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# Comparison of Different Communication Channels for Underwater Wireless Sensor Networks

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***Abstract :*** This paper compares the physical charateristics of different communication channels required for efficient exchange of information via underwater wireless sensor networks. These include physical waves like sound, radio, and light waves as the possible carriers among the nodes in an underwater sensor network. A comparision of the pros and cons for adopting different communication carriers (acoustic, radio, and optical), based on their physical characteristics and reliable utilisation is made. The review mainly focuses on densely deployed nodes placed in underwater sensor networks. Based on the comparison study, the most efficient communication carrier for underwater sensor networks is recommended.

***Keywords*:** Wireless communication, Underwater Sensor Networks (UWSNs), Unmanned or Autonomous Underwater Vehicles (UUVs, AUVs), acoustic waves, electromagnetic waves, optical waves.

## I. INTRODUCTION

Around 70% of the earth is covered by water. Efficient and reliable underwater communication remains the major research isuue in this age of communication. Networks of sensor nodes are deployed on the ocean floor to enable applications for oceanographic data collection, ocean environment monitoring, offshore exploration and surveillance applications Collaboratively functioning Unmanned or Autonomous Underwater Vehicles (UUVs, AUVs), equipped with underwater sensors are being used in exploration of natural undersea resources and gathering of scientific data[1]–[4].. All these applications have to be made viable in the most efficient manner. So, there is a need to enable underwater communications among underwater devices.

By using a distributed sensor network that is easily scalable in a 3-dimensional underwater space, each underwater sensor can be made to monitor events and detect environmental parameters locally. Compared to remote sensing, UWSNs provide a better sensing and surveillance technology to acquire much accurate data to understand the underwater environments. Present underwater communication systems involve the transmission of information in the form of sound, electromagnetic (EM), or optical waves. Each of these techniques has advantages and limitations.

Comparitively, *Acoustic communication* 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. But, in shallow water the use of acoustic waves can be adversely affected by temperature gradients, surface ambient noise, and multipath propagation due to reflection and refraction. Another limiting factor for efficient communication and networking is the speed of acoustic propagation in water, about 1500 m/s (meters per second), is much slower compared with that of electromagnetic and optical waves. Nevertheless, currently underwater communication is via acoustic waves.

The second type of carrier is *electromagnetic (EM) waves* in radio frequencies. Due to the conducting nature of the seawater, which is our medium, conventional radio does not work well in an underwater environment. Comparing the propagating speeds of acoustic and EM waves underwater, the latter is much faster and so is definitely a great advantage for faster and efficient communication among nodes.and vice-versa.

Use of *optical waves*, as wireless communication carriers underwater are generally limited to very short distances due to severe water absorption in optical frequency band and strong backscatter from suspending particles.the Even the clearest water has 1000 times the attenuation of clear air. Nevertheless, *optical waves*, especially in the blue-green wavelengths, underwater offer a practical choice for high-bandwidth communication (10-150 Mbps, bits per second) over moderate ranges (10-100 meters). This communication range is much needed for some applications like harbor inspection, linking submarines to land, etc...

This paper is organised as follows. First the communication needs and requirements for UWSNs is presented in next section. This is follwed by a brief discussion on the physical nature of acoustic, radio and optical waves and their relevance to wireless communication as carriers. Finally, the networking challenges for underwater acoustic sensor networks, followed by a short summarisation of the applicability of three types of waves in underwater sensor networks.

## II. COMMUNICATION REQUIREMENTS FOR UNDERWATER SENSOR NETWORKS

The underwater sensor networks (UWSNs) considered in this paper are underwater networks with densely deployed sensor nodes. High node density is the key characteristic of such networks. We roughly classify these dense sensor networks into two categories: 1) UWSNs for long-term underwater monitoring applications that are non-time critical (such as oceanographic data collection, pollution monitoring/detection, and off-shore oil/gas field monitoring); 2) UWSNs for short-term time-critical underwater exploration applications (such as submarine detection, hurricane disaster recovery) [2]. The former category of UWSNs can be either mobile(buoyancy-controlled) or static(fixed at sea floor) depending on the deployment of sensor nodes while the latter category are usually mobile since it is natural that the cost of deploying/recovering fixed sensor nodes is typically forbidden for short-term time-critical applications. Our main focus involves three types of UWSNs:

a. Mobile UWSNs for long-term non-time critical applications (*MLT-UWSNs* for short);
b. Static UWSNs for long-term non-time critical applications (*SLT-UWSNs* for short);
c. Mobile UWSNs for short-term time-critical applications (*MST-UWSNs* for short). Table I. summarizes the communication requirements for these three types of UWSNs.

Table I: Communication Requirements Of UWSNS

| **Requirements** | **MLT-UWSNs** | **SLT-UWSNs** | **MST-UWSNs** |
|---|---|---|---|
| **Data Rate** | Various | Various | Various |
| **Transmission Range** | Short (10m-1km) | Short (10m-1km) | Short (10m-1km) |
| **Deployment Depth** | Shallow Water | Shallow Or Deep | Shallow Water |
| **Energy Efficiency** | Major Concern | Major Concern | Major Concern |
| **Antenna Size** | Small | Small | Small |

## III. BASICS OF PHYSICAL WAVES AS UNDERWATER COMMUNICATION CARRIERS

In this section a layout of the fundamental physical properties and critical issues for each of the Acoustic, EM, and Optical wave propagations in underwater environments is presented. Each physical carrier's advantages and disadvantages towards efficient underwater wireless communication is discussed.

### *A. Acoustic Waves:*

Due to the relatively low absorption in underwater environments, acoustic waves are used as the primary carrier for underwater wireless communication among the three types of waves. The following section presents physical fundamentals and the implications of using acoustic waves as the wireless communication carrier in underwater environments.

***a. Physical Properties:*** Acoustic waves have a number of propagation characteristics that are unique from other waves, couple of which are highlighted below.

***b. Propagation Velocity:*** The extremely slow propagation speed of sound through water is an important factor that distinguishes it from electromagnetic propagation. The speed of sound in water depends on the water 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 4 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. Temperature plays a mojor role amogst the three on the surface of ocean . 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. But with increasing depth, the pressure of water has the largest effect on the speed of sound. To summarize, sound will travel faster in warmer water and slower in colder water. Approximately, the sound speed increases 4.0 m/s for water temperature rising by 1◦C . When salinity increases by 1 practical salinity unit (PSU), the sound speed in water increases 1.4 m/s. As the depth of water (also the pressure) increases 1 km, the sound speed increases roughly by 17 m/s.

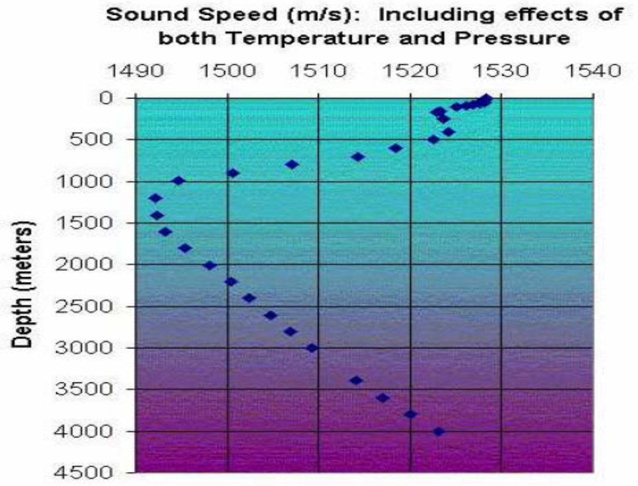


Figure. 1. A vertical profile of sound speed in seawater as the lump-sum function of depth

The slow propagation speed of sound impacts communication system performance and network protocol design.

***c. Absorption:*** Wave energy may be converted to other forms and absorbed by the medium during propagation . The absorptive energy loss is directly controlled the type of physical wave propagating through it and the material imperfections in the wave. For acoustic waves the material imperfection is inelasticity and wave energy is converted into the heat (while for EM waves the imperfection is the electric conductivity. 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 $f$. Fig. 2 shows the relative contribution from the different sources of absorption as a function of frequency[5].

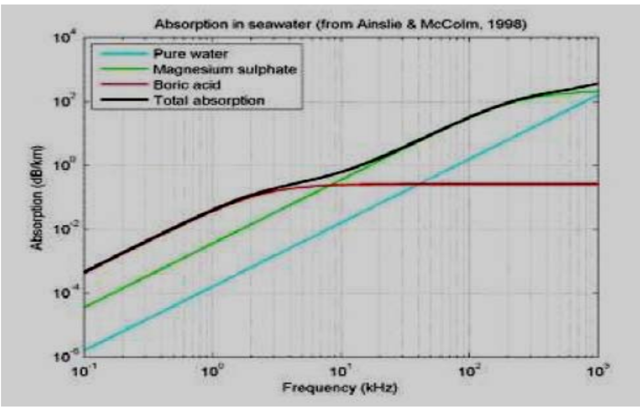


Figure. 2. Absorption in generic seawater

***B. Multipath:***

An acoustic wave can reach a certain destination node through multiple paths. Especially in 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. The wave refractions, too can cause significant multipath phenomena. Assuming that there are *P* distinct paths between the source and the receiver, $T_p$ denote the propagation delay for the *p*th path and *D* denote the *channel delay spread*, defined as the time difference between the first and the last arrivals of multipath propagation, i.e.,

$$D = T_{p-1} - T_0. \qquad (1)$$

Due to the slow speed, the channel delay spread rom multipath propagation is large. Typical underwater channels have delay spread around 10 ms, but occasionally delay spread can be as large as 50 to 100 ms [5]. Large channel delay spread may causes time dispersion of a signal, which leads to severe *inter-symbol interference*. This inturn may complicate the modulation and demodulation process

***C. Path Loss:***

For any propagation wave, there are three primary mechanisms for energy loss: (i) geometric spreading, (ii) absorptive loss, and (iii) scattering loss. The absorptive loss for acoustic waves has been discussed in Section 3.1.1. *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, for a cylindrical wave 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 $d^{\beta}$, where $\beta$ is between 1 (for cylindrical spreading) and 2 (for spherical spreading) [6]. 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 predominant. Surface scattering introduces not only power loss, but also spreading in delay of each surface bounce path and thus contributes to multipath phenomena as discussed already.

Assume that there are *P* paths, and let $\xi_p$ denote the scattering loss, $d_p$ the propagation distance and $T_p$ the propagation delay of the *p*th path. Then the pass loss along the *p*th 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. 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. Therefore, acoustic waves are considered practical for efficient communication in underwater sensor networks, where sensors are usually densely deployed.

***D. Effect Of Ambient Noise:***

Ambient noise is defined as “the noise associated with the background emanating from a number of unidentified sources. Its distinguishing features are that it is due to multiple individual sources and no one source dominates the received field”. 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[7]. The level of underwater ambient noise will 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. 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

Combining path loss and ambient noise, we may see the following effects on communication and networking:

For short-range acoustic communication, the level of ambient noise may be well below the desired signal. For long range acoustic communication, 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 of this kind of noises may cause highly dynamic link error rate or even link outage, which brings great challenges for networking design.

***E. Electromagnetic Waves:***

There are several advantages in using EM waves in radio frequency band 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. The fundamental physical behavior of EM field in underwater environments is discusses here. Then the practicality of using EM for

UWSNs is analyzed. Due to the different behaviour (propagation) of EM field in freshwater and seawater, a description of EM in these two types of media is presented.

*EM in Freshwater:* Freshwater is a *low- loss medium*. The propagation speed *c* can be expressed as [8]

$$c \approx \frac{1}{\sqrt{\epsilon\mu}}, \qquad (2)$$

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, $\varepsilon_0$ and the dimensionless relative permittivity, $\varepsilon_r$ (also known as the dielectric constant). As $\varepsilon_r$ 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 4 orders of magnitude, and it poses no problem in channel latency.

The absorption coefficient $\alpha$ for EM propagation in freshwater can be approximated as [7]

$$\alpha \approx \frac{\sigma}{2}\sqrt{\frac{\mu}{\epsilon}}, \qquad (3)$$

where $\sigma$ is the electric conductivity. Here the absorptive loss is essentially *frequency-independent*, and EM waves can literally propagate through freshwater body. As such, using EM waves as the communication carrier in freshwater environments appears very attractive. However, the limitation in using EM waves for communication in freshwater underwater sensor networks is the antenna size. The big antenna size of an EM transmitter (e.g., a couple of meters for a 50 MHz antenna) is practically impossible for the dense deployment of underwater sensor networks.

***a.*** ***EM in Seawater:*** Seawater is a *high-loss medium*. The electric conductivity $\sigma$ of seawater is higher than that of freshwater by about two orders. The higher conductivity in seawater is mainly due to the cumulative increase of total dissolved solid (TDS) concentration in oceans, greatly saline; 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 [7]

$$c \approx \sqrt{\frac{4\pi f}{\mu\sigma}}, \qquad (4)$$

while the absorption loss can be approximated as

$$\alpha \approx \sqrt{\pi f \mu\sigma}. \qquad (5)$$

A plot of the velocity and the absorption coefficient versus frequency for EM waves in seawater is provided in Fig. 3.

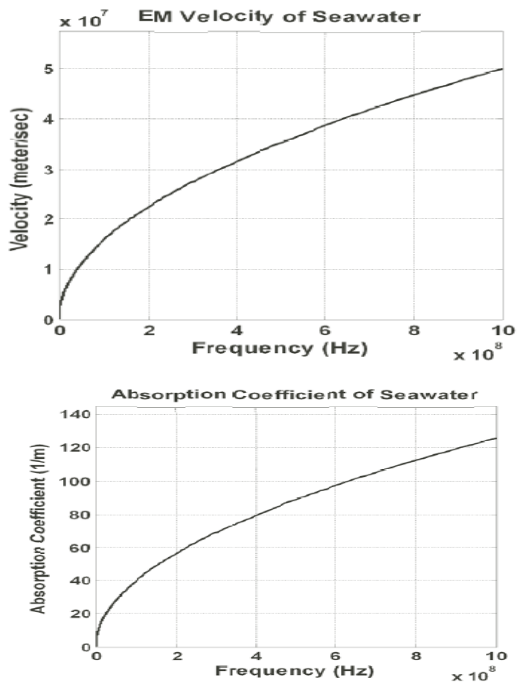


Figure. 3. Velocity and absorption versus frequency for EM waves in seawater.

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 for 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 electromagnetic (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.

Considering a carrier of frequency 10 MHz in seawater, which is much lower than seawater's transition frequency, then the EM field basically is not a wave anymore and it rather behaves like a diffusion field. On the other end of the spectrum, if a carrier with 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 5), 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 underwater sensor network communication, more innovative approaches must be sought.

### *F.* *Optical Waves:*

Using optical waves for communication has a big advantage in data rate, that can potentially exceed 1 Giga bps. However, there are a couple of limiting factors for utilisation of optical communication in water. Firstly, optical signals are rapidly absorbed in water. Secondly, optical scattering caused by suspending particles and sea planktons is significant. Thirdly, high level of ambient light in the upper part of the water column is another adverse effect for using optical communication.

Our discussion is limited to the situation of using only monochromatic light in deep water (where ambient light is not a major issue and usually neglected). Then optical scattering plays a vital significance 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 [9]. 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 equivalent to the particle diameter, light interacts with the particle over a cross-sectional area larger than the geometric cross section of the particle. The Mie theory provides scattering cross section $C_{sca}$ , defined as the total energy scattered by a particle in all directions, as [10]

$$C_{\text{sca}} = \frac{\int_0^{2\pi} \int_0^{\pi} I_{\text{sca}} r^2 \sin\phi \, d\phi \, d\theta}{I_0} \quad (6)$$

where $I_{sca}$ is the scattered light intensity, $I_0$ is the incident light intensity, and $r$ is the radius of the particle. The integration in (6) 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

$$dI/dx = -\zeta I \quad (7)$$

where $I$ is the light intensity, and $\zeta$ is the turbidity. Turbidity is a measure of the amount of cloudiness or haziness in seawater caused by suspending particles. The role of the turbidity $\zeta$ is exactly the same as the absorption coefficient 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, turbidity [10]:

$$\zeta = NC_{\text{sca}} \quad (8)$$

where $N$ is the number of particles in unit volume, and $C$sca is the scattering cross section of an individual particle. 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 underwater sensor networks.

### *G. Summary:*

For a more intuitive comprehension, a summarization of the major characteristics of acoustic, electromagnetic and optical carriers are tabulated in Table II.

Table II: Comparison Of Acoustic,Em And Optical Waves In Sea Water

| | **Acoustic** | **Electromagnetic** | **Optical** |
|---|---|---|---|
| Nominal speed | 1500 m/s | 33,333,333 m/s | 33,333,333 m/s |
| Power Loss | >0:1 dB/m/Hz | 28 dB/1km/100MHz | turbidity |
| Bandwidth | kHz | MHz | 10-150 MHz |
| Frequency band | kHz | MHz | 1014–1015 Hz |
| Antenna size | 0.1 m | 0.5 m | 0.1 m |
| Effective range | km | 10m | 10-100m |

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

## IV. NETWORKING CHALLENGES FOR UNDERWATER ACOUSTIC SENSOR NETWORKS

In this section, focus is put 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 that is being used in terrestrial radio networks could not be applied to underwater acoustic networks. A brief discussion on the network challenges for designing highly efficient and reliable underwater sensor networks (UWSNs) is presented here.

### *A. Medium access control:*

Due to the dense deployment of sensors in UWSNs, an efficient medium access control (MAC) protocol to coordinate the communication among sensors is to be deisigned. This is a largely unexplored challenge in the communication/networking community. On the one hand, there is no need for MAC protocols in existing smallscale 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 ALOHAtype 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.

### *B. Multi-hop Routing:*

Forwarding data from source nodes to 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 energyefficient routing protocols unsuitable for UWSNs. There are many routing protocols proposed for terrestrial sensor networks that 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 3-dimensional UWSNs. Geographic routing is considered promising for mobile UWSNs[11]. Another critical issue 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.

### *C. Reliable Data Transfer:*

Reliable data transfer is important in UWSNs, especially for those aquatic exploration applications requiring reliable information. There are two approaches that are typically used for reliable data transfer: end-to-end and hop-by-hop. The most common end-to-end solution TCP (Transmission Control Protocol). 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. One possible direction to solve the reliable data transfer problem in UWSNs is to investigate coding schemes like network coding, which, though introducing additional computational and packet overhead, can avoid retransmission delay and significantly enhance the network robustness.

### *D. Localization:*

Localization of mobile sensor nodes is ndispensable for UWSNs. Some applications such as aquatic monitoring demands *high-precision* localization, while other applications such as surveillance network requires a high-precision and scalable localization solutions due to the reasons 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- recision localization usually involves advanced signal processing algorithms.

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

## VI. CONCLUSION

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

a. 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.
b. For electromagnetic 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.
c. Optical carriers will remain as to be used for some special applications. The major hurdle is that optical communication 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 underwater sensor network. Acoustic wave remains the most robust and feasible carrier up to the date.

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