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Coherent Underwater Acoustic Communications - A Review

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ABSTRACT

Digital communications through the underwater acoustic channel has been an active area of research in recent years. Applications include data transmission from bottom instrumentation, control of autonomous underwater vehicles (AUVs), digital voice and video transmission, etc. The effects of multipath propagation, Doppler frequency shifts due to relative motion of transmitter and receiver, and channel time and space variability which cause intersymbol interference and phase fluctuations of signals impose unique requirements for system design. Most research has been focused on the development of algorithms to cope with intersymbol interference and phase fluctuations. Development of coherent communication systems has improved bandwidth efficiency and reliability. In this paper, the trends and results of recent research on underwater communications, including channel models, equalization, diversity and synchronization, are reviewed. Some of our own research results are presented to illustrate the feasibility and effectiveness of proposed transmission schemes.

1. INTRODUCTION

Parallel to increased ocean related activities, demand for underwater communications is increasing. Such communications are required for transmission of measurement data from underwater sensors, telemetry, AUVs, voice and video transmission, etc. [1, 2, 3, 4].

Acoustic signals in the underwater environment are attenuated. Attenuation rises rapidly with increasing frequency and distance [5]. This sets an upper limit for applicable carrier frequency and transmission bandwidth which limits data transmission throughput. Transmitted signals also suffer from phase shifts and amplitude fluctuations produced by multipath propagation, combined with Doppler shifts due to receiver and transmitter motions [6]. Effects of ambient noise caused by shipping and the effects of industrial noise, wind noise, and biological noise [5] must also be accounted for.

Techniques developed for terrestrial channels using electromagnetic waves have to be modified for underwater communications due to the distinct characteristics of shallow underwater channels [6, 7].

Table 1: Comparison between land mobile and underwater acoustic communications

Parameters	Land Mobile	Underwater Acoustic
carrier frequency (f_c)	1 GHz	10 kHz
channel bandwidth	30 kHz	2 kHz
signalling rate	24.3 ksymbols/sec	2 ksymbols/sec
multipath spread (T_m)	10 μs [8] (0.24 symbols)	50 - 1000 msec [9] (100 - 2000 symbols)
vehicle speed (v)	100 km/hr (highway)	18 km/hr (submersible)
Doppler frequency (f_d)	92.6 Hz	33.3 Hz
f_d/f_c	$9.26\text{x}10^{-6}$	$3.33\text{x}10^{-3}$
cycles/symbol	41152	5

Table 1 compares typical samples of land mobile communication and underwater acoustic communication. The underwater channel clearly shows a wider multipath spread and a larger Doppler frequency to carrier frequency ratio (f_d/f_c) compared with land mobile channels.

Spread spectrum techniques are used in a land mobile channel to mitigate the effects of multipath spread. However, these techniques are not suitable for underwater communication because of bandwidth limitations imposed by a practical acoustic transducer [10]. Frequency shift keying (FSK) and adaptive beamforming are alternative methods. However, FSK has poor bandwidth utilization and beamforming is not effective for use in a shallow water channel having very small arrival angles for the various multipaths. Equalization methods are better suited to data transmission in channels where differences in path length between the direct path and multipaths are small. A quite long channel impulse response of underwater channels as shown in Table 1 sets a requirement for an equalizer design different from that of terrestrial communications. Equalizers for acoustic channels need so many coefficients that is difficult to update them at real-time. Several studies addressing this problem have been performed recently [11, 12, 13].

The special issues on acoustic communications (Vol.21, No.2, April 1996) and on oceanic acoustic data telemetry (Vol.19, No.1, January 1991) in the IEEE Journal of Oceanic Engineering describe recent advances and research activities in the area of underwater communications. An extensive bibliographical review is also available [14, 15].

In this paper, trends and results of recent research on underwater communications, including channel modeling, equalization and synchronization, are reviewed. Some of our own research results are presented to illustrate the feasibility and effectiveness of proposed transmission schemes.

2. THE STATE OF THE ART

A. Underwater Acoustic (UWA) Channel Model

In system design one must address multipath propagation as well as spatial and temporal variability of acoustic signals in the underwater channel [6, 16]. Multipath propagation causes intersymbol interference (ISI) while channel variability causes phase fluctuations of received signals. The multipath structure depends on the channel geometry, environmental conditions and the frequency of transmitted signals. The channel geometry is given by ocean depth, transmitter and receiver depth and the distance between the transmitter and the receiver. The environmental conditions include effects of water pressure, temperature and density distribution [16, 17].

An adequate channel model suitable for computer simulations is desired because it can offer several advantages such as:

1) savings the high cost of experimentation with underwater communications systems;
2) an ability to deal with selected effects separately; and
3) an ability to compare performance of different system configurations under the same channel conditions.

For an acoustic channel with non-constant sound speed profile, the ray-tracing method is commonly utilized to find acoustic rays between transmitter and receiver [17, 18]. The acoustic rays of interest leave the transmitter and reach the receiver directly or via reflections at the sea surface or at the bottom (eigenrays). The received signal is a summation of a number of time-varying phasors with random amplitude and phase. To consider the fluctuations of amplitude and phase in acoustic propagation in the ocean, a Rayleigh fading model has been frequently utilized for a shallow water channel [19, 20]. According to Falahati [20], each individual statistically independent acoustic ray (eigenray) can be modeled by a single Rayleigh fading simulator while incorporating the Doppler shift due to the movement of transmitter and/or receiver.

A stochastic underwater acoustic channel model which accounts for fluctuations of the received signal using a combination of linear and nonlinear transforms on a Gaussian variable was proposed [21]. This model is flexible and able to reproduce arbitrary fluctuations measured in real experimentation as well as Rayleigh fading. Recently, C. Bjerrum-Niese et al. [22] developed a simulation tool for high data-rate acoustic communication in a shallow-water, time varying channel. Their channel model was developed based on physical aspects of the acoustic channel, emphasizing fluctuations of the signal transmission caused by time-varying multipath effects. Finally, the authors proposed a simple but effective channel model suitable for shallow water channels [23]. This was further studied using a numerical ray tracing model in a layered shallow water channel [24].

B. Equalization

As a method of reducing the intersymbol interference (ISI), an equalizer has been commonly employed [2, 9, 26]. In some cases equalization has been performed together with beamforming (beamsteering) [7, 25, 27]. While a beamforming technique is an effective method in channels with a small range-to-depth ratio (less than 10), it becomes increasingly difficult to employ a beamforming technique to resolve the very small inter-arrival angles of various multipaths in a channel with a large range-to-depth ratio (larger than 10). For this reason, equalization is most appropriate in a situation where differences in arriving angles and path lengths between adjacent path signals are small.

A linear equalizer operating under a least mean squares (LMS) algorithm [2, 26] and a decision-feedback equalizer (DFE) operating under a LMS [4] or a recursive least squares (RLS) algorithm [7] have been tested on several different channels. LMS algorithms have lower computational complexity whereas RLS algorithms and their variations have better convergence properties and numerical stability but higher complexity [28].

Carrier frequencies between 15 kHz and 50 kHz were employed achieving data rates between 1 kbps (deep long range channel) and 40 kbps (shallow water medium range channel) [7]. Purely phase-coherent detection methods based on joint synchronization and equalization algorithms have been successfully tested by Northeastern University and Woods Hole Oceanographic Institution [29]. The joint algorithm utilized the combination of a DFE and a digital phase-locked loop (DPLL) for the minimization of ISI and the carrier phase estimation. Because of this success, research has been broadened to include a multichannel DFE and acoustic local area networks (ALAN) [30]. The multichannel DFE is an extension of single sensor reception by utilizing spatial diversity; that is, by the processing of many input signals received using an array of sensors.

Another important issue regarding equalizer design for shallow water acoustic communication is the reduction of hardware complexity [11, 12]. Hardware complexity is related to the number of coefficients (equalizer taps) requiring update in real time. The channel impulse response in several cases required more than a hundred taps to be updated [11]. In order to reduce the computational load of the equalizer, the unique characteristics of acoustic channels can be exploited. That is, the multipath structure in shallow water is often sparse; signal arrivals tend to be clustered in groups with gaps in time between adjacent groups. Also, the channel response and ambient noise are often stable over several seconds which allows the equalizer parameters to be updated less frequently, once trained.

Recently, self-optimization or blind recovery has received considerable attention [31, 32]. Self-optimization will enable a receiver to adjust to changes in channel conditions with less frequent insertion of training sequences. Therefore, self-optimization or blind recovery receiver algorithms will increase data throughput.

C. Synchronization

Noncoherent detection of FSK signals does not require tracking the carrier phase, and therefore it has traditionally been employed as a modulation method for UWA communications [1, 33]. However, to overcome the effect of multipath propagation (that is, ISI), signal design with guard times have to be used. Guard times are inserted between successive pulses to ensure that reverberation vanishes before each subsequent pulse is received. However, it reduces data throughput. Recently, in order to increase the bandwidth efficiency of UWA communication systems, research on phase-coherent modulation techniques such as phase shift keying (PSK) and quadrature amplitude modulation (QAM) has been actively pursued [2, 3, 7]. Depending on the carrier synchronization method, a phase-coherent system can be divided into two categories: differentially coherent and purely phase-coherent systems. Differentially coherent detection has simple carrier recovery, but it has worse performance compared with purely coherent detection [28].

The Doppler effect arising from the relative motion between transmitter and receiver as well as the change of channel characteristics in time due to the moving ocean surface impose the difficulty of tracking the carrier phase in the presence of a complex multipath structure [34, 35]. Several algorithms have been developed for jointly adaptive equalization and synchronization [7, 29, 34]. A second order DPLL is frequently employed for carrier synchronization.

In order to achieve a better performance of the synchronizer, rapid acquisition and accurate and reliable tracking is required [35, 36, 37, 38]. Acquisition is the process of acquiring lock from unlocked conditions whereas tracking is the process of maintaining synchronization after initial acquisition. Rapid acquisition of synchronization allows the length of a training sequence to be minimized while accurate and reliable phase tracking is needed to minimize tracking error and probability of a cycle slip or losing lock. Losing synchronization reduces efficiency in the data detection process because inaccurate synchronization directly reduces the probability of making correct decisions. In addition, loss of synchronization may sometimes lead to successive errors before synchronization is recovered.

The authors have developed an algorithm which can satisfy both requirements adaptively [39]. The proposed algorithm allows for rapid acquisition at the initial period of data transmission and small tracking errors at tracking mode while it can also track Doppler frequency shifts.

3. A COMMUNICATION SYSTEM

We have performed several computer simulations using a DFE where the forward filter is fractionally spaced with spacing T/2 [40]. For the adaptation algorithm, we have chosen the LMS algorithm. Table 2 shows selected channel and system parameters.

Table 2: Channel and system parameters for simulation

Channel parameters		System parameters	
ocean depth	50 m	carrier frequency	10 kHz
wind speed	20 knots	system bandwidth	2 kHz
transmitter depth	25 m	transmission rate	4 kbaud
receiver depth	25 m		

The phase scatter diagrams before and after equalization are shown in Figure 1 for several distances between receiver and transmitter. Before actual data transmission, a training sequence of 200 random symbols known to the receiver is transmitted. After the training period, adjustment of equalizer coefficients is performed by an iterative procedure using receiver estimates of the transmitted sequence. We see that for both L = 10 and L = 15 km no distinct phase constellations are present when an equalizer is not employed. This indicates that even in the absence of other sources of noise, error-free transmission is impossible without an equalizer. For L=20 km, the scatter output forms distinct constellations, but the equalization reduces scatter and assures a better transmission performance. The scatter plots after equalization show that the ISI caused by multipath is dramatically reduced. Since an 8-PSK system allows transmission of 3bits per symbol, simulation results indicate that, neglecting ambient noise, error free data transmission at a data rate of 16 kbit/s might be possible over a distance of 20 km if an equalizer is employed.

4. CONCLUSIONS AND FUTURE RESEARCH

In this paper, recent advances and some research directions in underwater communication are described. Equalization and synchronization algorithms which cope with ISI and phase fluctuations are reviewed. Application of coherent communication has improved bandwidth efficiency and reliability. Our simulation results indicate that error free data transmission at a data rate of 16 kbit/s might be possible over a distance of 20 km if an 8-PSK system with an equalizer is employed and if ambient noise can be neglected.

Research in underwater acoustic communications seeks even faster rate of reliable data transmission to broaden the application of underwater acoustic communication such as real time video transmission. In order to increase the data rate throughput with the desired performance, receivers with advanced algorithms utilizing signal processing techniques have to be developed.

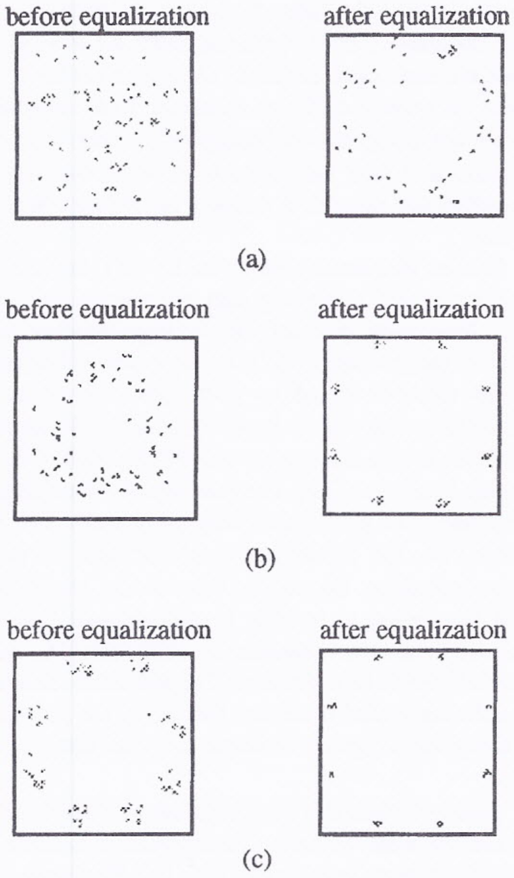

Figure 1. Scatter diagrams before/after equalization
(a) L = 10km, (b) L = 15km, (c) L = 20km.

REFERENCES

1. J. Captipovic, M. Deffenbaugh, L. Freitag and D. Frye, (1989), "An Acoustic Telemetry System for Deep Ocean Mooring Data Acquisition and Control," Proc. Oceans 89, Seattle, WA, pp. 887-892.
2. M. Suzuki and T. Sasaki, (1992), "Digital Acoustic Image Transmission System for Deep Sea Research Submersible," Proc. Oceans 92, Newport, RI, pp. 567-570.
3. J. Fischer, K. Bennett, S. Reible, J. Cafarella and I. Yao, (1992), "A High-rate, Underwater Acoustic Phone," Proc. Oceans 92, Newport, RI, pp. 571-576.
4. A. Goalic, J. Labat, J. Trubuil, S. Saoudi and D. Riouaten, (1994), "Toward a Digital Acoustic

Underwater Phone," Proc. Oceans 94, vol.3, Brest, France, pp. 489-494.

5. R. J. Urick, (1983), Principles of Underwater Sound, 3rd ed., McGraw-Hill, New York.
6. J. Captipovic, (1990), "Performance Limitations in Underwater Acoustic Telemetry," IEEE J. Oceanic Eng., vol.15, pp. 205-216.
7. M. Stojanovic, (1996), "Recent Advances in High-Speed Underwater Acoustic Communications," IEEE J. Oceanic Eng., vol.21, no.2, pp. 125-136.
8. N. W. K Lo and D. D. Falconer, (1991), "Adaptive Equalization and Diversity Combining for Mobile Radio using Interpolated Channel Estimates," IEEE Trans. Vehicular Technology, vol. 40, no. 3, pp. 636-645.
9. J.G. Proakis, (1991), "Adaptive Equalization Techniques for Acoustic Telemetry Channels," IEEE J. Oceanic Eng., vol.16, no.1, pp. 21-31.
10. R. Coates, M. Tseng and L. Wang, (1996), "BASS 300 PARACOM: A Model Underwater Parametric Communication System," IEEE J. Oceanic Eng., vol. 21, no. 2, pp. 225-232.
11. B. Geller, V. Capellano, J. Brossier, A. Essebbar and G. Jourdain, (1996), "Equalizer for Video Rate Transmission in Multipath Underwater Communications," IEEE J. Oceanic Eng., vol.21, no.2, pp. 150-155.
12. M. Johnson, D. Brady and M. Grund, (1995), "Reducing the Computational Requirements of Adaptive Equalization in Underwater Acoustic Communications," Proc. Oceans 95, San Diego, pp. 1405-1410.
13. P. S. D. Tarbit, G. Howe, O. Hinton, A. Adam, and B. Sharif, (1994), "Development of a Realtime Adaptive Equalizer for a High-rate Underwater Acoustic Communication Link," Proc. Oceans 94, vol.I, Brest, France, pp. 307-312.
14. R. Coates, R. Owens and M. Tseng, (1993), "Underwater Acoustic Communications: A second bibliography and review," Proc. Inst. Acoust., vol.15, pp. 1-11.
15. R. Coates and P. A. Wilson, (1987), "Underwater Acoustic Communications: A review and bibliography," Proc. Inst. Acoust., vol.9, pp. 54-62.
16. R. Coates, (1990), Underwater Acoustic Systems, Macmillan Education Ltd., New York.
17. A. Essebbar and E. Vercelloni, (1995), "Simulation of Communication System for Underwater Acoustic," Proc. Oceans 95, San Diego, pp. 1204-1207.
18. G. H. Sandsmark and A. Solstad, (1991), "Simulations of an Adaptive Equalizer Applied to High-speed Ocean Acoustic Data Transmission," IEEE J. Oceanic Eng., vol.16, no.1, pp. 32-41.
19. R. Galvin and R. Coates, (1994), "Analysis of the Performance of an Underwater Acoustic Communications System and Comparison with a Stochastic Model," Proc. Oceans 94, vol. III, Brest, France, pp. 478-482.
20. A. Falahati, B. Woodward and S. C. Bateman, (1991), "Underwater Acoustic Channel Models For 4800 b/s QPSK Signals," IEEE J. Oceanic Eng., vol.16, no.1, pp. 12-20.
21. R. Galvin and R. Coates, (1996), "A Stochastic Underwater Acoustic Channel Model," Proc. Oceans 96, vol. I, Fort Lauderdale, FL, pp. 203-210.
22. C. Bjerrum-Niese, L. Bjorno, M. A. Pinto and B. Quellec, (1996), "A Simulation Tool for High Data-Rate Acoustic Communication in a Shallow-Water, Time-Varying Channel," IEEE J. Oceanic Eng., vol.21, no.2, pp. 143-149.
23. A. Zielinski, Y. Yoon and L. Wu., (1995), "Performance Analysis of Digital Acoustic Communication in a Shallow Water Channel," IEEE J. Oceanic Eng., vol.20, no.4, pp. 293-299,
24. C. Bjerrum-Niese and L. Bjorno, (1996), "Simulated Design of an Acoustic Modem for an AUV in a Shallow Water Channel," Proc. Undersea Defense Technology, London, UK, pp. 20-24.
25. B. Billon and B. Quellec, (1994), "Performance of High Data Rate Acoustic Underwater Communication Systems Using Adaptive Beamforming and Equalizing," Proc. Oceans 94, vol.III, Brest, France, pp. 507-512.
26. A. Kaya and S. Yauchi, (1989), "An Acoustic Communication System for Subsea Robot," Proc. Oceans 89, Seattle, WA, pp. 765-770.
27. J. A. Neasham, D. Thompson, A. D. Tweedy, M. A. Lawlor, O. R. Hinton, A. E. Adams and B. S. Sharif, (1996), "Combined Equalization and Beamforming to Achieve 20kbits/s Acoustic Telemetry for ROVs," Proc. Ocean 96, vol. II, Fort Lauderdale, FL, pp.988-993.
28. J. G. Proakis, (1989), Digital Communications, 2nd ed., McGraw-Hill, New York, pp. 642-648.
29. M. Stojanovic, J. A. Catipovic and J. G. Proakis, (1994), "Phase-Coherent Digital Communications for Underwater Acoustic Channels," IEEE J. Oceanic Engineering., vol. 19, no. 1, pp. 100-111.
30. M. Stojanovic and Z. Zvonar, (1996), "Multichannel processing of broadband multi-user communication signals in shallow water acoustic channels," IEEE J. Oceanic Eng., vol.21, no.2, pp. 156-166.
31. L. Tong, G. Xu and T. Kailath, (1994), "Blind Identification and Equalization based on Second-order Statistics," IEEE Trans. Inform. Theory, vol.40, no.2, pp. 340-349.

32. P. Bragard and G. Jourdain, (1990), "A Fast Self-optimized LMS Algorithm for Nonstationary Identification. Application to Underwater Equalization," Proc. ICASSP 90, Albuquerque, NM, pp. 1425-1428.
33. S. Merriam and D. Porta, (1993), "DSP-based Acoustic Telemetry Modems," Sea Technology.
34. J. Labat, (1994), "Real time Underwater Communications," Proc. Oceans 94, vol.III, Brest, France, pp. 501-506.
35. S. S. Soliman, (1991), "Synchronization Issues in Ocean Telemetry," IEEE J. Oceanic Eng., vol.16, no.1, pp. 74-85.
36. H. Meyr and G. Ascheid, (1990), Synchronization in Digital Communications, Wiley, New York.
37. W. C. Lindsay and C. M. Chie, (1981), "A Survey of Digital Phase-locked Loops," Proc. IEEE, vol. 69, no.4, pp. 410-431.
38. P. F. Driessen, (1994), "DPLL Bit Synchronizer with Rapid Acquisition Using Adaptive Kalman Filtering Techniques," IEEE Trans. Commun., vol.42, no.9, pp. 2673-2675.
39. Y. Yoon and A. Zielinski, (1996), "Adaptive Carrier Recovery for Underwater Acoustic Communication," Proc. XIIIth Symposium on Hydroacoustics, Jurata, Poland, pp. 12-20.
40. Y. Yoon and A. Zielinski, (1995), "Simulation of the Equalizer for Shallow Water Acoustic Communications," Proc. Oceans 95, San Diego, pp. 1197-1203.