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Invited Paper

Prospects and problems of wireless communication for underwater sensor networks

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Summary

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 (UWSN). 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 (UWSNs) with densely deployed nodes. Based on the comparison study, we make recommendations for the selection of communication carriers for UWSNs with engineering countermeasures that can possibly enhance the communication efficiency in specified underwater environments. Copyright © 2008 John Wiley & Sons, Ltd.

KEY WORDS: underwater sensor networks; wireless communication; acoustic waves; electromagnetic waves; optical waves

1. Introduction

In the last several years, underwater sensor network (UWSN) has found an increasing use in a wide range of applications such as coastal surveillance systems, environmental research, autonomous underwater vehicle (AUV) operation, to name a few [1–4]. By deploying a distributed and scalable sensor network in a three-dimensional underwater space, each underwater sensor can monitor and detect environmental parameters and events locally. Hence, compared with remote sensing, UWSNs provide a better sensing and surveillance technology to acquire better data to understand the spatial and temporal complexities of underwater environments. Clearly, *efficient underwater communication* among units or nodes in a UWSN is one of the most fundamental and critical issues in the whole network system design.

Present underwater communication systems involve the transmission of information in the form of sound,

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electromagnetic (EM), or optical waves. Each of these techniques has advantages and limitations.

Acoustic communication (ACOMM) is the most versatile and widely used technique in underwater environments due to the low attenuation (signal reduction) of sound in water. This is especially true in thermally stable, deep water settings. On the other hand, the use of acoustic waves in shallow water can be adversely affected by temperature gradients, surface ambient noise, and multipath propagation due to reflection and refraction. The much slower speed of acoustic propagation in water, about 1500 m/s, compared with that of EM and optical waves, is another limiting factor for efficient communication and networking. Nevertheless, the currently favorable technology for underwater communication is upon acoustics.

On the front of using *EM waves* in radio frequencies, conventional radio does not work well in an underwater environment due to the conducting nature of the medium, especially in the case of seawater. However, if EM could be working underwater, even in a short distance, its much faster propagating speed is definitely a great advantage for faster and efficient communication among nodes.

Free-space optical (FSO) *waves* used as wireless communication carriers are generally limited to very short distances because the severe water absorption at the optical frequency band and strong backscatter from suspending particles. Even the clearest water has 1000 times the attenuation of clear air, and turbid water has more than 100 times the attenuation of the densest fog. Nevertheless, underwater FSO, especially in the blue-green wavelengths, offers a practical choice for high bandwidth communication (10–150 Mbps, Megabits per second) over moderate ranges (10–100 meters). This communication range is much needed in harbor inspection, oil-rig maintenance, and linking submarines to land, to just name a few of the demands on this front.

In this paper, we review the physical fundamentals and engineering implementations for efficient communication, via acoustic, EM and optical waves, among nodes in a UWSN. We first present the communication needs and requirements for UWSNs in the next section. Then, we discuss the fundamental physics of acoustic, radio and optical waves, and pertinent concerns as wireless communication carriers. After that, we compare the engineering countermeasures for the shortcomings of each individual carrier. Finally, we discuss the networking challenges for underwater acoustic sensor networks, followed by a short summary of the applicability of three types of waves in underwater sensor networks (UWSNs).

2. 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/nodes can be spaced out by several kilometers. This type of networks has its unique communication requirements, and it is not the focus of this paper.

3. 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 propagations in underwater environments. We discuss each physical carrier's advantages and disadvantages towards efficient underwater wireless communication.

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Table I. Communication requirements of UWSNs.

Requirements	M-LT-UWSNs	S-LT-UWSNs	M-ST-UWSNs
Data rate	Various	Various	Various
Transmission range	Short (10 m–1 km)	Short (10 m–1 km)	Short (10 m–1 km)
Deployment depth	Shallow water	Shallow or deep	Shallow water
Energy efficiency	Major concern	Major concern	Minor concern
Antenna size	Small	Small	Small
Real-time delivery	Minor concern	Minor concern	Major concern

3.1. 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.

3.1.1. Physical properties

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

Propagation velocity: The extremely slow propagation speed of sound through water is an important factor that differentiates it from EM propagation. The speed of sound in water depends on the water properties of temperature, salinity, and pressure (directly related to the depth). A typical speed of sound in water near the ocean surface is about 1520 m/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. Near shore and in estuaries, where the salinity varies greatly, salinity can have a more significant effect on the speed of sound in water. As depth increases, the pressure of water has the largest effect on the speed of sound.

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°C. When salinity increases 1 practical salinity unit (PSU), the sound speed in water increases 1.4 m/s. As the depth of water (therefore also the pressure) increases 1 km, the sound speed increases roughly 17 m/s. It is noteworthy to point out that the above assessments are only for rough quantitative or qualitative discussions, and the variations in sound speed for a given property are not linear in general. The overall effect of sound speed in seawater is illustrated in Figure 1.

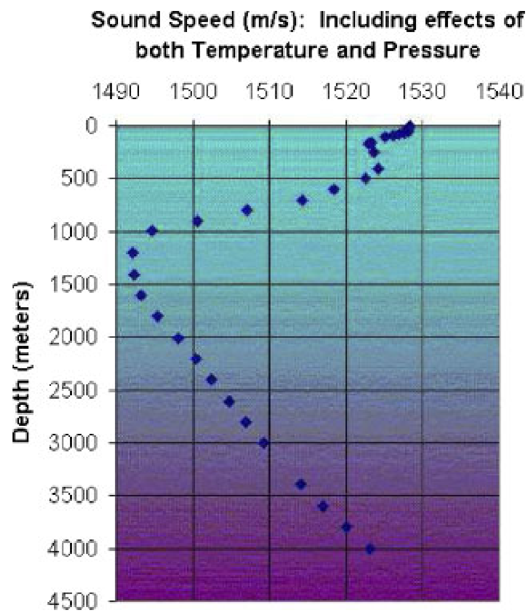

Fig. 1. A vertical profile of sound speed in seawater as the lump-sum function of depth (from http://www.coexploration.org/bbsr/classroombats/html/sofarfig4.html).

The slow propagation speed of sound impacts communication system performance and network protocol design in a number of ways, as will be discussed in later sections on engineer countermeasures and networking challenges.

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

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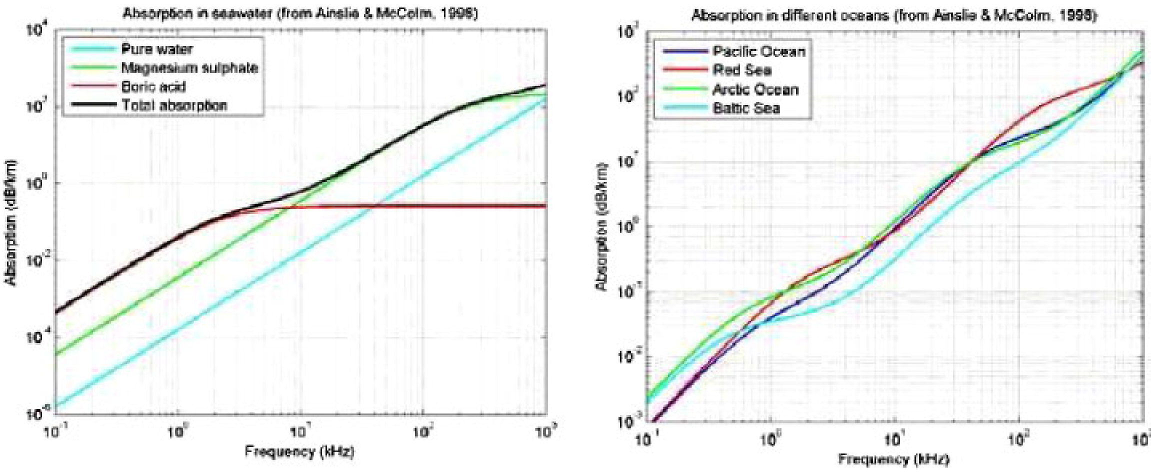

Fig. 2. Absorption in generic seawater (left panel) and in different oceans (right panel) (from Ainslie and McColm, 1998 [5]).

wave propagating through it. For acoustic waves, this material imperfection is the inelasticity, 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.).

The absorptive loss for acoustic wave propagation is frequency-dependent, and can be expressed as $e^{\alpha(f)d}$, where d is the propagation distance and $\alpha(f)$ 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 [5]:

$$\alpha(f) = \frac{A_1 P_1 f_1 f^2}{f_1^2 + f^2} + \frac{A_2 P_2 f_2 f^2}{f_2^2 + f^2} + A_3 P_3 f^2 \quad (1)$$

where the first term on the right side is the contribution from boric acid, the second term is from the contribution of magnesium sulphate, and the third term is from the contribution of pure water; A_1, A_2, and A_3 are constants; the pressure dependences are given by parameters P_1, P_2, and P_3; and the relaxation frequencies f_1 and f_2 are for the relaxation process in boric acid and magnesium sulphate, respectively. Figure 2 shows the relative contribution from the different sources of absorption as a function of frequency, and the variation in total absorption with frequency for four different oceans [5].

3.1.2. 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 may be neglected. Due to the spatially varying sound speed, the wave refractions, however, can cause significant multipath phenomena.

Assume that there are P distinct paths between the source and the receiver, and let τ_p denote the propagation delay for the pth path. Further, we use D to denote the *channel delay spread*, defined as the time difference between the first and the last arrivals of multipath propagation, i.e., $D = \tau_{P-1} - \tau_0$. Due to the slow speed, the channel delay spread from multipath propagation is large. For example, two physical arrivals that differ 15 m in path length lead to an arrival time difference of 10 ms (here we assume that the propagation speed of sound is 1500 m/s). Typical underwater channels have delay spread around 10 ms, but occasionally delay spread can be as large as 50 – 100 ms [6].

Large channel delay spread introduces time dispersion of a signal, which causes severe *inter-symbol interference*. Consider a signalling scheme with bandwidth of $B = 4$ kHz. Each symbol interval is about $T_s = 0.25$ ms. In the presence of a channel with delay spread of 10 ms, each symbol will affect the subsequent $10/0.25 = 40$ symbols due to waveform spreading. This brings grand challenges for efficient modulation and demodulation.

3.1.3. Path loss

We now discuss the energy loss of channels.

For any propagation wave, there are three primary mechanisms for energy loss: (i) geometric spreading,

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(ii) absorptive loss, and (iii) scattering loss. The absorptive loss for acoustic waves has been discussed in Section 3.1.1. We next focus on geometric spreading and scattering loss.

Geometric spreading is the local power loss of a propagating acoustic wave due to energy conservation. When an acoustic impulse propagates away from its source with longer and longer distance, the wave front occupies larger and larger surface area. Hence, the wave energy in each unit surface (also called *energy flow*) becomes less and less. For the spherical wave generated by a point source, the power loss caused by geometric spreading is proportional to the square of the distance. On the other hand, the cylindrical waves generated by a very long line source, the power loss caused by geometric spreading is proportional to the distance. For a practical underwater setting, the geometric spreading is a hybrid of spherical and cylindrical spreading, with the power loss to be proportional to d^{β}, where β is between 1 (for cylindrical spreading) and 2 (for spherical spreading) [7]. Note that geometric spreading is frequency-independent.

Scattering is a general physical process whereby one or more localized non-uniformities in the medium, such as particles and bubbles, force some forms of wave radiation to deviate from a straight trajectory. It also includes deviation of reflected radiation from the angle predicted by the law of reflection. This is especially relevant to underwater channels. When the wind speed increases, the surface roughens and the effect of surface scattering becomes evident [8]. Surface scattering introduces not only power loss, but also spreading in delay of each surface bounce path (thus contributes to multipath phenomena as discussed in Section 3.1.2).

Now we are ready to formulate path loss. Still assume that there are P paths, and let ξ_p denote the scattering loss, d_p the propagation distance and τ_p the propagation delay of the pth path. Then the pass loss along the pth path can be written as $d_p^{\beta} e^{\alpha(f) d_p} \xi_p$, combining the effects of spreading loss, absorptive loss, and scattering loss. Assuming that the channel is static within a certain time interval, the channel transfer function at frequency f can be described as

$$H(f) = \sum_{p=0}^{P-1} \frac{1}{\sqrt{d_p^{\beta} e^{\alpha(f) d_p} \xi_p}} e^{-j2\pi f \tau_p} \tag{2}$$

We can then easily draw a conclusion that the overall channel attenuation is dependent not only on the distance but also on the frequency. Since $\alpha(f)$ increase as f increases, high frequency waves will be considerably attenuated within a short distance, while low frequency acoustic waves can travel very far. As a result, the bandwidth is extremely limited for long-range applications, while for short-range applications, several tens of kHz bandwidth could be available (a thorough study on the relationship between bandwidth (capacity) and distance is reported in [9]). Therefore, acoustic waves are considered practical for efficient communication in UWSNs, where sensors are usually densely deployed.

3.1.4. Ambient noise

Ambient noise is defined as 'the noise associated with the background din emanating from a myriad of unidentified sources. Its distinguishing features are that it is due to multiple sources, individual sources are not identified, and no one source dominates the received field' [10]. The common sea-surface noise sources include the surface-ship radiated noises, breaking waves associated with ensuing bubble production, and so on; and the deep water noises mainly come from marine animals. Moreover, surface ships that cross ocean basins could produce a general low frequency background traffic noise that may not in fact sound like coming from surface shipping [11].

The level of underwater ambient noise may have large fluctuations upon a change in time, location or depth. Nevertheless, it is still possible to sketch out a function describing the approximate magnitude range to characterize underwater ambient noises in very general terms. Often *pressure spectral density*, defined as the mean squared pressure of noise within a given frequency band divided by the bandwidth Δf, is used. The unit of pressure spectral density is pressure squared per Hertz. Figure 3 plots the compiled spectral density from different water bodies over the world oceans. It should be noted that noise level is frequency-dependent. Thus, when selecting a suitable frequency band for communication, besides path loss, noise should be also considered [8,9].

Combining path loss and ambient noise, we may see the following effects on communication and networking: For short-range ACOMM, the level of ambient noise may be well below the desired signal. For long-range or covert ACOMM, the noise level would be a limiting factor for communication performance. For networking, the most severe effect may be from some impulsive noises. The presence

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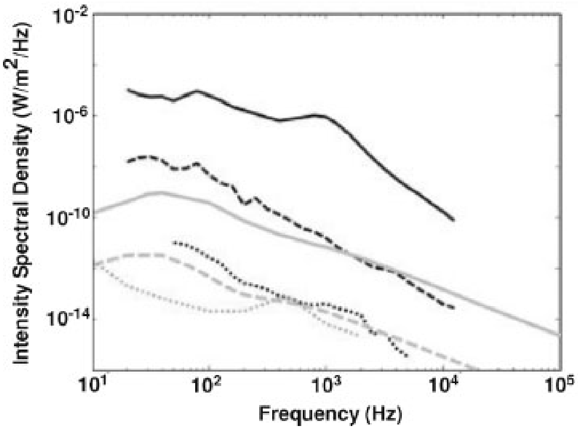

Fig. 3. Noise intensity spectral densities for different environments in air and under water. Solid black: interstate-5 in Seattle, 4 m off center of right lane; dashed black: quiet city residence with distant traffic noise; dotted black: background noise at Hermit Basin, Grand Canyon National Park; solid gray: high shipping traffic and sea state 6 (strong gale); dashed gray: low shipping traffic and sea state 0 (glassy calm); dotted gray: under smooth sea ice in the Antarctic with no wind (from Reference [12]).

of this kind of noises may cause highly dynamic link error rate or even link outage, which brings great challenges for networking design.

3.2. 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 freshwater and seawater, we describe EM in these two types of media separately as follows.

3.2.1. EM in Freshwater

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

$$c \approx \frac{1}{\sqrt{\epsilon\mu}} \tag{3}$$

where ϵ is the dielectric permittivity and μ is the magnetic permeability, whose value has no significant changes for most non-magnetic media. The dielectric permittivity ϵ can be further expressed as the product of the permittivity in air, ϵ_0 $(= 10^{-9}/(36\pi))$, and the dimensionless relative permittivity, ϵ_r (also known as the dielectric constant). Since ϵ_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.

The absorption coefficient α for EM propagation in freshwater can be approximated as [13]

$$\alpha \approx \frac{\sigma}{2}\sqrt{\frac{\mu}{\epsilon}} \tag{4}$$

where σ is the electric conductivity. Note that here the absorptive loss is essentially *frequency-independent*, and EM waves can literally propagate through freshwater body. For example, ground penetrating radar (GPR) has been successfully operated on the lake surface to map lake-bottom sediments. As such, using EM waves as the communication carrier in freshwater environments appears very attractive. However, the key problem in using EM waves for communication in freshwater UWSNs is the antenna size. The big antenna size of an EM transmitter (e.g., a couple of meters for a 50 MHz antenna) is unpractical for the dense deployment of UWSNs.

3.2.2. 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. The propagation speed of EM waves in seawater can be expressed as [13]

$$c \approx \sqrt{\frac{4\pi f}{\mu\sigma}} \tag{5}$$

while the absorption loss can be approximated as [13]

$$\alpha \approx \sqrt{\pi f \mu\sigma} \tag{6}$$

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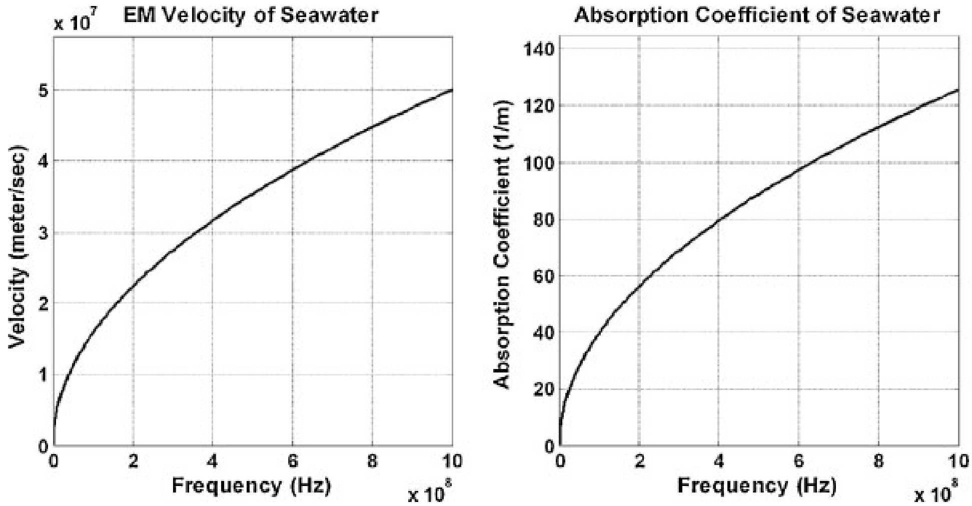

Fig. 4. Velocity and absorption versus frequency for EM waves in seawater.

A plot of the velocity and the absorption coefficient versus frequency for EM waves in seawater is provided in Figure 4. 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.

Practicality of EM in water for a given medium, the ratio of the electric conductivity and the dielectric permittivity, σ/ϵ, referred to as *transition frequency*, defines the border of the behavior of an EM field in that medium. If the frequency of an EM field is lower than the transition frequency, it behaves mostly like a diffusion field; if the frequency is higher than the transition frequency, the EM field is mostly like a propagating wave. For seawater, the conductivity σ is about 4 Siemens/meter, and the dielectric permittivity ϵ is $81 \times 10^{-9}/(36\pi)$. These values yield a transition frequency of about $4 \times 36\pi \times 10^9/(2 \times 81\pi) = 888$ MHz. This means that if a carrier works on the frequency of 10 MHz in seawater, which is much lower than seawater's transition frequency, then the EM field is basically no longer a wave and it rather behaves like a diffusion field. On the other end of the spectrum, if a carrier with a frequency of 1 GHz is used, the EM field will mostly behave like a wave. However, due to the high absorption of seawater (see Equation (6)), the EM wave can hardly propagate. Therefore, EM communication in seawater is literally unpractical when using classical approaches based on wave propagation.

In summary, the key limitation of using EM waves in freshwater is the big antenna size, and the critical problem of using EM waves in seawater is the high attenuation. Thus, to make the use of EM waves practical for UWSN communication, more innovative approaches must be sought.

3.3. 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 particles and 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 wavelength 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.

According to the Mie theory, when the light wavelength is similar to the particle diameter, light interacts with the particle over a cross-sectional area larger than the geometric cross section of the particle.

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The Mie theory provides scattering cross section C_{sca}, defined as the total energy scattered by a particle in all directions, as [14]

$$C_{\text{sca}} = \frac{\int_0^{2\pi} \int_0^{\pi} I_{\text{sca}} r^2 \sin\phi \, \mathrm{d}\phi \, \mathrm{d}\theta}{I_0} \tag{7}$$

where I_{sca} is the scattered light intensity, I_0 the incident light intensity, and r is the radius of the particle. The integration in (7) goes over the entire surface area of the sphere. When multi-scattering is predominant, i.e., when water has numerous suspending particles in a unit volume, the scattering cross section C_{sca} is related to the transmission of a light beam through multiple scatterers.

The attenuation due to optical scattering can be expressed as [14]

$$\frac{\mathrm{d}I}{\mathrm{d}x} = -\zeta I \tag{8}$$

where I is the light intensity and ζ is the turbidity. Turbidity is a measure of the amount of cloudiness or haziness in seawater caused by suspending particles. Turbidity provides an indication of the clarity of the seawater and is measured using the nephelometric turbidity units (NTU). Seawater has a wide range turbidity, varying from tens to several thousands of NTU [15]. Solving the above ordinary difference equation about multi-scattering light intensity leads to a solution very similar to EM absorption:

$$I_d = I_0 e^{-\zeta d} \tag{9}$$

where I_d is the intensity at distance d through the medium with multiple scatterers and I_0 is the incident light intensity. Obviously, the role of the turbidity ζ is exactly the same as the absorption coefficient α in wave absorption loss. However, the physics is completely different: absorption is the power loss due to energy conversion to heat, while scattering is the power loss due to energy diffraction to all directions.

The measure of contribution from individual scatterers to the total scattering is through turbidity. For the simplest case of all scatterers possessing the same size, a simple relation exists for turbidity [14]:

$$\zeta = N C_{\text{sca}} \tag{10}$$

where N is the number of particles in unit volume and C_{sca} is the scattering cross section of an individual particle. For more complicated case of multi-scattering, for example, if the sizes of the particles are not the same, the turbidity will have a more complicated relationship with individual scattering particles as

$$\zeta = \int C_{\text{sca}}(x) p(x) \, \mathrm{d}x \tag{11}$$

where x is the particle diameter, $C_{\text{sca}}(x)$ the scattering cross section for particles with diameter x, and $p(x)$ is the probability distribution function of particle size.

Based on the Mie scattering theory, the light intensity can be accurately estimated when using light as the carrier for UWSN communication. Apparently, the accurate knowledge of water turbidity is the first requirement to estimate the range of communication with the use of Mie theory.

In short, in addition to the common issues of absorption loss and ambient 'noise' from the environment as for other waves, water turbidity plays an important role in deciding whether optical waves can be used as communication carriers for UWSNs.

3.4. Summary

For a more intuitive comprehension, we summarize the major characteristics of acoustic, EM, and optical carriers in Table II.

Apparently, each of the three physical wave fields physically has its own advantages and disadvantages for acting as an underwater wireless communication carrier. The engineering ways taking the advantages

Table II. Comparison of acoustic EM, and optical waves in seawater environments.

	Acoustic	Electromagnetic	Optical
Nominal speed (m/s)	~ 1500	$\sim 33\,333\,333$	$\sim 33\,333\,333$
Power Loss	> 0.1 dB/m/Hz	~ 28 dB/1 km/100 MHz	$\propto$ turbidity
Bandwidth	$\sim$ kHz	$\sim$ MHz	$\sim$ 10–150 MHz
Frequency band	$\sim$ kHz	$\sim$ MHz	$\sim 10^{14}$–10^{15} Hz
Antenna size	~ 0.1 m	~ 0.5 m	~ 0.1 m
Effective range	$\sim$ km	~ 10 m	$\sim$ 10–100 m

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and overcoming the shortfalls of different carriers will be discussed in the next section.

4. 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.

4.1. 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 1 MHz 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 50 kHz) can be used only for short-range communication. For moderate range communication, frequency range from 20 to 50 kHz is often used. Low frequency waves (e.g., below 10 kHz) 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*.

Second, ACOMM is severely *interference-limited.* Besides impulsive ambient noises, the major source of interference is the self-interference induced by the time- and frequency-dispersive nature of the underwater acoustic channel. On the one hand, the slow speed of acoustic waves and significant multipath phenomena cause very large channel delay spread, which leads to severe ISI due to the waveform time-dispersion (also called *time-spreading*). On the other hand, in motion environments (such as platform motion and scattering of the moving sea surface), the slow propagation speed of sound introduces large Doppler spread or shifts, which causes severe interference among different frequency components of the signal (also referred to as *frequency-spreading*). On the outset, large Doppler spread results in a reduction in the *channel coherence time* (the time period when the channel can be viewed as static) or an apparent increase in the rate of channel fluctuation [8]. For example, consider $v = 1.5$ m/s and $f_c = 30$ kHz, where v is the rate of change of the propagation path length (e.g, the platform velocity), and f_c is the carrier frequency. The Doppler shift frequency f_d at frequency f_c is given by $f_d = v/cf_c = 30$ Hz, where c is the speed of sound in water. Further assume that a signal bandwidth of 4 kHz is used, which results a symbol duration of $T = 0.25$ ms. The normalized Doppler per symbol time is $f_d T = 0.75 \times 10^{-2}$. This implies that channel variation shall be accounted for on a symbol by symbol basis. Having large delay and Doppler spreads at the same time entails a complex interference pattern that is hard to deal with.

In short, *the objective of underwater ACOMM is to overcome the performance limitations induced by the highly dispersive channel, while at the same time improve the bandwidth efficiency as much as possible*. We next discuss various approaches that have been used in underwater ACOMM.

4.1.1. *Frequency shift keying (FSK)*

In FSK modulation, information bits are used to select the carrier frequencies of the transmitted signal. The receiver compares the measured power at different frequencies to infer what has been sent. Using only energy detector at the receiver, this scheme bypasses the need for channel estimation, and is thus robust to channel variations. However, guard bands are needed to avoid the interference caused by frequency-spreading, and guard interval is inserted between successive symbol transmissions for channel clearing to avoid the interference caused by time-spreading. As a result, the data rate of FSK is very low. Frequency hopped (FH) FSK improves the data rate as it does not need to wait the channel clearing corresponding to the previous symbol transmission on a different frequency. However, due to the bandwidth expansion via frequency hopping, the overall bandwidth efficiency remains low, typically much below 0.5 bits/sec/Hz.

Commercial modems such as those from Teledyne-Benthos [16] are based on FSK. The WHOI Micro-Modem has two operating modes, with the low-power low-rate mode based on non-coherent FSK of 80 bps over a bandwidth of 4 kHz [17].

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4.1.2. Direct sequence spread spectrum (DSSS)

In DSSS modulation, a narrow band waveform of bandwidth W is spread to a large bandwidth B before transmission. This is achieved by multiplying each symbol with a spreading code of length B/W, and transmitting the resulting sequence at a high rate as allowed by bandwidth B. Multiple arrivals at the receiver side can be separated via the de-spreading operation which suppresses the time-spreading induced interference, thanks to the nice auto-correlation properties of the spreading sequence. Channel estimation and tracking are needed if phase-coherent modulation such as phase shift keying (PSK) is used to map information bits to symbols before spreading [18]. For noncoherent DSSS, information bits can be used to select different spreading codes to be used, and the receiver compares the amplitudes of the outputs from different matched filters, with each one matched to one choice of spreading code. This avoids the need for channel estimation and tracking.

DSSS is used in commercial modems such as those from LinkQuest [19], DSPCOMM [20], and Tritech [21]. Due to the spreading operation, the data rates are often in the order of hundreds of bps while using bandwidth of several kHz, resulting in a bandwidth efficiency well below 0.5 bits/sec/Hz.

4.1.3. Single carrier phase-coherent modulation with adaptive channel equalization

One major step towards high rate communication is the direct transmission of phase-coherent modulations, including PSK and quadrature amplitude modulation (QAM) [22]. The channel introduces a great deal of ISI due to multipath propagation. Advanced signal processing at the receiver side is used to suppress the interference; this process is termed as *channel equalization*. Although widely used for slowly-varying multipath channels in radio applications, channel equalization for fast-varying underwater channel is a big challenge. The canonical receiver in Reference [22] successfully combined a second-order phase-locked-loop to track channel phase variations with an adaptive decision feedback equalizer to suppress the ISI.

Without the guard interval insertion and the spreading operation, much higher data rates can be achieved with single carrier phase-coherent modulation that those of FSK and DSSS. The WHOI Micro-Modem has a high-rate mode that provides a variable rate from 300 to 5000 bit/s with a bandwidth of 4 kHz [17]. One concern about single carrier transmission is that the receiver may be less robust as the parameters in the adaptive receiver need to be fine-tuned depending on channel conditions.

When data symbols are transmitted at a higher rate, the same physical channel leads to more channel taps in the discrete-time equivalent model. The complexity of time-domain equalization grows quickly as the number of channel taps increases, which will eventually limit the rate increase for single-carrier phase-coherent transmission. However, a frequency-domain equalization approach recently proposed in Reference [23] may effectively deal with channels with a large number of taps.

4.1.4. Multicarrier modulation

The idea of multicarrier modulation is to divide the available bandwidth into a large number of overlapping subbands, so that the waveform duration for the symbol at each subband is long compared to the multipath spread of the channel [24,25]. Consequently, ISI may be neglected in each subband, greatly simplifying the receiver complexity of channel equalization. Precisely due to this advantage, multicarrier modulation in the form of orthogonal frequency division multiplexing (OFDM) has prevailed in recent broadband wireless radio applications. However, underwater channels entail large Doppler spread which introduces significant interference among OFDM subcarriers. Lacking effective techniques to suppress the inter-carrier interference (ICI), early attempts at applying OFDM to underwater environments had a very limited success.

Recently, there have been extensive investigations on underwater OFDM communication, including [26] on non-coherent OFDM based on on-off-keying, [27] on a low-complexity adaptive OFDM receiver, and [28] on a pilot-tone based block-by-block receiver. The block-by-block receiver does not rely on channel dependence across OFDM blocks, and thus it is robust to fast channel variations across OFDM blocks [29,30]. In contrast to single carrier phase-coherent transmission, OFDM has one desirable property that one signal design can be easily scaled to fit into different transmission bandwidths with negligible changes on the receiver [31]. With bandwidth varying from 3 to 50 kHz, data rates from 1.5 to 25 kbps after rate 1/2 coding and quadrature phase shift keyed (QPSK) modulation are reported in Reference [31]. Further, with different bandwidths of 12, 25, and

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50 kHz, data rates of 12, 25, and 50 kbps after rate 1/2 coding and 16-QAM modulation are also achieved [31]. These recent studies demonstrate the feasibility and flexibility of OFDM for underwater ACOMM.

4.1.5. Multi-input multi-output techniques

A wireless system that employs multiple transmitters and multiple receivers is referred to as a multiple-input multiple-output (MIMO) system. It has been shown that the channel capacity in a scattering-rich environment increases linearly with $\min(N_t, N_r)$, where N_t and N_r are the numbers of transmitters and receivers, respectively [32,33]. Such a drastic capacity increase does not incur penalty on precious power and bandwidth resources, but rather it comes from the utilization of spatial dimension virtually creating parallel data pipes. Hence, MIMO modulation is a promising technology to offer yet another fundamental advance on high data rate underwater ACOMM [34].

MIMO has been applied in both single carrier transmission and multicarrier transmission. For single carrier transmission, existing adaptive channel equalization algorithms are leveraged to deal with MIMO channels [34,35]. The data rate increases substantially. For example, a 12 kbps rate is achieved with 3 kHz bandwidth at the range of 2 km, leading to a bandwidth efficiency of 4 bits/sec/Hz, using six transmitters and QPSK modulation [35]. Due to OFDM's unique strength in handling long dispersive channels with low equalization complexity, the combination of MIMO and OFDM is another appealing solution for high data rate transmission but with low receiver complexity. Reference [36] reports experimental results for a MIMO-OFDM system with two transmitters and four receivers, where the data rate is 12 kbps with a 12 kHz bandwidth, leading to a bandwidth efficiency of 1 bits/sec/Hz, after rate 1/2 coding and QPSK modulation, which doubles the efficiency of single antenna transmission in Reference [30] when using the same coding and modulation.

MIMO introduces additional interference among parallel data streams from different transmitters. Also, each receiver has more channels to estimate, which requires more overhead spent on training symbols. For fast varying underwater channels, the number of transmitters might not be large for best rate-and-performance tradeoff. In addition to co-located antennas, distributed MIMO is also possible if clustered single-transmitter nodes could cooperate [37]. Certainly, implementation of distributed MIMO needs to address challenging practical issues such as node synchronization and cooperation.

In summary, there has been significant progress on ACOMM over recent years, in particular in the front of multicarrier modulation and MIMO techniques. For short range communication with bandwidth in the order of several tens of kHz and bandwidth efficiency in the order several bits per second per Hz, data rates up to 100 kbps can be made available for UWSNs.

4.2. 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 80 Hz 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 1–20 MHz are able to propagate over distances up to 100 m by using dipole radiation with transmission powers in the order of 100 W [39]. This will yield high data rates beyond 1 Mbps which allows video images to be propagated at standard camera frame rates (25 Hz) [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.

In September 2006, the first commercial underwater radio-frequency (RF) modem in the world, model S1510, was released by Wireless Fibre Systems [41]. Its data rate is 100 bps and communication range is about several tens of meters. In January 2007, a broadband underwater RF modem, model S5510, came into existence. It supports 1–10 Mbps within 1 meter range [41].

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Table III. Summary of ACOMM, EMCOMM, and OCOMM for UWSN in seawater environments.

	ACOMM	EMCOMM	OCOMM
Major hurdles	Bandwidth-limited, interference-limited	Power-limited	Environment-limited
Data rate	Up to 100 kbps	Up to 10 Mbps	Up to 1 Gbps
Antenna complexity	Medium	High	Medium
Transmission range	$\sim$ 50 m–5 km	$\sim$ 1 m–100 m	$\sim$ 1 m–100 m

Due to the propagation property of EM waves, EMCOMM is an appealing choice only for very short range applications. One example is the communication between autonomous underwater vehicles (AUVs) and base stations, where the AUVs can move within the communication range of a base station to offload data and receive further instructions [38].

4.3. 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 UWSNs and 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 1 Gbps rate over a 2 m path in a water pipe with up to 36 dB of extinction [44]. The source at 532 nm wavelength was derived from a 1064 nm continuous-wave laser diode that was intensity modulated, amplified, and frequency-doubled in periodically poled lithium niobate. Measurements were made over a range of extinction by the addition of $Mg(OH)_2$ and $Al(OH)_3$ suspension to the water path, and no evidence of temporal pulse broadening was observed. Using Monte Carlo simulations over seawater paths of several tens of meters indicates that OCOMM data rates > 1 Gbps can be supported and are compatible with high-capacity data transfer applications that require no physical contact [44].

Another interesting technique is the *acousto-optical hybrid* approach. In the linear regime of optical-acoustic conversion, the laser beam incident at the air–water boundary is exponentially attenuated by the medium, creating an array of thermo-acoustic sources related to the heat energy and physical dimensions of the laser beam in water, thus producing local temperature fluctuations that give rise to volume expansion and contraction. The volume fluctuations in turn generate a propagating pressure wave with the acoustic signal characteristics of the laser modulation signal [45–47]. Therefore, a number of acoustic signals such as frequency modulated sweeps (also known as CHIRPs), binary phase shift keyed (BPSK), QPSK, frequency shift keyed (FSK), and multi-frequency shift keyed (MFSK) signals can be created for communication purposes.

4.4. Summary

We now summarize ACOMM, EMCOMM, and OCOMM in Table III. Combining Tables II and III, we can readily determine that EMCOMM and OCOMM are not suitable for UWSNs with densely deployed nodes (referring to Table I for the communication requirements of UWSNs), or at least the current techniques have not made EMCOMM and OCOMM practical for UWSNs. As for ACOMM, though it is applicable to UWSNs from the communication perspective, there are tremendous challenges in networking design, which will be discussed in the next section.

5. 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

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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.

5.1. Medium Access Control

Due to the dense deployment of sensors in UWSNs, we need to design an efficient medium access control (MAC) protocol to coordinate the communication among sensors. This is a largely unexplored challenge in the communication/networking community. On the one hand, there is no need for MAC protocols in existing small-scale acoustic networks, since in such networks, sensors are sparsely separated from each other, and point-to-point communication is sufficient. On the other hand, most existing MAC protocols in radio-based networks assume that the signal propagation delay between neighbor nodes is negligible, as is significantly different from the scenario in UWSNs, where the propagation delay of sound in water is five-magnitude higher than that of radio in air. Moreover, the bandwidth capacities of acoustic channels are very low compared with those of RF channels. While ALOHA-type of random access protocols used in satellite networks address the long delay issue to some extent, medium access control handling both long propagation delay and low bandwidth is fairly uninvestigated. Furthermore, energy efficiency of MAC protocols in satellite networks is usually not a major concern. In short, a viable MAC solution for UWSNs should take long propagation delay, low available bandwidth, energy efficiency (for long-term applications) and node mobility (for mobile UWSNs) into account.

So far, various approaches have been explored. Among the scheduling-based protocols (including time-division multiple access (TDMA), frequency division multiple access (FDMA) and code division multiple access (CDMA)), CDMA is considered a promising technique for underwater senor networks. In Reference [48], a distributed CDMA scheme is proposed. For contention-based protocols (where nodes compete for a shared channel, resulting in probabilistic coordination), the applicability of random access methods and RTS/CTS-based approaches in UWSNs has been studied in Reference [49]. Consistent with the conclusions drawn from this paper, several protocols have been proposed with different objectives. For example, in Reference [50], Park *et al*. design a random access based MAC protocol, called UWAN-MAC, for UWSNs with very low and evenly distributed traffic. On the other hand, coordination-based protocols, R-MAC [51] and T-Lohi [52] are suitable for dense UWSNs with high traffic rate.

5.2. Multi-Hop Routing

Forwarding data from source nodes to command/control stations efficiently is very challenging in UWSNs, especially in mobile UWSNs for long-term applications. In such networks, saving energy is a major concern. At the same time, routing should be able to handle node mobility. This requirement makes most existing energy-efficient routing protocols unsuitable for UWSNs. There are many routing protocols proposed for terrestrial sensor networks, such as Directed Diffusion [53], and Two-Tier Data Dissemination (TTDD) [54]. These protocols are mainly designed for stationary networks. They usually employ query flooding as a powerful method to discover data delivery paths. In mobile UWSNs, however, most sensor nodes are mobile, and the 'network topology' changes very rapidly. The frequent maintenance and recovery of forwarding paths is very expensive in highly dynamic networks, and even more expensive in dense three-dimensional UWSNs.

Geographic routing is considered promising for mobile UWSNs. In Reference [55], Xie *et al*. propose the first routing protocol, called vector-based forwarding (VBF), for mobile UWSNs. VBF is essentially a geographic routing protocol [56]. It employs a novel concept of 'routing vector', which is defined as the vector connecting the source to the sink. In VBF, the information of the routing vector is carried in each data packet. All nodes that are close to the vector are qualified to forward data packets. In order to improve the robustness of VBF in sparse networks, Nicolaou *et al*. [57] propose a hop-by-hop approach, called hop-by-hop vector-based forwarding (HH-VBF). In HH-VBF, the routing vector is no longer global. Instead, each forwarding node has a routing vector, which is represented by the vector from the current node to the target.

Another critical issue that challenges routing in UWSNs is the link outrage due to water turbulence, currents, obstacles (e.g. ships), etc., as may cause intermittent network partitioning (that is, some nodes are disconnected from the other nodes). There may be situations where no connected path exists at any given time between the source and the destination.

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Delay/Disruption Tolerant Network (DTN) technique [58] shows promise in handling network disruption. Guo *et al*. [59] have performed some initial study along this direction. In this work, an adaptive DTN routing protocol is proposed for UWSNs. The adaptation is obtained by exploiting message redundancy and resource reallocation in order to achieve different performance requirements.

5.3. Reliable Data Transfer

Reliable data transfer is important in UWSNs, especially for those aquatic exploration applications requiring reliable information. There are typically two approaches to reliable data transfer: end-to-end and hop-by-hop. The most common end-to-end solution Transmission Control Protocol (TCP). In UWSNs, due to the high and dynamic channel error rates and the long propagation delay, TCP's performance will be problematic. There are a number of techniques that can be used to render TCP's performance more efficient. However, the performance of these TCP variants in UWSNs is yet to be investigated. Another type of approach for reliable data transfer is hop-by-hop. The hop-to-hop approach is favored in wireless and error-prone networks, and is believed to be more suitable for sensor networks [60]. There are a couple of reliable data transfer protocols proposed for terrestrial sensor networks such as PSFQ [60], RMST [61], and RBC [62]. These protocols mainly take hop-by-hop approach with ARQ. Due to the long propagation delay of acoustic signals, conventional ARQ will cause very low channel utilization in underwater environments. Thus, new approaches are desired for efficient reliable data transfer in UWSNs.

One possible direction to solve the reliable data transfer problem in UWSNs is to investigate coding schemes, including erasure coding and network coding, which, though introducing additional computational and packet overhead, can avoid retransmission delay and significantly enhance the network robustness. Xie *et al*. [63] propose an approach called Segmented Data Reliable Transport (SDRT), which is essentially a hybrid approach of ARQ and FEC. It adopts efficient erasure codes, transferring encoded packets block by block and hop-by-hop. Compared with traditional reliable data transfer protocols used in underwater acoustic networks, SDRT can reduce the total number of transmitted packets significantly, improve channel utilization, and simplify protocol management. In Reference [64], a network coding scheme is proposed for UWSNs. This scheme carefully couples network coding and multi-path routing for efficient error recovery.

5.4. Localization

Localization of mobile sensor nodes is indispensable for UWSNs. Some applications such as aquatic monitoring demands *high-precision* localization, while other applications such as surveillance network require a localization solution that can *scale* to a large number of nodes. However, underwater acoustic propagation characteristics and sensor mobility pose great challenges on high-precision and scalable localization solutions in that: (i) underwater acoustic channels are highly dispersive, and time delay of arrival (TDOA) estimation is hampered by dense multipath; (ii) acoustic signal does not travel on a straight path due to the stratification effect; (iii) underwater acoustic channels have extremely low bandwidth that renders any approach based on frequent message exchange not appealing; (iv) large scale sensor deployment prevents centralized solutions; and (v) sensor mobility entails dynamic network topology change.

To effectively handle the channel effects, high-precision localization usually involves advanced signal processing algorithms. In Reference[65], a depth-based approach is proposed to compensate the stratification effect for improved underwater ranging. In the presence of dense multipath and fast channel variations, a multicarrier-signaling based solution for precise timing and Doppler estimation is considered promising [66].

In the front of scalable localization, Zhou *et al*. [67] have proposed a hierarchical approach which divides the whole localization process into two sub-processes: anchor node localization and ordinary node localization. Many existing localization techniques for small scale networks (such as GIB [68], PARADIGM [69], and silent positioning [70]) can be used in the former. For the ordinary node localization process, a distributed localization scheme which novelly integrates a three-dimensional Euclidean distance estimation method with a recursive location estimation method has been developed. In a follow-up paper [71], a scalable localization approach with mobility prediction has been investigated.

5.5. Summary

From the above discussions (though the problem list is far from complete), we can conclude that, although acoustic waves are practical for underwater acoustic sensor networks from the physics and communication

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point of view, a tremendous amount of work is demanded from the networking perspective.

6. 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 stays with 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.

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Lanbo Liu received the B.S. and M.S. degrees in Geophysics from Peking University, Beijing, China. After working as a geophysicist for 7 years in the State Seismological Bureau (now China Earthquake Administration) on earthquake studies Lanbo furthered his advanced education in U.S.A. He received M.S. degree in Civil and Environmental Engineering and Ph.D. degree in Geophysics from Stanford University, Stanford, California.

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Lanbo is a member of American Geophysical Union, Acoustic Society of America, Society of Exploration Geophysicists, Society of Seismology of America, and Society of Environmental and Engineering Geophysics. He has served as a peer-reviewer for many journals and grant agencies, and a grant review panelist for U. G. Geological Survey and Department of Defense. He is an invited speaker at numerous professional conferences and various educational, industrial, and governmental institutions.

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