Physical Layer Design Consideration for Underwater Acoustic Sensor Networks

Wang Chen and Fang Yanjun
Department of Automation
Wuhan University
Wuhan, China
e-mail: wangchen1206@126.com

***Abstract*—Unlike that of terrestrial sensor networks, the physical layer design of Underwater Acoustic Sensor Networks (UW-ASNs) faces far more challenges because of the limited band-width, extended multipath, refractive properties of the medium, severe fading and large Doppler shifts. This paper takes a tutorial overview of the physical properties of acoustic propagation, modulation schemes and power efficiency that are relevant to the physical layer design for UW-ASNs, and analyses the design consideration on each aspect. In the end, it presents several open research issues, aiming to encourage research efforts to lay down fundamental basis for the development of new advanced underwater networking techniques in the near future.**

Keywords- underwater sensor networks; physical layer; propagation effects; modulation schemes; power efficiency

I. INTRODUCTION

Underwater communication applications mostly involve oceanographic data collection, pollution monitoring, offshore exploration, disaster prevention, and tactical surveillance applications. The traditional approach for these applications is to deploy oceanographic sensors, record the data, and recover the instruments [1]. This approach has such draw-backs as long lags in receiving the recorded information and the instability when some nods confront with accidental damage. So one ideal solution for these applications is to enable underwater communications among underwater devices, i.e. to develop underwater acoustic sensor networks (UW-ASNs).

The design of an information network is commonly carried out in the form of a layered architecture [2]. The first layer of this hierarchical structure is the physical layer, which is in charge of converting the logical information (bits 0 and 1) into signals that are transmitted over the communi-cation channel. At the receiving end, it is in charge of detecting the signal corrupted by noise and other channel distortions and converting it back into logical bits. It provides framing, modulation and error correction capability. It also provides additional functionality such as parameter settings, parameter recommendation and carrier sensing [3].

Unlike that of terrestrial sensor networks, the physical layer design of UW-ASNs faces far more challenges because of the limited band-width, extended multipath, refractive properties of the medium, severe fading, rapid time-variation and large Doppler shifts [4]-[5]. A series of review papers provide excellent analyses of the architecture and protocols of UW-ASNs and discuss how to solve these problems until the end of the last decade [6]-[9], but so far there are still no more agreements on the implementation of the physical layer.

Under this circumstance, this paper tries to take a tutorial overview of the physical properties of acoustic propagation and communication techniques that are relevant to the physical layer design for UW-ASNs. Normally, frequency generation and signal detection are crucial factors that impact physical layer much; as they have more to do with the underlying hardware and transceiver design [10], and hence are beyond the scope of this paper. So in this paper, we focus on underwater acoustic physics, modulation schemes and power efficiency for UW-ASNs, aiming to encourage research efforts to lay down fundamental basis for the development of new advanced underwater networking techniques in the near future.

The remainder of this paper is organized as follows. Section II describes underwater acoustic physics including acoustic propagation velocity, multipath, ambient noise and Doppler effects. Section III analyses different modulation schemes and discusses how they affect the physical layer design. Power efficiency, as a crucial factor that has to be considered, is evaluated in section IV, and some concluding remarks along with open research issues are proposed in section V.

II. UNDERWATER ACOUSTIC PHYSICS

The underwater acoustic channel is often referred to be highly temporally and spatially variable due to the nature of underwater acoustic physics. Hereafter we analyze the key factors that pose real challenges for the physical layer design for UW-ASNs.

A. Physical properties

Among a number of physical properties of underwater acoustic waves, the two highlighted below deserve more concern.

1) Propagation velocity: A typical speed of acoustic waves near the ocean surface is about 1500m/s, more than four times faster than the speed of sound in air but five orders of magnitude smaller than the speed of electro-magnetic in air. And the speed of sound v in water can be calculated according to the empirical formula as

978-1-4244-5540-9/10/$26.00 ©2010 IEEE

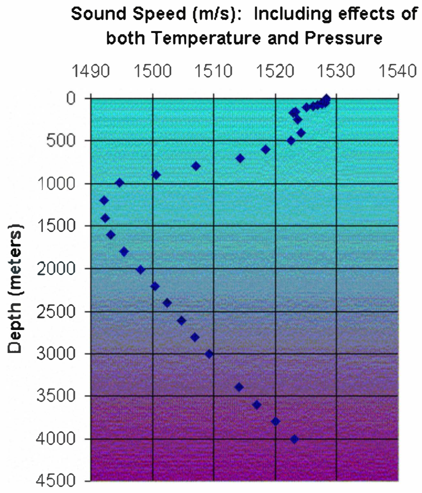

Figure 1. A vertical profile of sound speed in seawater.

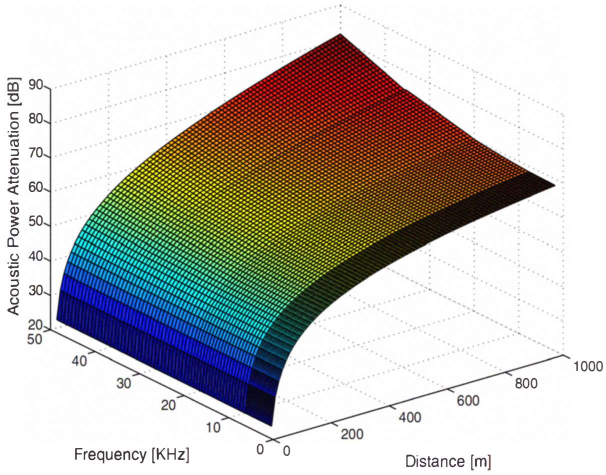

Figure 2. Energy Absorption of short range shallow UW-A channels.

$$v = 1450 + 4.21T - 0.037T^2 + 1.14(S - 35) + 0.175P \quad (1)$$

where T, S and P respectively represent the temperature, salinity, and depth (the pressure). Fig. 1 shows the effect of sound speed, temperature and pressure included, in seawater (from http://www.coexploration.org/bbsr/classroombats/html /sofarfig4.html).

The slow propagation speed of sound impacts the performance of communication system and network protocol design in a number of ways. It brings about large Doppler spread that causes severe interference among different frequency components of the signal and it is also responsible for inter-symbol interference (ISI), which will be discussed below.

2) Propagation loss: Propagation loss causes a sound wave's amplitude to gradually diminish as it travels. One way sound waves can be attenuated is through absorption by the carrier and wave energy is converted to other forms (like heat). The absorption increases with distance and frequency. This effect is more evident for long-distance transmission and high-frequency applications. Fig. 2 shows the acoustic attenuation with varying frequency and distance for a short range shallow water UW-A channel, according to the propagation model in [11]. Another reason for the propagation loss of sound wave is the spherical spreading, which is attributed to this spherical expansion and is known as spherical spreading loss.

B. Multipath

Multipath formed in water is caused by two effects: one is the sound reflection off the surroundings such as the surface, bottom in this case, etc, and the other is the sound refraction in the water (Of course, the slow speed of water has to answer for it). Multipath is considered to be the most difficult aspect for underwater communications, and it as well affects the performance of underwater acoustic communication system.

As the path length of acoustic wave propagation in different paths and the energy at the receiving point are consequently different, signals will have great fading and waveform distortion. That's why you may find the signal-to-noise ratio (SNR) to bring down instead of raising when the launching power is put up in short distance communication. Besides, multipath propagation may be responsible for severe degradation of the acoustic communication signal, since it generates severe ISI. And this can cause minor and even total cancellation as the signals are shifted through 180 degree (as is called destructive interference), and as well brings grand challenges for efficient modulation schemes that will be discussed in next section.

Multipath, however, will be beneficial for the communication in shallow water to some extent. If the multipath energy from multipath signals can be best used, the SNR of the receiver will be increased. Indeed, it is very difficult to realize, especially for random multipath signals. But in shallow water it is necessary to make best advantages of multipath signals, because a certain distance away the receiver cannot get a valid signal directly.

C. Ambient noise

Ambient noise is defined as "the noise associated with the background din emanating from a myriad of unidentified sources". It is related to hydrodynamics (movement of water including tides, currents, storms, etc), seismic (underwater volcanoes, earthquakes, shifting of the seabed, etc) and biological phenomena (whales, dolphins, etc).

The ambient noise field is so complex that magnitude of the noise directly affects the SNR of the receiver, and largely determines the transmitting power. Typically, the minimum transmission carrier frequency depends on ambient noise, while the maximum carrier frequency depends on the absorption of acoustic waves, which together determine the narrow band characteristics of underwater acoustic channel.

Ambient noise cannot simply be regarded as Gaussian distribution, for different sound sources have different bandwidth and noise level, and they change with time and space. So it cannot be accurately calculated beforehand. Experiments show that noise below 10 Hz mainly comes from movement of seawater; noise between 50 Hz and 500 Hz mainly from sailing and geographical location; noise between 500Hz and 50 kHz from the uneven surface of the sea and noise above 50 kHz from the movement of the seawater molecules.

Another severe effect for physical layer design 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 will bring great challenges for networking protocol design.

D. Doppler effects

Movements of the receiver or transmitter, or mismatch between their sampling rates contribute additionally to the changes in the channel response. This is caused by the Doppler effect which brings about frequency shifting and frequency spreading. As we mentioned before, the velocity of sound is really low, so motion-induced Doppler distortion of an acoustic signal can be drastic. However, even without intentional motion, underwater instruments are subject to coasting with waves, currents and tides, which may occur at equivalent speed. Namely, in the system there is always some motion present, and as a result, we have to take this fact into consideration when the physical layer has to be designed.

When acoustic waves propagate in multipath, the power spectrum of receiving signals spread as is called Doppler spread. Although emission frequency is single-frequency *fs*, the received signal power spectrum *S(f)* is broadened *fs-fm* and *fs+fm*. The reciprocal of Doppler spread is defined as channel coherent time, which represents the fading beat of time-varying channel that is caused by Doppler effect and occurs in a specific time period of the transmitted waveform. Slow fading channel has large coherent time while fast fading channel has small coherent time. Time selective fading has significant impact on the bit error rate (BER) performance of digital signal, so in order to reduce its impact, the symbol rate has to be much greater than the rate of the fading beat.

Two effects associated with Doppler spreading have to be mentioned. One is the simple frequency translation that is relatively easy for a receiver to compensate for and the continuous spreading of frequencies that leads to a truly Doppler spread, not shifted, signal. The latter is much more difficult for a receiver to compensate for this effect.

III. MODULATION SCHEMES

As a crucial point, the choice of modulation scheme has to balance several factors: the required and desirable data rate and symbol rate, the implementation complexity, the relationship between radiated power and target BER, and the expected channel characteristics.

A. Single-carrier modulation

The first component of the acoustic communication system is software modulation, which takes digital data as input and modulates an acoustic signal with the data. The potential choices of modulation schemes for software modems include amplitude shift keying (ASK), phase shift keying (PSK), quadrature amplitude modulation (QAM) and frequency shift keying (FSK).

Due to the harsh condition in the underwater channel earlier development in modulation techniques was based on non-coherent FSK because it relies on energy detection. This means that phase tracking is not necessary, which is an important benefit in an underwater channel because of Doppler spreading that makes it quite difficult to track the phase. Non-coherent modulation techniques have high power efficiency but low bandwidth efficiency. For high data rate sensors this may be a problem and coherent modulation techniques, such as PSK and QAM, may be seen as the appropriate technique.

When choosing modulation technique, there is always a tradeoff between high bandwidth efficiency and low SNR to save energy. To reduce the effect of ISI, channel equalization techniques should be implemented. The complex slowly varying channel response can be tracked with the use of decision feedback equalizers (DFE) for optimal channel estimation, and this gives a high through put given that the channel is varying slowly. The DFE can be combined with a phase locked loop (PLL) when the channel is varying fast and this will in a rapid and stable way estimate and compensate for the phase offset.

B. Multicarrier modulation

A different approach to overcoming the frequency selective distortion is through multicarrier modulation, which is implemented by dividing the available bandwidth into a sequence of subchannels; signals confined to each of the subchannels are generated and may employ any form of coherent or incoherent modulation. One example is multiple frequency shift key (MFSK) signaling, while in recent years, the orthogonal frequency division multiplexing (OFDM) attracts more attentions.

OFDM modulation can easily be accomplished by using fast Fourier transforms (FFT). Channel equalization is done in the frequency domain because this is much simpler than time domain equalization. The OFDM technique requires an estimate of the underwater channel, which can be attained using probe packets. Accurate estimate of the channel can be obtained with high probing rate and large probe packet size. This, however, results in higher overhead that reduces the channel capacity and increases the energy consumption.

The weakness of OFDM system is the severe sensitivity to frequency offset due to the limited bandwidth of each sub-carrier. This may be a large problem when the Doppler spreading is taken into consideration. OFDM system can only tolerate frequency offsets that are much smaller than the frequency separation between the carrier frequencies, and this makes frequency synchronization very important. Doppler spreading in a wideband UWA system makes different carriers experience different frequency offsets. The transmitted signal will also experience multipath that may become a trouble because of the slow speed of the sound. Besides, OFDM is quite complicated and demands more power, which is another challenge for UWA-SN.

C. Spatial modulation

Information theoretic studies have shown that the capacity of a channel increases linearly with the minimum of the number of transmitting and receiving antennas. This increase in capacity translates to a corresponding increase in achievable data rate through the use of multiple input multiple output (MIMO) processing techniques and space-time coding. The promise of increased throughput and spatial diversity in practical MIMO systems can only be achieved if the transducers in transmit and receive arrays are placed with spacing larger than the spatial coherence scale at the frequency of interest [12].

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. 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.

MIMO introduces additional interference among parallel data streams from different transmitters. Also, each receiver has more channels to estimate, which requires more over head spent on training symbols. Certainly, implementation of distributed MIMO needs to address challenging practical issues such as node synchronization and cooperation.

IV. Power Efficiency

In UW-ASNs, transmit power dominates, and is typically about 100 times more than receive power. Transmission power depends on the distance, and its typical values are on the order of tens of Watts. In contrast, the power consumed by the receiver is much lower, with typical values ranging from about 100mW to no more than a few Watts. In sleep mode, from which a node can be woken on command, no more than 1mW may be needed. So the physical layer in a UW-ASN has to take energy efficiency into consideration.

Minimizing the energy consumption at the physical layer requires that the circuitry energy and transmission energy be optimized. Circuitry energy can be minimized with the reduction of wakeup and startup time. Modulation schemes have been proposed to reduce the energy for transmitting each bit. One way to save the energy is by transmitting at a higher bit rate. Another way is by minimizing the number of retransmissions.

It is not simply the power, but the energy consumption that matters as underwater instruments are battery-powered. Besides battery capacity, transmit power may be limited for reasons. One standard networking would be to promote spatial reuse. And in the field of military networks, maintaining covert communication is another big goal.

V. Conclusion

In short, this paper has analyzed several key aspects that have to be considered when designing the physical layer for UW-ASNs. In order to enable physical layer solutions specifically tailored to UW-ASNs, the following open research issues need to be addressed:

- Designing no flow-complexity suboptimal filters characterized by rapid convergence and real-time underwater communications with decreased energy expenditure.
- Creating simple modulation schemes to reduce synchronization and energy cost, determining the optimal transmission power.
- To overcome stability problem in the coupling between PLL and DCE.

Acknowledgment

This work is supported by the National Natural Science Foundation of China under grant NO.60772107 and the Self-research Program for Ph.D. Candidates of Wuhan University under grant NO.20082080101000036.

Authors are particularly grateful to Jingshan Lin and the reviewers for most valuable comments and suggestions that improved the quality of this paper.

References

[1] E. M. Sozer, M. Stojanovic, and J. G. Proakis, "Underwater acoustic networks," IEEE Journal of Oceanic Engineering, vol. 25, Jan. 2000, pp. 72-83, doi: 10.1109/48.820738.

[2] A. Tannenbaum, Computer Networks, 3rded. Englewood Cliffs, NJ: Prentice Hall, 1996.

[3] M. Chitre, L. Freitag, E. Sozer, S. Shahabudeen, M. Stojanovic and J. Potter, "An architecture for underwater networks," Proc. OCEANS 2006 - Asia Pacific, May 2007, IEEE Computer Society, pp: 1-5, doi: 10.1109/OCEANSAP.2006.4393953.

[4] M. Chitre, S. Shahabudeen, and M. Stojanovic, "Underwater acoustic communications and networking: Recent advances and future challenges," Marine Technology Society Journal, vol. 42, Spring, 2008, pp. 103-116, doi: 10.4031/002533208786861263.

[5] M. Chitre, S. Shahabudeen, L. Freitag and M. Stojanovic, "Recent advances in underwater acoustic communications networking," Proc. OCEANS 2008, IEEE Computer Society, Sept. 2008, pp. 1-10, doi: 10.1109/OCEANS.2008.5152045

[6] I. F. Akyildiz, D. Pompili and T. Melodia, "Underwater acoustic sensor networks: research challenges," Ad Hoc Networks, vol. 3, Mar. 2005, pp. 257-279; doi: 10.1016/j.adhoc.2005.01.004.

[7] L. Liu, S. Zhou, and J. H. Cui, "Prospects and problems of wireless communication for underwater sensor networks," Wireless Communications and Mobile Computing, vol. 8, Aug. 2008, pp. 977-994, doi: 10.1002/wcm.654.

[8] J. Partan, J. Kurose and B. N. Levine, "A survey of practical issues in underwater networks," First ACM International Workshop on Underwater Networks (WUWNet 2006), Association for Computing Machinery, Sep. 2006, pp. 17-24, doi: 10.1145/1161039.1161045.

[9] M. Stojanovic, "Underwater acoustic communications: Design considerations on the physical layer," 2008 5th Annual Conference on Wireless on Demand Network Systems and Services (WONS 2008), IEEE Computer Society, Jan. 2008, pp. 1-10, doi: 10.1109/WONS.2008.4459349.

[10] N. Nasri, A. Kachouri, L. Andrieux and M. Samet, "Design considerations for wireless underwater communication transceiver," Proc. 2008 2nd International Conference on Signals, Circuits and Systems (SCS 2008), IEEE Computer Society, Nov. 2008, pp 1-5, doi: 10.1109/ICSCS.2008.4746954.

[11] R.J. Urick, Principles of Underwater Sound, McGraw Hill, 1983.

[12] T. C. Yang, "A study of spatial processing gain in underwater acoustic communications," IEEE Journal of Oceanic Engineering, vol. 32, Mar. 2007, pp. 689-709, doi: 10.1109/JOE.2007.897072.