Review of Underwater Internet of Things Technologies

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***Abstract*—This paper reviews the innovations and research into the field of Underwater Internet of Things. This field presents new and different challenges compared to similar networks designed for terrestrial uses due to the variability of the aquatic domain. The types of communication signals is the primary question for solving these different challenges. However, as work in this field continues, Underwater Internet of Things are becoming more and more of a possibility and are revolutionizing the possibilities of aquatic data collection.**

I. Introduction

AN Internet of Things (IoT) is today defined a network of interconnected sensors collecting data for a specified purposes [1]. This technology has grown into one of the most prosperous fields of the Information Era due to the desire for data collection around the globe. However, many of these IoTs are based terrestrially using electromagnetic waves as the mode of communication. Therefore, different innovations are necessary for operating in areas where electromagnetic waves may be unusable (or inefficient). Underwater Internets of Things (UIoT) are a type of IoTs which are deployed in water, whether at the water's surface or at the bed of the body of the water. The most pressing issue for developing an UIoTs is that electromagnetic waves propagate poorly through water, meaning much of existing IoTs technology does not easily convert to an underwater system. However, issues with marine fouling, ocean currents, and accessibility are also a major concern [2]. Marine fouling can cause inconsistencies in transmission for some communication types and corrosion of hardware [3]. Ocean current can mean the location of each node may be slightly non-static and case distortions in some types of signals. And, since these systems are deployed underwater, battery life and the capability for recharging are crucial considerations. Each of these issues makes deploying and maintaining a cost-effective and useful system increasingly difficult. However, these systems can provide access to information which would otherwise be unobtainable.

Despite at least two centuries of humanity traveling the seas, the aquatic domain remains a difficult and dangerous domain for humans to analyze. Effective UIoTs will be able to bridge this gap in knowledge by being able to collect otherwise inaccessible data. For example, a system containing multiple underwater sensors could communicate collected data (temperature, pressure, etc.) to a base station and provide monitoring of a sea bed (see figure 1).

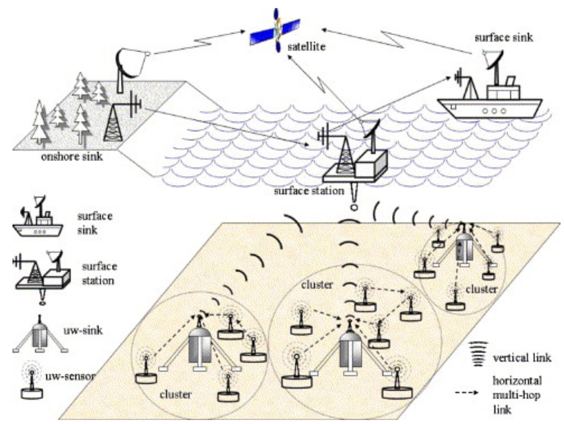

Fig. 1. Architecture for 2D underwater sensor networks. [2]

This application showcases a monitoring system which could be useful for surveying or aquatic surveillance. It utilizes both acoustic communications and electromagnetic communications. A more commercial application could be an implementation in a fish farm which could be used to monitor both the fish itself and the water quality of the enclosure (see figure 2).

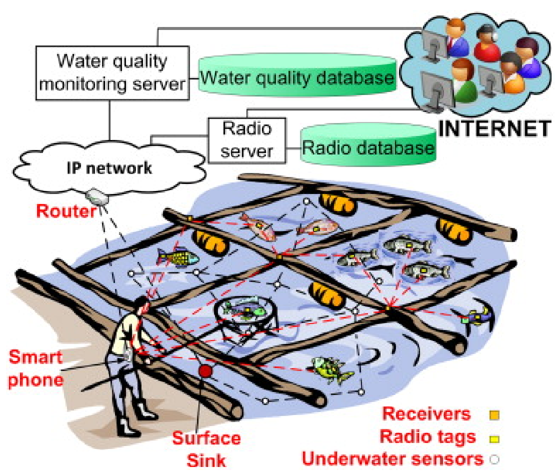

Fig. 2. Fish farm Underwater Internet of Things. [4]

Both of these systems proposed use a combination of different types of technologies to collect and transmit data, and shows the variety of solutions which can be developed on a system by system basis dependent on transmission distance and depth. UIoTs are critical for gathering data about the most unexplored domain on earth. Advances and progress in the various related communication fields will help these systems become much more commonplace.

II. Types of Underwater Communication

This section details various types of communication in relation to building underwater communications systems. Notably, the implications of these underwater communications will be discussed in relation to the creation and maintenance of an UIoTs.

A. Underwater RF Communication

Underwater radio frequency communication stands for utilizing electromagnetic signals to communicate between underwater things. Since the very beginning of radio, researchers have been studying underwater electromagnetic communications [5]; this interest resurfaced in the 1970s [6]. At that time, terrestrial radio is able to provided services like Morse code or some analog voice communications over great distances. But none of those services were available in the sea, so scientist were trying to find a way to implement those services in the underwater environment. However, after much effort had been made, the only successfully deployed underwater electromagnetic application is thought to be the Extremely Low Frequency (ELF) submarine communications system [7]. The purpose of this system is to send short radio messages at a very low data rate, and summon submarines from the sea to the surface. But people soon discovered that utilizing radio frequency communication underwater is very inefficient, so the idea that electromagnetic signals are impractical underwater quickly spread.

More specifically, due to water's high electrical conductivity and permittivity, electromagnetic propagation through it differs significantly from that through the air. Plane-wave attenuation is substantial in comparison to air and increases rapidly with frequency. Water has one of the greatest relative permittivity values of any substance, at 80, which has a significant impact on the how electromagnetic waves refract when reaching the air/water interface. Normal fresh water's conductivity can change a lot, but is still way lower than sea water's conductivity. Despite having a similar permittivity to sea water, fresh water has a far lower attenuation of electromagnetic signals. Conduction's impact on the electric field component is a major cause of loss, and it results in a significant attenuation of electromagnetic propagating waves because propagating waves continuously exchanging energy between the electric and magnetic fields[8].

In conclusion, electromagnetic propagation through salt water is very different from propagation through the air because of salt water's high permittivity and electrical conductivity, and radio waves do not travel well through good electrical conductors, especially salt water. Thus, underwater radio frequency communication is susceptible to electromagnetic interference, and has a very limited range through the sea water.

B. Underwater Acoustic Communication

With radio frequency communications propagating in water poorly, different types of communications need to be explored. Acoustic communications are a promising type for underwater communications due to how well sound waves propagate underwater. Acoustic communications have been conceived for underwater data collection since the early 1900s [9]. At first, acoustic signals were used for underwater echolocation, better known today as sonar. The ultrasonic (sound waves at a frequency ¿20kHz) signals generated by sonar systems are pulses which will reflect off of objects underwater objects and return to the sonar system; this allows for distance to an underwater object to be determined. At first, these acoustic signals were used to record distance data from a single source to an oceanic object. However, what can be considered the first UIoT based on acoustics would be developed by the United States in the 1950s and declassified in the early 1991: a system known as the Sound Surveillance System (SOSUS) [10]. This system is an array of hydrophones (a type of underwater transducers) connected to a base station which interprets received frequencies into a spectrogram. This system was designed to identify frequencies emitted by enemy submarines, but also had the capabilities to listen for seismic activities and other environmental effects. By the early 1990s, the concepts for modulation with underwater acoustic communications are being developed in the field, and this will lead UIoTs to slowly come to resemble terrestrial IoTs, despite using a different communication medium and signal type [11].

Acoustic communication has become the primary type of signals used in the field of UIoTs due to how well longitudinal waves propagate in water and how readily available hardware is used in these systems. As previously discussed, signals sent acoustically have an effective range of multiple kilometers. Longitudinal waves propagate significantly better in water compared to electromagnetic waves, and are therefore uniquely advantaged in the field of underwater communications [12]. This advantage allows for a hydro-acoustic network to have an impressive range for communication per node, meaning less nodes are necessary for links to a hypothetical base station [13]. This is the primary reason for building a UIoT using acoustics: high transmission distance means the system is less expensive. Furthermore, because sonar is such a widespread technology, transducers are readily available for prospective systems. Because of this, the field is much more developed than other signal types. The benefits inherent to the acoustic channel contribute to making it the most popular choice for UIoTs.

However despite these benefits, acoustic communication does inherently have some drawbacks: propagation speed and bandwidth, acoustic noise and interference, and multi-path [2]. First, using sound waves as opposed to electromagnetic waves will cause issues. The bandwidth at which a hydrophone communicates with is inversely related to the possible transmission distance. Therefore, the data rate is inversely related to the transmission distance. These communications can be done utilizing fully coherent modulation schemes like Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM), as these produce significantly more robust results than Amplitude Shift Keying (ASK) or Frequency Shift Keying (FSK). Even so, it is difficult to build an acoustic system which can deliver real-time data due to the limited data rate[14]. Acoustic noise, interference, and loss of connectivity is commonplace in the underwater channel, with sources being

TABLE I
TYPICAL $a(\lambda)$, $b(\lambda)$, AND $c(\lambda)$ FOR DIFFERENT WATER TYPES

Water types	$a(\lambda)$ (m^{-1})	$b(\lambda)$ (m^{-1})	$c(\lambda)$ (m^{-1})
Pure sea water	0.041	0.003	0.044
Clear ocean water	0.114	0.037	0.151
Coastal ocean water	0.179	0.219	0.398
Turbid harbour water	0.366	1.824	2.190

anything from wildlife [15] or hydrodynamics [16]. The noise sources must either be filtered out through signal processing or avoided altogether. Multi-path is also a significant issue with inter-symbol interference (ISI), which can cause a high BER [11]. These drawbacks need to be taken into account when building the physical and link layers of a system.

As a whole, utilizing acoustic communications for UIoTs purposes is the most popular choice for multiple reasons. Its ability to propagate well through the medium for long distances is critical to its popularity. Another contributing factor is that the hardware required is well understood and popular due to the long existence of hydrophones for underwater communication. However, this field is still under development due to the limitations inherent to the acoustic channel: the bandwidth, the large and inconsistent noise sources, and the issues which can be caused through multi-path and reflections. A well designed acoustic UIoT system must take these limitations into account.

C. Underwater Optical Communication

Other than acoustic communication, another promising option for underwater communication is optical communication. Underwater optical communication (UWOC) uses optical waves to transmit signals underwater and has been a rapidly growing field in the past few years.

In UWOC systems, one of the major challenges is signal attenuation due to two main factors: absorption and scattering. Absorption is common from the photons being absorbed by objects, mainly plants like phytoplankton, while scattering is common from the photons colliding with water and other particles. The attenuation coefficient, which is used to model the amount of attenuation expected in a signal, is often modeled as a sum of the absorption coefficient and scattering coefficient, all related to wavelength, as seen in Equation 1:

$$c(\lambda) = a(\lambda) + b(\lambda) \tag{1}$$

where $c(\lambda)$ is the attenuation coefficient, and $a(\lambda)$ and $b(\lambda)$ are the coefficients for absorption and scattering, respectively. Common values can be seen in Table I, below [17].

As can be seen, attenuation varies greatly based on the type of water. However, type of water is not the only factor in attenuation. Attenuation varies based on the depth that the signal is being sent in. To explain, closer to the surface of the water, both phytoplankton growth and higher salinity cause higher amounts of absorption and scattering, respectively, which increases attenuation significantly [18][19].

Other than signal attenuation, another challenge faced by UWOC systems is the signal being blocked by objects (marine life, debris, etc.). This can be an issue for the traditional line-of-sight (LOS) systems, where there is a direct line between the transmitter and receiver. Therefore, a new method of sending the signal through underwater mediums is through non-line-of-sight (NLOS) methods. These methods use the reflectivity of the water's surface to bounce signals to the receiver. This solves the issue of needing a direct line between transmitter and receiver; however, there are many challenges that are still preventing this from being a reliable form of signal transfer. One of the major challenges faced by NLOS UWOC systems is the random slope of the sea surface due to high winds. These slopes can cause random scattering and can destroy any signal received [20]. It has been since found that multiple scattering of light reduces the error of the received signal [21]. The wavelength-dependent path-loss was then analyzed and optimal wavelengths for different scenarios were found by Liu. et al. [22].

Both LOS and NLOS systems have been compared to see if different water situations affect the received power of a signal. Water turbulence with variations in temperature, salinity and presence of air bubbles have been experimentally tested. It has been found that in LOS systems in turbulence, an increase in salinity, temperature, or air bubbles all negatively effect the signal that is received, while with NLOS systems the temperature gradient does not seem to have an effect and air bubbles increased the received power of signals (salinity not tested in NLOS experiment) [23][24].

In terms of the actual transmitters in UWOC systems, there are two main transmitters commonly used: laser diodes (LDs) and light emitting diodes (LEDs). Laser diodes have seen a significant amount of promising results for both distance and transmission speed. This is largely due to LD's small divergence angle (a few miliradians vs. up to 140 for LED), so the signal is much more condensed and less susceptible to diminish from scattering and absorption. The fastest signals being sent by LD transmitters are sending at 30Gbps with a distance of 12.5m in tap water and 2.5m in harbour water. On the other hand, the longest distance an LD signal has travelled has been 144m at 500bps, but a more realistic application would be 117m at 2Mbps. These results are very promising for UWOC systems. In terms of LED transmitters, the fastest signal sent had a speed of 20.09Gbps over a distance of 1.2m in tap water, while the longest distance an LED transmitter has sent was a 5MHz signal over 46m. While LDs perform much better compared to LEDs, LED are still a worthy signal for UWOC systems for a few reasons. One of the main benefits of LEDs is that the cost is much lower than the cost of an LD transmitter. Furthermore, LEDs consume lower power at shorter distances and are able to transmit to a larger area in a short distance given the larger divergence angle. Therefore, LEDs are a great option for short-distance cost-effective UWOC systems, while LDs are mainly used for higher-speed, longer-distance systems.

Overall, UWOC is a promising field in underwater communication; however, the field is still very underdeveloped and has a lot of improvements and issues that need to be addressed before becoming a very reliable method of underwater communication.

III. Simulations

In this section, two simulations have been conducted to compare different communications approach. At first simulation two scenarios has been investigated: short-range scenario and long-range scenario. For the second simulation, bit error rate has been calculated for two popular modulations in optical communications.

In all simulation, it assumed that the water medium is salty (like ocean) which makes conductivity of water higher. For RF communication, Acoustic communications and optical communications, the carrier frequencies are 900 MHz, 1 kHz, 432 THz respectively.

A. Path Loss

Path loss of channel (large-scale attenuation) can be formulated as a function of distance and frequency. For acoustic channel, it can be modeled by this equation [25]:

$$10 \log PL(d, f) = 10k \log d + d \times 10 \log a(f) \tag{2}$$

$10 \ \log a(f) \ = \ 0.11 \left(\frac{f^2}{1+f^2}\right) + 44 \left(\frac{f^2}{4100+f^2}\right) + 2.75 \times 10^4 f^2 + 0.003 \text{ dB/km}$

For the RF communication, Friis Path loss formula has been used:

$$10 \log_{10} PL = 20 \log_{10} \left(\frac{\lambda}{4\pi d}\right) \tag{3}$$

For the optical communication, there is no long-range path loss model since it never reaches long distances and only for LoS path we have [13]:

$$10 \log_{10} PL(\lambda, d) = 10 \log_{10}(\exp^{-c(\lambda)d}) \tag{4}$$

where $c(\lambda)$ is a constant which defers in different type of water.

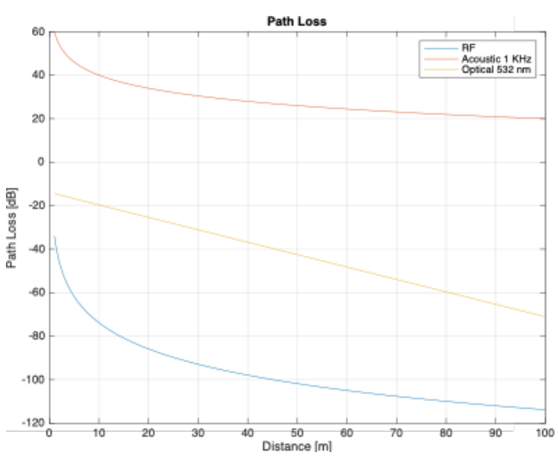

Fig. 3. Path Loss of short-range scenario for RF, acoustic and optical communications

As it can be seen in figure 3, form 1 meter to 100 meters, both optical and acoustic communication have acceptable performance. In contrast, RF communication have a huge path loss due to the conductivity of water and it can not be used. Since optical communications have better performance in energy consumption and data rate aspect it is the best candidate for short-range scenarios.

For the other scenario, optical communication can not be modeled as it have large amount of path loss and it never reached its destination. Again, RF communication have a significant path loss and it can not be considered. Thus, only option for long-range scenarios like 1 kilometer to 10 kilometers, acoustic communication is the only option.

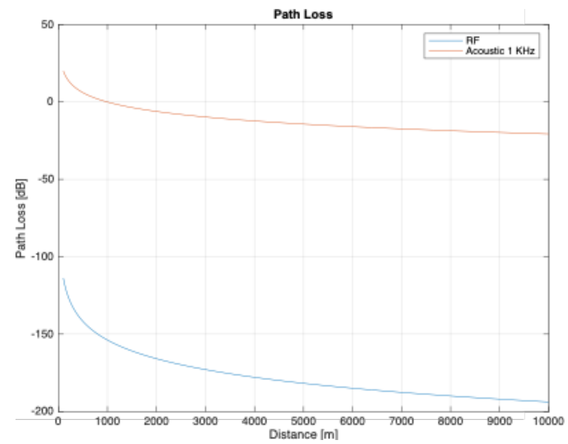

Fig. 4. Path Loss of long-range scenario for RF, acoustic and optical communication

B. Bit Error Rate

For this simulation whole digital communication system in physical layer has been implemented as it is showed in figure 5.

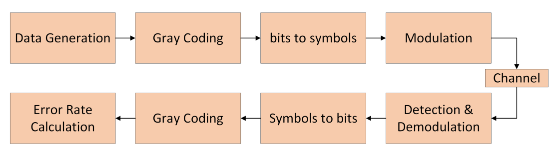

Fig. 5. Flow chart of bit error rate simulation.

Two modulation has been investigated, first one which is on-off keying is the simplest modulation that exist, just by turning on or off the LED we can utilize this modulation. However, as it can be seen in figure 6, its performance is worse since it needs high SNR to work properly. So in cases which have low SNR like fresh water or shorter distances, it can be used.

In contrast, phase-shift keying has better performance in lower SNRs which makes it compatible with any situations. Nevertheless, its implementation is harder as it needs special equipment at both receiver and transmitter. Therefore, environment and application should be taken into account for further decisions.

IV. Conclusion

To conclude, underwater communication is a very promising field in IoT, with a lot of potential for improvements in the near future. The two main methods of communication that have

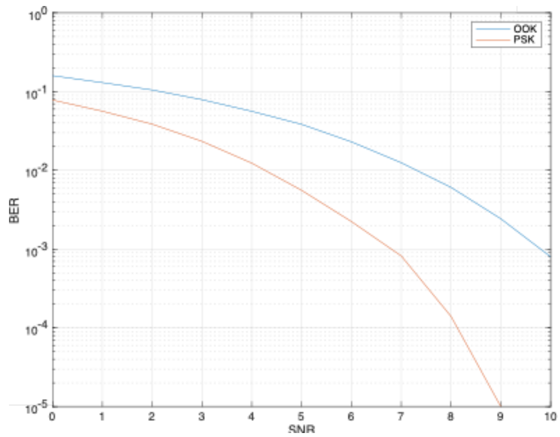

Fig. 6. Bit error rate plot for two popular modulation: OOK and PSK.

proven to be the best for underwater communication stand to be acoustic communication and optical communication. Even though RF communication is used so commonly in over-water communication, electromagnetic waves do not propagate well enough underwater, especially in high-salinity water to make it a viable option for most IoT purposes. Between acoustic and optical communication, on the other hand, the specifications of the specific IoT application can change which type of communication is better. To explain, for long distance communication, acoustic still remains to be the best type of communication underwater, as optical signals can only reach approximately 150m. Using optical communication for long distances would require many nodes, which would require significantly more cost and maintenance than acoustic communication methods. On the other hand, if the application is prioritizing low latency and shorter distances, optical communication comes out as the better option. Acoustic communication transmits signals at very slow rates and requires more power to transmit, while optical signals can be transmit at high speeds (up to Gbps) with low power usage.

Overall, underwater communication is still a young field of IoT, especially with using optical signals, so there is still a lot of growth potential for the field and improvements in technology in the future.

Acknowledgment

Codes for simulation can be found at GitHub.

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