay, higher bandwidth consumption, and higher energy consumption. To investigate the reliability of IoUT, the channel models would definitely play a vital role. In this paper, we thoroughly investigate the channel models, and validate the models by simulations.

This paper provides a comprehensive study of IoUT, and the main contributions of this paper are threefold: (1) we introduce the practical underwater applications, which can point out the importance of IoUT; (2) we highlight the differences between UWSNs and traditional TWSNs, and the differences are the main challenges for IoUT; (3) we investigate and evaluate the channel models, which are the technical core for designing reliable communication protocols on IoUT.

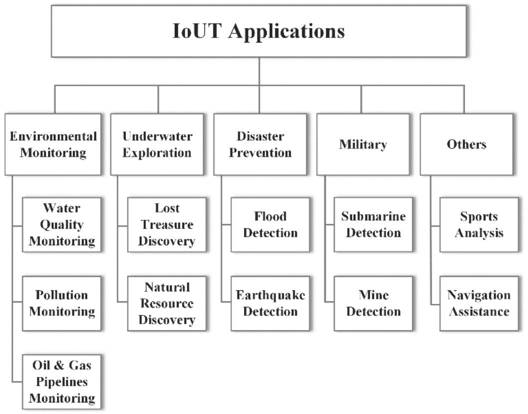

Fig. 2 The IoUT applications.

Applications

In the last decade, researchers have presented numerous potential IoUT applications [8][9][10]][11][12]. We classify the applications into five types: (1) environmental monitoring, (2) underwater exploration, (3) disaster prevention, (4) military, and (5) others, as shown in Fig. 2.

A. Environmental Monitoring

One of the most commonly used IoUT application types is environmental monitoring [8], including water quality monitoring, chemical and biological pollution monitoring, thermal pollution monitoring, pressure and temperature monitoring, and fishes tracking. In addition, oil and gas pipelines monitoring can be achieved by using UWSNs.

B. Underwater Exploration

The concept of IoUT can also be applied to lost treasure discovery. For instance, the discovery of the Titanic in 1985 (by the Woods Hole Oceanographic Institution) benefits from the autonomous underwater vehicles (AUVs) [9]. The natural underwater resource (e.g., minerals, metals, corals, and coral reefs) discovery can benefit from the infrastructure of UWSNs as well.

C. Disaster Prevention

The water-based natural disasters are potentially dangerous. For example, the Fukushima Daiichi nuclear disaster (on 11 March 2011) initiated primarily by the tsunami following the Tōhoku earthquake. IoUT is expected to detect flood and earthquake (underwater), and to provide applications for management and prevention of such disasters [10].

D. Military

The military often reflects the ability of a country to defend itself against any form of attack, including the form of underwater attack. IoUT is required for defense purposes, and can be applied to submarine detection and underwater mine detection [11].

E. Others

With the advancements in UWSNs, more and more IoUT applications are becoming attractive, such as the sports [12] and navigation applications. Imagine, for example, underwater sensors can be used as location reference points, and thus can provide swimmers, divers, ships, and underwater vehicles with valuable information.

Challenges

The current pace of research on IoUT is slow due to the challenges arising from the uniqueness of UWSNs. Specifically, the main challenges for IoUT are the differences between UWSNs and TWSNs. First, UWSNs usually rely on acoustic communications rather than radio communications. This is because radio signals would be absorbed by water very quickly. Second, the propagation speed of acoustic channels (1500 m/s) is much lower than that of radio channels (300,000,000 m/s). Thus, how to guarantee the bounded end-to-end delay would be a challenging issue. Third, the transmission range of UWSNs could be ten times longer than that of TWSNs. This may cause more interference and collisions during the data transmission. Fourth, acoustic communication uses a narrow bandwidth; hence, the transmission speed is low (approximately 10 kbps). Fifth, the underwater sensors are difficult to recharge; thus, energy efficiency is an important concern for IoUT. Sixth, the underwater sensors may move with water currents, and suffer from dynamic topology changes. Seventh, the link reliability in underwater environments is unstable and low. We summarize the differences in Table I.

TABLE I THE DIFFERENCES BETWEEN TWSNS AND UWSNS

Features	TWSNs	UWSNs
Transmission Media	Radio Wave	Sound Wave
Propagation Speed	300,000,000 m/s	1,500 m/s
Transmission Range	10-100 m	100 m-10 km
Transmission Speed	~250 kbps	~10 kbps
Difficulty to Recharge	Depend on Applications	Difficult
Mobility (of nodes)	Depend on Applications	High
Reliability (of links)	Depend on Applications	Low

The differences are the challenges for IoUT. In recent years, researchers have discussed and tackled some of the challenging issues. Although much research has been done on the issues of the propagation delay [13], energy consumption [14], narrow bandwidth, and dynamic topology (see more related works in [15]), few studies concentrate on the more fundamental issue of reliability. As we can imagine, low reliability would lead to frequent data retransmission; then, frequent retransmission will eventually result in longer delay, higher energy consumption, and higher bandwidth consumption. The above imagination reminds us that reliability is of critical importance. Therefore, we are particularly interested in the issues of reliability. In the next section, we introduce how to estimate the reliability of links through the underwater channel models.

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Channel Models

To calculate the reliability (of links) on IoUT, we investigate the channel models for underwater environments. The aim of the models is to calculate the Bit Error Rate (BER) of the links over UWSNs. The BER (between a pair of sensor nodes) refers to the reliability, and is valuable information for designing reliable communication protocols on IoUT.

The underwater channel models consist of several parts. We first investigate the relationship between the transmitter power and signal-to-noise ratio (SNR). Furthermore, we investigate the relationship between the SNR and BER. Consequently, the channel models can provide us with a systematic way to calculate the reliability of links for IoUT (i.e., the BER).

Let γ be the SNR. The SNR can be divided into four parts [16], and be expressed as follows:

$$\gamma = S_{level} - T_{loss} - N_{level} + D_{index}. \quad (1)$$

where S_{level}, T_{loss}, N_{level}, and D_{index} are the source level, transmission loss, noise level, and directivity index, respectively. Note that the unit of each factor is dB.

First, the source level S_{level} is defined as the effective level of sound. To calculate S_{level}, we need to start from the relationship between S_{level} and transmitted signal intensity I [17]. The relationship can be expressed by

$$S_{level} = 10\left[\log(I) - \log\left(0.67\times10^{-18}\right)\right]. \quad (2)$$

To calculate I, we also need the relationship between the transmitter power P and transmitted signal intensity I. The relationship can be expressed as follows

$$P = 4\pi r^2 \times I, \quad (3)$$

where r is the range (i.e., the radius of an imaginary sphere); note that the units of P and r are W and m, respectively. Using Equation (3), we can first compute the intensity I by

$$I = \frac{P}{4\pi r^2}. \quad (4)$$

Using Equations (2) and (4), we can compute the source level as follows

$$S_{level} = 10\left[\log(P) - \log\left(4\pi r^2\right) - \log\left(0.67\times10^{-18}\right)\right]. \quad (5)$$

Second, the transmission loss T_{loss} is defined as a measure of the rate at which sound energy is lost. The underwater T_{loss} [18] over a distance d (in m) for a signal of frequency f (in kHz) can be derived by

$$T_{loss} = 20\log d + \alpha(f)\times d\times10^{-3}, \quad (6)$$

where $\alpha(f)$ is the absorption coefficient in dB/km. To calculate $\alpha(f)$, we can use Thorp's formula [19] as follows:

$$a(f) = \frac{0.11f^2}{1+f^2} + \frac{44f^2}{4100+f^2} + 2.75\times10^{-4}f^2 + 0.003. \quad (7)$$

Third, the noise level N_{level} is affected by a number of sources, such as turbulence, shipping, waves, etc. The author in [20] provides a practical approximation of the noise level in underwater environments. The approximation of N_{level} can be calculated by the following equation:

$$N_{level} = 50 - 18\log f. \quad (8)$$

Fourth, the directivity index D_{index} can be set as 0. This is because the underwater hydrophones are often omnidirectional.

Combining Equations (1), (5), (6), and (8), we can model the relationship between the transmitter power P and SNR γ as follows:

$$\gamma = 10\left[\log(P) - \log\left(4\pi r^2\right) - \log\left(0.67\times10^{-18}\right)\right] - 20\log d - \alpha(f)\times d\times10^{-3} - 50 + 18\log f. \quad (9)$$

In addition, we investigate the suitable model for calculating the Bit Error Rate (BER) in underwater environments. For modulation scheme, the BPSK modulation is chosen because BPSK is widely used in underwater acoustic sensor networks [21]. For signal propagation, the Rayleigh fading channel is chosen because Rayleigh fading is an appropriate model for the multipath effect in both the shallow and deep water [19]. Accordingly, the BER of BPSK in a Rayleigh fading channel can be derived by [22]

$$BER(\gamma) = \frac{1}{2}\left(1 - \sqrt{\frac{10^{\gamma/10}}{1+10^{\gamma/10}}}\right), \quad (10)$$

where $BER(\gamma)$ is the estimated number of bit errors per unit time over a communication channel when the SNR is equal to γ.

Based on the channel models, given the transmitter power P, transmission distance d, and frequency f, we can first compute the SNR γ for IoUT by using Equation (9) with Equation (7). Then, using the SNR γ, we can calculate the reliability (i.e., the BER) for IoUT by using Equation (10). In summary, given the transmitter power (with transmission distance and frequency), the channel models can provide a quick and accurate way of estimating the reliability in UWSNs.

Results

In this section, we verified the channel models by simulations.

A. Simulation Environment

The simulations were conducted using C++. We consider an underwater wireless sensor network (UWSN) with the BPSK modulation. The frequency is set as 10 kHz. According to the commercial LinkQuest underwater acoustic modems [23], we set the transmitter power in the range of 1-40 W [24].

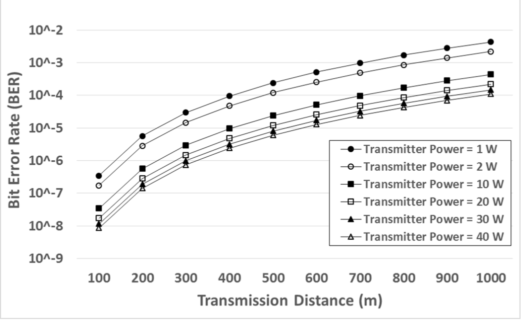

Fig. 3 Simulation results when the channel models are applied to different transmitter powers (1-40 W) and distances (100-1000 m).

B. Evaluation of the Channel Models

Fig. 3 shows the simulation results when the transmitter powers are set as 1W, 2W, 10W, 20W, 30W, and 40W. This figure plots the Bit Error Rate (BER) as a function of the transmission distance.

First, when the transmission distance is increasing, the BER is increasing. The same phenomenon happens in all the cases of different transmitter powers. This phenomenon confirms that our channel models are reasonable and applicable to different transmitter powers.

Second, when the transmitter power is higher, the BER is lower. Specifically, when the transmission distance is the same, the transmitter powers from low BERs to high BERs are: 40W, 30W, 20W, 10W, 2W, and then 1W. Because the results are consistent in all the cases of different transmission distances (from 100m to 1000m), the simulation results confirm that our channel models are also applicable to different distances. Note that although the 10-40W transmitters outperform the 1-2W transmitters in terms of the BER, the 10-40W devices are potentially heavy and expensive [24].

Conclusions

In this paper, we study a new class of IoT, called IoUT (i.e., the Internet of Underwater Things). This paper provides useful information about the IoUT (1) applications, (2) challenges, and (3) channel models. The simulation results have confirmed that our channel models are practical and applicable to different transmitter powers (i.e., 1-40 W) and to different transmission distances (i.e., 100-1000 m). In the future, we will apply the channel models to further investigate the effects of different parameters (e.g., the transmit mode power consumption and operating frequency) on the IoUT communication protocols, such as the MAC protocols and routing protocols. Moreover, the channel models can also be applied when researchers investigate the reliable communication protocols on IoUT.

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