Prospects and problems of wireless communication for underwater sensor networks

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Abstract

This paper reviews the physical fundamentals and engineering implementations for efficient information exchange via wireless communication using physical waves as the carrier among nodes in an underwater sensor network (USWN). The physical waves under discussion include sound, radio, and light. We first present the fundamental physics of different waves; then we discuss and compare the pros and cons for adopting different communication carriers (acoustic, radio, and optical) based on the fundamental first principles of physics and engineering practice. The discussions are mainly targeted at underwater sensor networks (USWN) with densely deployed nodes. Based on the comparison study, we make recommendations for the selection of communication carriers for USWNs with engineering countermeasures that can possibly enhance the communication efficiency in specified underwater environments.

1 Communication Requirements for Underwater Sensor Networks

The UWSNs targeted by this paper are underwater networks with densely deployed sensor nodes. High node density is the key characteristic of such networks. Depending on the applications,we can roughly classify the targeted dense sensor networks into two categories: (1) UWSNs for long-term non-time critical aquatic monitoring applications (such as oceanographic data collection, pollution monitoring/detection, and offshore oil/gas field monitoring); (2) UWSNs for short term time-critical aquatic exploration applications (such as submarine detection, loss treasure discovery, and hurricane disaster recovery) [2]. The former category of UWSNs can be either mobile or static depending on the deployment of sensor nodes (buoyancy-controlled or fixed at sea floor), while the latter category of UWSNs is usually mobile since it is natural to imagine that the cost of deploying/recovering fixed sensor nodes is typically forbidden for short term time-critical applications. To summarize, we will focus on three types of UWSNs: (1) mobile UWSNs for long-term non-time critical applications (M-LT-UWSNs for short); (2) static UWSNs for long term non-time critical applications (S-LT-UWSNs for short); (3) mobile UWSNs for short-term time-critical applications (M-ST-UWSNs for short). Obviously,different types of UWSNs have different communication requirements. We summarize the communication requirements for all three types of UWSNs in Table I. Besides the UWSNs we discussed above, underwater networks also include sparse mobile AUV or unmanned underwater vehicle(UUV)networks,where vehicles/node scan be spaced out by several kilometers. This type of networks has its unique communication requirements, and it is not the focus of this paper.

2 Fundamentals of Physical Waves as Underwater Communication Carriers

Understanding the first principles of each physical wave used in UWSN wireless communication is critically important. In this section we lay out the fundamental physical properties and critical issues for each of the acoustic, EM, and optical wave propagation in underwater environments. We discuss each physical carrier's advantages and disadvantages towards efficient underwater wireless communication

Table 1: Communication requirements of UWSNs.

Requirements	M-LT-UWSNs	S-LT-UWSNs	M-ST-UWSNs
Data rate	Various	Various	Various
Transmission range	Short (10 m - 10km)	Short (10 m - 10km)	Short (10 m - 10km)
Deployment Depth	Shallow water	Shallow or depth	Shallow water
Energy Efficiency	Major concern	Major concern	Minor concern
Antenna Size	Small	Small	Small
Real-time delivery	Minor concern	Minor concern	Major concern

2.1 Acoustic Waves

Among the three types of waves, acoustic waves are used as the primary carrier for underwater wireless communication systems due to the relatively low absorption in underwater environments. We start the discussion with the physical fundamentals and the implications of using acoustic waves as the wireless communication carrier in underwater environments

2.1.1 Physical properties

Acoustic waves have a number of propagation characteristics that are unique from other waves, two of which are highlighted below.

A typical speed of sound in water near the ocean surface is about 1520m/s, which is more than four times faster than the speed of sound in air,but five orders of magnitude smaller than the speed of light.The speed of sound in water increases with increasing water temperature, increasing salinity, and increasing depth. Most of the changes in sound speed in the surface ocean are due to the changes in temperature. This is because the effect of salinity on sound speed is small and salinity changes in the open ocean are small.

Under most conditions the speed of sound in water is simple to understand. Sound will travel faster in warmer water and slower in colder water. Approximately, the sound speed increases 4.0 m/s for water temperature arising 1 Degree Celcius.When salinity increases 1 practical salinity unit(PSU),the sound speed in water increases 1.4m/s. As the depth of water(therefore also the pressure)increases 1 km,the sound speed increases roughly 17 m/s.

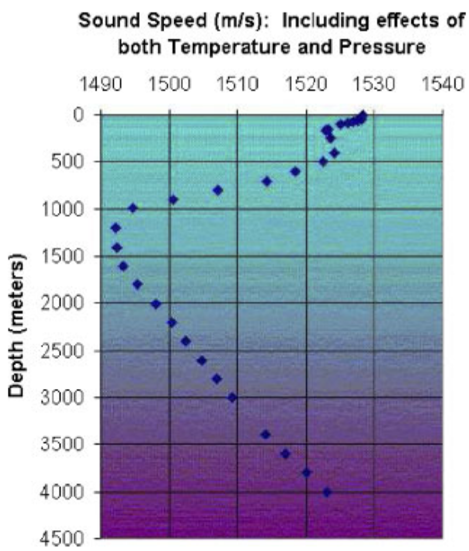

Figure 1: A vertical profile of sound speed in seawater as the lump-sum function of depth

Absorption: During propagation, wave energy may be converted to other forms and absorbed by the medium. The absorptive energy loss is directly controlled by the material imperfection for the type of physical wave propagating through it. For acoustic waves, this material imperfection is the in elasticity, which converts the wave energy into heat (while for EM waves the imperfection is the electric conductivity, as will be discussed in Section 3.2.).

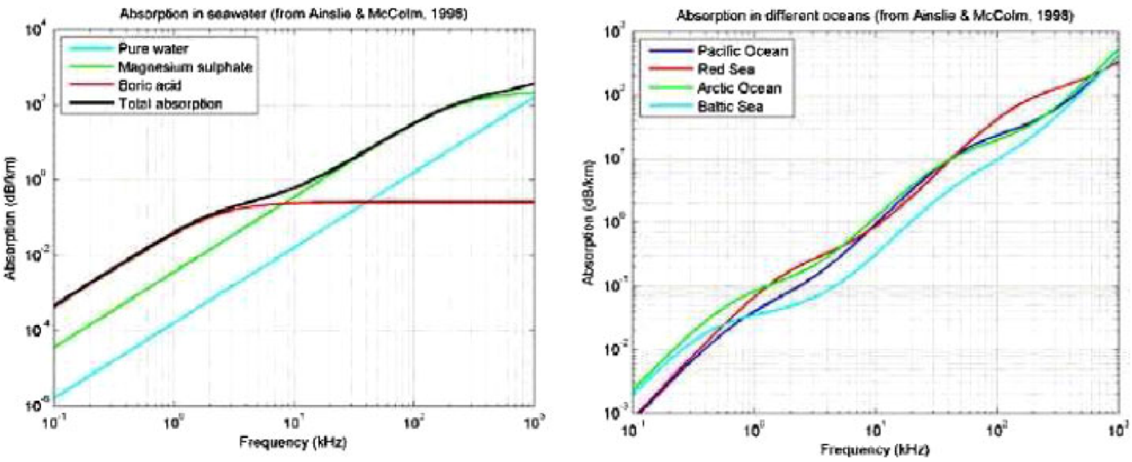

Figure 2: Absorption in generic seawater (left panel) and in different oceans (right panel) (from Ainslie and McColm, 1998 [5]).

The absorptive loss for acoustic wave propagation is frequency-dependent, and can be expressed as $e\alpha(\mathrm{f})\mathrm{d}$, where d is the propagation distance and $\alpha(\mathrm{f})$ is the absorption coefficient at frequency f. For seawater, the absorption coefficient at frequency f in kHz can be written as the sum of chemical relaxation processes and absorption from pure water

2.1.2 Multipath

An acoustic wave can reach a certain point through multiple paths. In a shallow water environment, where the transmission distance is larger than the water depth, wave reflections from the surface and the bottom generate multiple arrivals of the same signal. In deep water applications,surface and bottom reflections maybe neglected.Due to the spatially varying sound speed, the wave reflections, however, can cause significant multipath phenomena.
Large channel delay spread introduces time dispersion of a signal, which causes severe inter symbol interference. Consider a signal ling scheme with bandwidth of B =4kHz. Each symbol interval is about Ts =0.25ms. In the presence of a channel with delay spread of 10ms, each symbol will affect the subsequent 10/0.25=40 symbols due to waveform spreading. This brings grand challenges for efficient modulation and demodulation.

2.2 Electromagnetic Waves

The use of EM waves in radio frequency band has several advantages over acoustic waves, mainly on faster velocity and high operating frequency (resulting in higher bandwidth).However,there are many limiting factors when using EM waves in water. In this section, we will first discuss the fundamental physical behavior of EM field in underwater environments. We then analyze the practicality of using EM for UWSNs Due to the fact that EM field propagates very differently in fresh water and seawater,we describe EM in these two types of media separately as follows

2.2.1 EM in Freshwater

Freshwater is a low-loss medium. The propagation speed c can be expressed as [13]

$$c \approx \frac{1}{\sqrt{\epsilon\mu}}$$

where $\in$ is the dielectric permittivity $\in$ and μ is the magnetic permeability, whose value has no significant changes for most non-magnetic media. The dielectric permittivity $\in$ can be further expressed as the product of the permittivity in air, ∈0 (=10 − 9 /(36 π)), and the dimensionless relative permittivity, ∈r (also known as the dielectric constant). Since ∈r for water (saline and fresh alike) is about 81, the speed of underwater EM waves is slowed down by only a factor of 9 of the speed of light in free space. Clearly this speed is still much faster than that of underwater acoustic waves, by more than four orders of magnitude,and it poses no problem in channel latency.

2.2.2 EM in Seawater

Seawater is a high-loss medium. The electric conductivity σ of seawater is about two orders higher than that of freshwater. The higher conductivity in seawater is mainly due to the cumulative increase of total dissolved solid (TDS) concentration in oceans, shown as the great salinity; the average salinity in seawater is about 34 parts per thousand(ppt).In highly conductive media, both the propagation velocity and the absorptive loss of EM waves are functions of carrier frequency

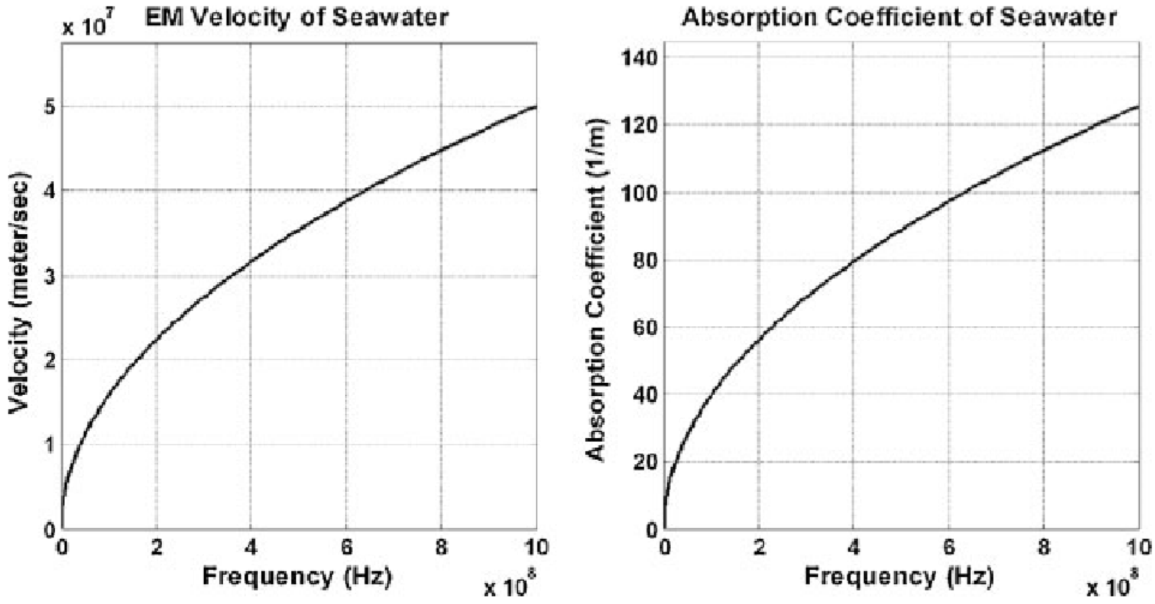

Figure 3: Velocity and absorption versus frequency for EM waves in seawater.

A plot of the velocity and the absorption coefficient versus frequency for EM waves in seawater is provided in Figure 3. Note that they are now frequency dependent, approximately proportional to the square root of frequency. This is the primary motivation for using lower frequency in highly conductive media. Seawater is a perfect example of this type of media

2.3 Optical Waves

Using optical waves for communication obviously has a big advantage in data rate, that can potentially exceed 1 Giga bps. However, there are a couple of disadvantages for optical communication (OCOMM) in water.Firstly,optical signals are rapidly absorbed in water. Secondly, optical scattering caused by suspending particle sand planktons is significant.Thirdly,high level of ambient light in the upper part of the water column is another adverse effect for using OCOMM. Now let us constrain our discussion to the situation of using only monochromatic light in deep water (where ambient light is usually not a major issue).Then optical scattering is the topic more pertinent to using optical waves for communication. The scattering process of optical waves and the wavelength dependence of underwater optical channels can be evaluated by the Mie scattering theory [14]. In contrast to Rayleigh scattering [14], which is valid in the region where the wave length is much larger than the size of the scattering particles, the Mie solution to the scattering problem is rigorously valid for all possible ratios of particle diameter to wavelength.

3 Engineering Countermeasures

In this section, we describe the engineering countermeasures that have been developed to address the physical challenges for each wave used as the communication carrier in UWSNs. These are physical layer techniques to achieve point-to-point communication among sensor nodes.

3.1 Acoustic Communication (ACOMM)

Acoustic waves propagate well in seawater and can reach a far distance,as is the main reason why acoustic waves are widely used in underwater communication. The main limitations and challenges of ACOMM are summarized as follows. First,ACOMM is fundamentally bandwidth-limited. Frequencies up to 1MHz have been tried in field tests [6]. However, the usable frequency band depends on the transmission distance, as discussed in Section 3. Very-high-frequency bands (e.g., above 50kHz) can be used only for short-range communication. For moderate range communication,frequency range from 20 to 50kHz is often used. Low frequency waves (e.g., below 10kHz) are effective for very long-range communication,e.g.,in the order of tens of kilometers. The bandwidth for ACOMM is typically in the order of kHz to tens of kHz,which is far inferior to that of radio communication. How to utilize the limited bandwidth efficiently is one major objective for ACOMM, as amounts to increasing the number of bits per second communicated per unit bandwidth(bits/sec/Hz),which is usually called bandwidth efficiency.

3.2 Electromagnetic Communication (EMCOMM)

As discussed in Section 3.2,the main challenge in using radio underwater is the severe attenuation due to the conducting nature of seawater.As a result,EMCOMM works in the power-limited region. Extremely low frequency (ELF) radio signals have been used in military applications.Germans pioneered EMCOMM in radio frequency for submarines during World War II, where the antenna was capable of outputting up to 1–2 Mega-Watt (MW) of power [38]. An ELF signal, typically around 80Hz at much lower power, has been used to communicate with naval submarines globally today. This is possible mainly because most of the transmission paths are through the atmosphere [38]. It was deemed impractical to use high frequency wave for communication purposes. However, theoretical analysis and experiments show that radio waves within a frequency range of 1–20MHz are able to propagate over distances up to 100m by using dipole radiation with transmission powers in the order of 100W [39]. This will yield high data rates beyond 1Mbps which allows video images to be propagated at standard camera frame rates (25Hz) [40]. The antenna design in such case is very different from that of the antennas used for conventional service in the atmosphere [38–40]. Instead of having direct contact with seawater, the metal transmitting and receiving aerials are surrounded by waterproof electrically insulating materials [39,40]. This way, an EM signal can be launched from the transmitter into a body of seawater and picked up by a distant receiver.

3.3 Optical Communication (OCOMM) and Acousto-Optical Hybrid

As pointed out in Section 3.3, water quality plays a key role in deciding whether optical waves can be used for underwater communication. As a result, the applicability of OCOMM heavily depends on environments. Using the same analogy for acoustic and EM waves, we say that OCOMM works in the environment-limited region. So far, there are not many commercial activities on underwater OCOMM, and no commercial optical modems are available specifically for underwater. Recent interests in UWSN sand sea floor observatories have greatly stimulated the interest in short-range high rate OCOMM in water.For example,in Reference[42], an optical modem prototype is designed for deep sea floor observatories; in Reference [43], a dual mode (acoustic and optic)transceiver is used to assist robotic networks. Lab testings have shown that very high data rates can be achieved within a short range. For example, a laboratory experiment for underwater optical transmission achieves 1Gbps rate over a 2m path in a water pipe with up to 36dB of extinction [44]. The source at 532nm wavelength was derived from a 1064nm continuous-wave laser diode that was intensity modulated, amplified, and frequency-doubled in periodically poled lithium niobate.

4 Networking Challenges for Underwater Acoustic Sensor Networks

In this section, we focus on the networking challenges for underwater acoustic sensor networks. Due to the unique characteristics of underwater acoustic channels (long latency and low bandwidth) and the harsh underwater environments (resulting in high channel dynamics),technology used in terrestrial radio networks could not be applied to underwater acoustic networks. Next we discuss several typical networking problems in the design of UWSNs. We identify the design challenges and brief some recent solutions in the literature.

5 Concluding Remarks

Based on the discussion in previous sections, we have the following summary points.

- Up to date and extending to the near future, acoustic waves will be staying as the major carrier of wireless communication in UWSNs. For acoustic wave carriers, apparently the key challenges are in communication and networking.
- For EM radio wave carriers, the main shortcoming stay swith the high absorption of EM waves in water, especially in seawater. Though short-range wireless communication using EM waves in seawater has seen certain breakthroughs, it will still be a long way to expand the approach to be used in UWSNs.
- Optical carriers will remain as to be used for some special applications. The major hurdle is that OCOMM in water is largely constrained by environments.

In short, this review article has analyzed the necessity of considering the physical fundamentals of an underwater environment for a particular kind of physical wave to be used as the carrier of wireless communication among nodes in an UWSN. Acoustic wave remains the most robust and feasible carrier up to the date