CHALLENGES BEING FACED BY UNDERWATER WIRELESS SENSOR NETWORKS AND ITS COUNTERMEASURES

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ABSTRACT

The aim of this paper is to highlight the prospects and problems of optical wireless communication for applications in the field of Underwater Wireless Sensor Networks (UWSNs).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. Here the physical waves under discussion are sound, radio, and light. We first present the requirements; then we discuss and compare the pros and cons for adopting different communication carriers (acoustic, radio, and optical). The problem of wireless underwater communication is a challenging field of investigation since radio wireless links used in terrestrial devices, cannot be used underwater. Also current underwater available technologies, which are mainly based on acoustical solutions, are still not suitable due to low propagation speed of sound in water and low data-rate. After making comparisons, we will make recommendations for the selection of communication carrier for underwater sensor networks with engineering counter measures that can possibly enhance the communication efficiency in specified underwater environments.

I. INTRODUCTION

In last several years, underwater sensor network (UWSN) has found an increasing use in a wide range of applications, such as environmental research, coastal surveillance systems etc. By deploying a distributed and scalable sensor network in a 3-dimensional underwater space, each underwater sensor can detect and monitor environmental parameters and events locally. Hence, in contrast to remote sensing, underwater sensor networks 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, optical or electromagnetic (EM) waves. However, each of these techniques has some advantages as well as limitations.

Here, we explore the physical fundamentals and engineering implementations for efficient communication, via acoustic, EM and optical waves among nodes in a UWSN. Beginning with the communication needs and requirements for UWSNs, we extend our discussion to the physical problems. After that, we compare the engineering counter measures for the shortcomings of each individual carrier. At the end, we will be discussing the networking challenges for underwater acoustic sensor networks, followed by a short summary of the recent progress in this field.

II WHAT ARE THE REQUIREMENTS FOR UNDERWATER SENSOR NETWORKS?

Here we are talking about the underwater networks with densely deployed sensor nodes. The key characteristic of such networks is high density nodes. Depending on the applications, we can classify the targeted dense sensor networks into two categories: 1) UWSNs for long-term non-time critical aquatic monitoring applications (such as pollution monitoring/detection, off-shore oil/gas field monitoring, and oceanographic data collection); 2) UWSNs for short-term time-critical aquatic exploration applications (such as submarine detection, loss treasure discovery, and hurricane disaster recovery). The first category can be either mobile or static depending on the deployment of sensor nodes (buoyancy-controlled or fixed at sea floor), while the second one 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. We summarize the communication requirements in Table I.

TABLE I REQUIREMENTS OF UWSNS

Requirements	M-LT-UWSNs	S-LT-UWSNs	M-ST-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	Minor Concern
Antenna Size	Small	Small	Small
Real-time Delivery	Minor Concern	Minor Concern	Major Concern

III PHYSICAL CHALLENGES

Unlike terrestrial application, the UWC is not a straight forward process. Researchers always consider power consumption, bit error, SNR ratio, symbol interference, error coding, modulation strategies, channel model (underwater), attenuation, transmission distance, instrumentation and underwater interferences for UWC. Interferences are mainly caused by three major factors:

3.1 Characteristics of signal carrier

There are 3 types of carrier wave that are used in underwater communication.

3. 1.1 Electromagnetic wave

Using electromagnetic wave, the communication can be established at higher bandwidth and frequency. However, limitation is due to high absorption/attenuation that significantly affects the transmitted signal. Big antennas are also needed for this type of communication, thus affecting the design, complexity and cost.

3. 1.2 Optical wave

Optical wave offers high data rate transmission. But the signal is rapidly absorbed in water and suffers from scattering effect. This will affect the data transmission accuracy.

3. 1.3 Acoustic wave

Acoustic is the most preferred signal used as carrier in many applications, due to its low absorption characteristic in underwater communication. Although the data transmission is slower as compared to other carrier signal, but the low absorption characteristic enables the carrier to travel at longer range as less absorption faced by the carrier.

3.2 Environment/Propagation Medium

In UWC, water itself is the main source for the signal interference. The type of water (sea water/ freshwater), water composition, depth pressure, dissolved impurities and temperature affect the sound propagation. Common terrestrial phenomena like reflection, scattering, refraction also occurs in underwater communication.

3.3 Instrumentation System Devices

Factors such as transducer parameters (transduction mechanism, directivity, resolution sensitivity, power consumption, noise immunity, and properly matched impedance must be taken into account during the design process. One of the important areas is the receiver (sensor) design.

Table II Comparison of Acoustic, Em and Optical Waves

	Acoustic	Electromagnetic	Optical
Nominal speed(m/s)	~ 1,500	~ 33,333,333	~ 33,333,333
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	~ 10 m	~ 10-100 m

IV ENGINEERING COUNTERMEASURES

Following are the counter measures that have been developed to address the physical challenges for each wave used as the communication carrier in underwater sensor networks. 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 at a greater distance, which is the main reason why acoustic waves are widely used in underwater communication. The main disadvantages and challenges of ACOMM are summarized as follows. First, acoustic communication is fundamentally bandwidth-limited. The bandwidth for ACOMM is typically in the order of kHz - tens of kHz, which is 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, acoustic communication is severely interference-limited. On the one hand, the slow speed of acoustic waves and significant multipath phenomena cause very large channel delay spread, which leads to inter-symbol interference due to the time-spreading (waveform time-dispersion). On the other hand, in motion environments (such as platform motion of the moving sea surface and scattering), the slow propagation speed of sound introduces large Doppler spread or shifts, which causes severe interference among different frequency components of the signal (frequency spreading). On the outset, large Doppler spread results in a reduction in the channel coherence time or an apparent increase in the rate of channel fluctuation. Thus, the objective of underwater acoustic communication is to overcome the performance limitations induced by the highly dispersive channel. It also emphasises on the improvement of the bandwidth efficiency as much as possible. Now we discuss various approaches that have been used in underwater acoustic communication.

4.2 Frequency Shift Keying (FSK)

In FSK modulation, information bits are used to select the carrier frequencies of the transmitted signal. At the receiver end, comparison is made to measure power at different frequencies to infer what has been sent. Using only energy detector at the receiver end, this scheme bypasses the need for channel estimation, and is thus robust to channel variations. But the 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. Therefore, 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. But, due to the bandwidth expansion via frequency hopping, the overall bandwidth efficiency remains low (below 0.5 bits/sec/Hz).

4.3 Direct Sequence Spread Spectrum (DSSS)

In DSSS modulation, a narrow band waveform of bandwidth W is spread to a large bandwidth B before transmission. It can be done by multiplying each symbol with a spreading code (with length $B=W$), and transmitting the resulting sequence at a high rate which is 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. For noncoherent DSSS, information bits are used to select different spreading codes, and the receiver compares the amplitudes of the outputs from different matched filters, with each one matched to one choice of spreading code, which avoids need for channel estimation and tracking. Due to this spreading operation, data rates are often in the order of hundreds of bps while using bandwidth of several kHz, resulting in bandwidth efficiency well below 0:5 bits/sec/Hz.

4.4 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 phase shift keying (PSK) and quadrature amplitude modulation (QAM) . The channel introduces a great deal of inter-symbol interference (ISI) due to multipath propagation. To suppress the interference, advanced signal processing at the receiver side is used; this process is termed as *channel equalization*. 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.

At higher rate of data symbol transmission, the same physical channel leads to more channel taps in the discrete-time equivalent model. Time-domain equalization becomes more complex as the number of channel taps increases. It will eventually limit the rate increase for single-carrier phase-coherent transmission.

4.5 Multicarrier modulation

The idea of multicarrier modulation is to divide the available bandwidth into a large number of overlapping sub bands, such that the waveform duration for the symbol at each sub band is long compared to the multipath spread of the channel. Consequently, inter-symbol interference may be neglected in each sub band, greatly simplifying the receiver complexity of channel equalization. However, underwater channels entail large Doppler spread which introduces significant interference.

4.6 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. Also the channel capacity in a scattering-rich environment increases linearly with min (Nt,Nr), where Nt and Nr are numbers of transmitters and receivers, respectively. Such a drastic capacity increase does not incur penalty on precious bandwidth and power 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 acoustic communication. MIMO has been applied in both single carrier transmission and multicarrier transmission. In short we can say that there has been significant progress on ACOMM over recent years, in particular in the front of multicarrier modulation and MIMO techniques.

4.7 Electromagnetic Communication (EMCOMM)

The main problem in using radio underwater is the severe attenuation due to the conducting nature of seawater. Thus, EMCOMM works in the *power-limited* region. It was impossible to use high frequency wave for communication purposes. However, theoretical analysis and experiments show that radio waves within a frequency range 1 to 20MHz is able to propagate over distances up to 100 m by using dipole radiation with transmission powers in the order of 100 W .To avoid direct contact with seawater, the transmitting and receiving aerials are surrounded by waterproof electrically insulating materials. This way, an EM signal can be launched from the transmitter into a body of seawater and picked up by a distant receiver. EMCOMM is an appealing choice only for very short range applications, due to its propagation property. An example is the communication between autonomous underwater vehicles (AUVs) and base stations. In this, the AUVs can move within the communication range of a base station to offload data and receive further instructions.

4.8 Optical Communication (OCOMM) and Acousto-Optical Hybrid

We know that water quality plays a key role in deciding whether optical waves can be used for underwater communication. Therefore, the applicability of OCOMM heavily depends on environments. Thus, OCOMM works in the *environment-limited* region. Using Monte Carlo simulations over seawater paths of several tens of meters indicates that optical communication data rates > 1 Gbps can be supported and are compatible with high-capacity data transfer applications that require no physical contact.

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

TABLE III SUMMARY OF ACOMM, EMCOMM, AND OCOMM

	ACOMM	EMCOMM	OCOMM
Major hurdles	bandwidth-limited, interference-limited	power-limited	Environment-limited
Data rate	Upto 100kbps	Upto 10 mbps	Upto 1gbps
Antenna complexity	Medium	High	Medium
Transmission range	~50m-5km	~1m-100m	~1m-100m

V. NETWORKING CHALLENGES FACED BY 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), terrestrial radio network technologies could not be applied to underwater acoustic networks. Following are several typical networking problems in the design of Underwater sensor networks (UWSNs)

5.1 Medium Access Control

Although, there is no need for MAC protocols in existing small-scale acoustic networks, because in such networks, sensors are sparsely separated from each other, and point-to-point communication is sufficient. But, most existing MAC protocols in radio-based networks assume that the signal propagation delay between neighbor nodes is negligible, which is 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. In short, a viable MAC solution for UWSNs should take low available bandwidth, long propagation delay, energy efficiency (for long-term applications) and node mobility (for mobile UWSNs) into account. Among the scheduled 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.

5.2 Routing

The process of forwarding data from source nodes to command/control stations efficiently is very challenging in UWSNs, especially in mobile UWSNs for long-term applications. In this, saving energy is a major concern. At the same time, routing should be able to handle node mobility. This makes most existing energy efficient routing protocols unsuitable for UWSNs. In mobile UWSNs, most sensor nodes are mobile and the “network topology” changes very rapidly. Geographic routing is considered promising for mobile UWSNs. The first routing protocol, called Vector-Based Forwarding (VBF), is a geographic routing protocol .It employs a novel concept of “routing vector”. It 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. Nodes that are close to the vector are qualified to forward data packets. To improve the robustness of VBF in sparse networks, a hop-by-hop approach, called Hop-by-Hop Vector-Based Forwarding (HH-VBF) is used. In HH-VBF, the routing vector is not global. Instead, each forwarding node has a routing vector, which is represented bythe vector from the current node to the target. Another critical issue challenges routing in UWSNs is the link outrage due to currents, water turbulence, obstacles (e.g. ships), etc., DTN (Delay/Disruption Tolerant Network) technique shows promise in handling network disruption. In DTN the adaptation is obtained by exploiting message redundancy and resource reallocation in order to achieve different performance requirements.

5.3 Reliable Data Transfer

There are essentially two approaches to 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. Another type of approach for reliable data transfer is hop-by-hop. This approach is favoured in error-prone and wireless networks. It is believed to be more suitable for sensor networks. Another way to solve the reliable data transfer problem in UWSNs is to investigate coding schemes, including network coding erasure coding, which, though introducing additional computational and packet overhead, can avoid retransmission delay and significantly enhance the network robustness. An approach called Segmented Data Reliable Transport (SDRT) adopts efficient erasure codes, thus, transferring encoded packets block by block and hop by hop. SDRT can improve channel utilization, can reduce the total number of transmitted packets significantly, and simplify protocol management.

5.4 Localization

Localization of mobile sensor elements is crucial for UWSNs. On the one hand, aquatic monitoring demands *high-precision* localization, while on the other hand, applications such as surveillance network require a localization solution that can *scale* to a large number of nodes. But , underwater acoustic propagation characteristics and sensor mobility pose great challenges on high-precision and scalable localization solutions: i) underwater acoustic (UWA) 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) UWA channels have extremely low bandwidth that renders any approach based on frequent message passing 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, it usually involves advanced signal processing algorithms. In the presence of fast channel variations and dense multipath, a multicarrier-signalling based solution for precise timing and Doppler estimation is considered promising.

VI. RECENT PROGRESS

Although there are various applications of the complete system for underwater communication, research in this field is still going on due to its diversity. Research in this field can be said as an ongoing research as technology advancement in instrumentation element such as signal processing unit, sensor, communication modem and transceiver, has always changed rapidly. Today researchers are competing in developing a better system with better performance. Power consumption becomes one of the main concerns when developing a system. As a result, system with low power consumption is admirable and leads to a cost and energy efficient system. Many important parameters should be considered in order to minimize the power consumption. Right selection of carrier frequency is one of the approaches that can be utilized to optimize the power consumption.

VII MEMS APPROACH

Today, electronic devices are designed to be small. Small devices generally offer several advantages over the conventional methods. In electronic industries, the manufacturers are competing to produce a device with better performance and in smaller size. This has alleviated the IC and MEMS technology to grow faster in electronic industries. Till today, most of the application that utilizes this approach mainly focuses in imaging industries owing to the fact that this type of sensor can offer a high bandwidth and sensitivity.However, the realisation of MEMS in underwater communication especially in sensor design could be a worth effort to bridge the gap between the terrestrial and underwater communication system.

Reduction in size has offered a lot of advantages in terms of its portability, power consumption, cost, and production. Although the exploration of this approach in underwater communication is still new, the potential of this new approach to be implemented is technically possible. The main advantage is its ability to overcome the problem caused by the size and power consumption. For example, in Autonomous Underwater Vehicles (AUV), the utilisation of MEMS device with smaller battery will reduce the overall weight of the AUV, thus reducing the power needed to drive the vehicles. Researchers are mainly concentrating on other aspect such as communication protocol, overall system development, conventional transducers, and signal processing. Therefore MEMS based sensor for underwater communication provide a new platform for researchers to explore more of what this technology can offer and it can be thought of as a new research area that require an extensive studies and could contribute to many novel outcome.

Till date, most of the application that utilizes this approach mainly focuses in imaging industries owing to the fact that this type of sensor can offer a high bandwidth and sensitivity. Besides imaging, MEMS based sensor is also thought be worthwhile if it can also be implemented for communication purposes, specifically for underwater.

VIII CONCLUSION

Based on the above discussions, we have the following summary points:-

1) 1)Up to date and extending to the near future, waves that will be staying as the major carrier of wireless communication in UWSNs are acoustic waves. For acoustic wave carriers, the key challenges are in communication and networking.

2) For electromagnetic radio wave carriers, shortcomings stay with the high absorption of EM waves in water, especially in seawater. Although short-range wireless communication using EM waves in seawater has seen certain breakthroughs, it will take a long way to expand the approach to be used in UWSNs.

3) Optical carriers will remain as to be used for some special applications. The major problem is that optical Communication in water is largely limited by environments.

In short, this paper 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 UWSNs. Acoustic wave remains the most robust and feasible carrier up to the date.

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