Advancing Underwater Acoustic Communication for Autonomous Distributed Networks via Sparse Channel Sensing, Coding, and Navigation Support

Shengli Zhou
Electrical and Computer Engineering Department
University of Connecticut
Storrs, CT 06269
phone: (860) 486-4593 fax: (860) 486-5585 email: shengli@engr.uconn.edu

Award Number: N00014-09-1-0704
Sponsor: Department of Defense (PECASE)
Dr. Robert Headrick

LONG-TERM GOALS

The long-term goal is to significantly advance underwater acoustic communication technologies for autonomous distributed underwater networks, through innovative signal processing, coding, and navigation algorithms. Providing highly reliable and high data rate communication links will be critical towards the development of a new era of underwater distributed networks.

OBJECTIVES

We have three objectives in this project.

1. **Advanced communication techniques of sparse channel sensing and nonbinary LDPC coding.** Underwater acoustic channels are naturally sparse, but how to effectively exploit the sparsity is a challenging task. We will investigate the recently developed “compressive sensing” algorithms for sparse channel estimation in the context of multicarrier acoustic communications. On the other hand, channel coding is one integral part of an advanced communication system, and is dispensable in approaching the theoretical limit predicted by the Shannon theory. We will thoroughly investigate nonbinary low-density-parity-check (LDPC) codes, and especially pursue fast encoding and decoding algorithms and practical implementations.
2. **High-resolution ranging and navigation.** Wideband multicarrier waveform has a dual use that it can yield precise timing information for the receiver to infer the distance from the sender. With range estimates from multiple buoys, each underwater vehicle can self localize and navigate. We will investigate ranging and tracking algorithms that achieve high positioning accuracy. We aim to integrate the communication and navigation capabilities into the OFDM modem under development, which will greatly facilitate the development of emerging underwater distributed networks.

3. **Testbed development and medium access control.** We plan to develop a network testbed to illustrate the cooperative networking scenario. We first will determine an effective medium access control protocol to improve the system throughput for multiple users equipped with high-rate OFDM modems. We will then carry out demonstrations in three settings: 1) point to point links with advanced communication techniques; 2) ranging and navigation in a setup with four buoys and one underwater node; and 3) cooperative networking in a setup with four buoys and multiple underwater nodes.

APPROACH

Our technical approach is to develop advanced signal processing algorithms to improve the robustness and increase the data rate of underwater acoustic communication. Specifically, 1) we will use compressive sensing algorithms to exploit the sparsity nature of the underwater acoustic channels, 2) we will develop advanced capacity-achieving nonbinary LDPC codes to improve the error performance, 3) we will improve the localization and navigation performance through the use of wideband OFDM waveforms, which has much increased time-resolution for ranging purposes, and 4) we will investigate effective medium access protocols along with a testbed demonstration with multiple nodes.

We work with Dr. Jie Huang from the University of Connecticut (UConn) to carry out the research tasks on sparse channel estimation and nonbinary LDPC coding. We collaborate with Drs. Zhijie Shi and Jun-Hong Cui from UConn on testbed development.

WORK COMPLETED

We have developed sparse channel estimation algorithms and advanced channel coding schemes, and have tested them using extensive data sets from the following experiments:

1) RACE 08 experiment, Narragansett Bay, March 2008 (led by Dr. James Preisig)
2) SPACE08 experiment, Martha's Vineyard, MA, Oct. 2008 (led by Dr. James Preisig)

Also, we started to interact with Dr. Josko Catipovic to develop receiver algorithms for OFDM in deep water channels with very large delay spread. The experimental data were collected in the Atlantic Undersea Test and Evaluation Center (AUTEC) around Andros Island near the Tongue of the Ocean, Bahamas, Dec. 2008.

We have been using the OFDM modem prototypes to test the localization algorithm in a swimming pool and in local lakes.

This year, we have supervised three undergraduate students into research through their senior design projects:

- Project: "On the Power and Networking Issues of the OFDM Underwater Acoustic Modems". Duration: Spring10-Fall10. Team: John Canevari, Michael Fowler, Richard Scarpetti.

RESULTS

We next highlight our progresses made on the following topics: 1) sparse channel estimation, 2) an advanced progressive receiver, and 3) nonbinary LDPC codes, 4) localization using OFDM modems, 5) OFDM receiver design for deep water channels, and 6) miscelleaous topics such as blind channel shortening and acoustic channel tracking.

1) Comparision of sparse channel sensing algorithms for underwater OFDM. As reported in last year, we have investigated various channel estimators that exploit channel sparsity in the time and/or Doppler domain for a multicarrier underwater acoustic system. We have shown that sparse channel estimation, implemented with orthogonal matching pursuit (OMP) and basis pursuit (BP) algorithms, has impressive performance gains over alternatives that do not take advantage of the channel sparsity, for underwater acoustic (UWA) communications.

In this work, we have compared the performance and complexity of three popular BP algorithms, namely l1_ls, SpaRSA, and YALL1, using both simulation and experimental data for underwater orthogonal frequency division multiplexing (OFDM) systems with both single and multiple transmitters. We find that all BP solvers achieve similar block-error-rate performance, considerably outperforming OMP. In terms of complexity, both SpaRSA and YALL1 reduce the runtime by about one order of magnitude relative to l1_ls, catching up with OMP. See the illustrations in Figure 1. The efficient BP solvers such as SpaRSA and YALL1 are thus appealing to be implemented in real-time underwater OFDM modems.

We have been invited to contribute an overview paper to IEEE Communications Magazine, which will appear Nov. 2010, entitled ``Application of Compressive Sensing to Sparse Channel Estimation."

2) A progressive receiver for underwater OFDM that self adapt to varying channel conditions. Fast variation of UWA channels destroys the orthogonality of the sub-carriers and leads to inter-carrier interference (ICI), which degrades the system performance significantly. In this work we propose a progressive receiver dealing with time-varying UWA channels, as shown in Figure 2.

The progressive receiver is in nature an iterative receiver, based on the turbo principle. However, it distinguishes itself from existing iterative receivers in that the system model for channel estimation and data detection is itself continually updated during the iterations. When the decoding in the current iteration is not successful, the receiver increases the span of the ICI in the system model and utilizes the currently available soft information from the decoder to assist the next iteration which deals with a channel with larger Doppler spread. Numerical simulation and experimental data collected from the SPACE08 experiment show that the proposed receiver can self adapt to channel variations, enjoying low complexity in good channel conditions while maintaining excellent performance in adverse channel conditions.

Figure 3 shows the block success rate averaged over the eight consecutive days using the proposed progressive receiver with the MMSE equalizer. At short (S1) to medium (S3) ranges, when the number of hydrophones is small, the performance of the ICI-ignorant receiver (D=0) is limited, and many more OFDM symbols can be decoded by applying the progressive procedure, with a larger D. When the number of hydrophones is large, the ICI-ignorant receiver already achieves excellent results for all the blocks. Checking the results using four hydrophones, about 90 % OFDM blocks can be decoded at the D=0 stage, and the success rate increases to 95 % when D_max=1, and up to 98.8 % when D_max=3.

Hence, the progressive receiver enjoys both the low complexity and good performance.

3) Large-Girth Nonbinary QC-LDPC Codes of Various Lengths. In this work, we have constructed nonbinary quasi-cyclic low-density parity-check (QC-LDPC) codes whose parity check matrices consist of an array of square sub-matrices which are either zero matrices or circulant permutation matrices. We propose a novel method to design the shift offset values of the circulant permutation sub-matrices, so that the code length can vary while maintaining a large girth. Extensive Monte Carlo simulations demonstrate that the obtained codes of a wide range of rates (from 1/2 to 8/9) with length from 1000 to 10000 bits have very good performance over both AWGN and Rayleigh fading channels. Furthermore, the proposed method is extended to design multiple nonbinary QC-LDPC codes simultaneously where each individual code can achieve large girth with variable lengths. The proposed codes are appealing to practical adaptive systems where the block length and code rate need to be adaptively adjusted depending on traffic characteristics and channel conditions. Figure 4 shows the performance of the proposed codes with different rates in Rayleigh fading channels.

4) Underwater Localization Based on Multicarrier Waveforms. In this work, we have investigated the problem of localizing an underwater sensor node based on message broadcasting from multiple surface nodes. With the time-of-arrival measurements from a DSP-based multicarrier modem, each sensor node localizes itself based on the travel time differences among multiple senders to the receiver. Using one-way message passing, such a solution can scalably accommodate a large number of nodes in a network.

We carried out a test in a local lake in Storrs, Connecticut. The area in which the testing occurred had an average depth of approximately 3 meters, and all nodes were placed near the surface of the lake. As such, the depth was a known constant, and all transducer equipment was approximately 1 meter below the surface. For the purposes of position estimation, the depth component can be ignored. Four transmitting nodes were used, with a fifth node receiving and localizing itself.

Due to certain constraints on the shape and depth of the lake, a perfectly square anchor node deployment was not achieved. Our following results are based on the deployment in Figure 5. The location estimates by the exhaustive search method are shown in Figure 5. We see that the estimates from both methods are biased using these data sets. A localization error below 10 m is achieved after averaging over multiple samples.

5) OFDM in Deep Water Acoustic Channels with Extremely Long Delay Spread. Deep water horizontal channels usually have very long delay spreads relative to shallow water channels. The delay spread can be several hundreds of milliseconds, which covers several blocks of orthogonal frequency division multiplexing (OFDM) transmissions, leading to severe inter-block-interference (IBI). There are usually two significant well-separated clusters, one from direct paths and the other from surface reflections.

Viewing the signals arrived along the two clusters as from two virtual users, we developed a multiuser based OFDM receiver to address IBI, where both channel estimation and data detection algorithms are presented. This receiver can effectively combine signals from multiple senors with different delay spread structures, where each block is decoded in the presence of interference from multiple different blocks. Further, we developed a factor-graph based receiver which addresses both IBI and ICI in a unified factor-graph representation. Data detection is performed according to the Gaussian message passing (GMP) principle which operates on the factor graph in an iterative manner. Compared with the multiuser receiver, the factor-graph based receiver enjoys better block-error-rate performance and appealing expansion capability when multiple receiving-elements are used.

Experimental data from the Atlantic Undersea Test and Evaluation Center (AUTEC) environment are used to validate the performance of the proposed receiver. Figure 6 shows sample channel estimates for two clusters.

6) Blind channels shortening and acoustic channel tracking. We have also spent some efforts on two topics 1) blind channel shortening so that the OFDM receiver can work with channels with delay spread larger than the guard interval, and 2) the use of advanced trackers from Radar and Sonar applications to estimate and predict the acoustic channels, and hence to enhance the receiver performance. So far simulation results have been carried out, and verification of the algorithms with experimental data are planned.

IMPACT/APPLICATIONS

The success of our project will have a deep impact. Providing high-data-rate and reliable acoustic communication with navigation functionalities, our project will directly contribute to the development of distributed autonomous underwater networks that are of great interest to Navy, e.g., the AUV/UUV/Glider networks.

RELATED PROJECTS

This reported project aims to significantly advance the research on multicarrier underwater acoustic communications, which was initiated from the ONR project N00014-07-1-0805, entitled “The Next Milestone: A Multicarrier Acoustic MODEM with Channel- and Network-Adaptivity for Underwater Autonomous Distributed Systems,” 6/1/2007-5/31/2010, PI: Shengli Zhou.

PUBLICATIONS

1. C. R. Berger, Z.-H. Wang, J.-Z. Huang, and S. Zhou, "Application of Compressive Sensing to Sparse Channel Estimation," IEEE Communications Magazine, (invited), Nov. 2010.
2. J. Huang, L. Liu, W. Zhou, and S. Zhou, "Large-Girth Nonbinary QC-LDPC Codes of Various Lengths," IEEE Trans. on Communications, 2010 (to appear).
3. Z. Zhou, J.-H. Cui, and S. Zhou, ``Efficient Localization for Large-Scale Underwater Sensor Networks," Ad Hoc Networks, vol. 8, no. 3, May 2010.
4. J. Huang, S. Zhou, and P. Willett, ``Structure, Property, and Design of Nonbinary Regular Cycle Codes," IEEE Transactions on Communications, vol. 58, no. 4, April 2010.
5. C. R. Berger, S. Zhou, J. Preisig, and P. Willett, ``Sparse Channel Estimation for Multicarrier Underwater Acoustic Communication: From Subspace Methods to Compressed Sensing,"IEEE Trans. Signal Process., vol. 58, no. 3, pp. 1708--1721, Mar. 2010.
6. Z.-H. Wang, S. Zhou, J. Catipovic, and J. Huang, "OFDM in Deep Water Acoustic Channels with Extremely Long Delay Spread," in Proc. of the ACM International Workshop on UnderWater Networks (WUWNet), Woods Hole, MA, September 31, 2010.

7. P. Carroll, S. Zhou, H. Zhou, J.-H. Cui, and P. Willett, "Underwater Localization Based on Multicarrier Waveforms," in Proc. of MTS/IEEE OCEANS Conference, Seattle, Washington, September 20-23, 2010.
8. Z.-H. Wang, S. Zhou, J. Catipovic, and J. Huang, "A Factor-Graph based ZP-OFDM Receiver for Deep Water Acoustic Channels," in Proc. of MTS/IEEE OCEANS Conference, Seattle, Washington, September 20-23, 2010.
9. W. Chen, J. Huang, Z.-H. Wang, and S. Zhou, "Blind Channel Shortening for Zero-Padded OFDM," in Proc. of MTS/IEEE OCEANS Conference, Seattle, Washington, September 20-23, 2010.
10. R. Georgescu, J.-Z. Huang, D. Crouse, S. Choi, S. Zhou, and Peter Willett, ``Acoustic channel tracking with the cardinalized probability hypothesis density filter and the multiple hypothesis tracker," Proc. of European Underwater Acoustics Conference (ECUA), Istanbul, Turkey, July 5-9, 2010.
11. J.-Z. Huang, S. Zhou, J. Huang, C. R. Berger, and P. Willett, ``Progressive inter-carrier interference equalization for OFDM transmission over time-varying underwater acoustic channels," in Proc. of MTS/IEEE OCEANS Conference, Sydney, Australia, May 24--27, 2010.
12. J.-Z. Huang, C. R. Berger, S. Zhou, and J. Huang, ``Comparison of basis pursuit algorithms for sparse channel estimation in underwater acoustic OFDM," in Proc. of MTS/IEEE OCEANS Conference, Sydney, Australia, May 24--27, 2010.
13. J. Huang, S. Zhou, and P. Willett, ``Near-Shannon-Limit Linear-Time-Encodable Nonbinary Irregular LDPC Codes," in Proc. of Global Telecommunications Conf., Honolulu, Hawaii, USA, Nov. 30-Dec. 4, 2009.

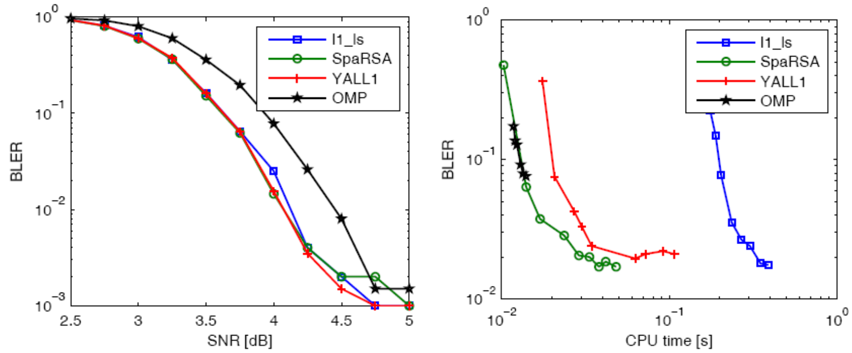


Figure 1.Comparion of different basis-pursuit algorithms. Left: Block error rate vs signal to noise ratio. Right: Block error rate as a function of complexity (running time).

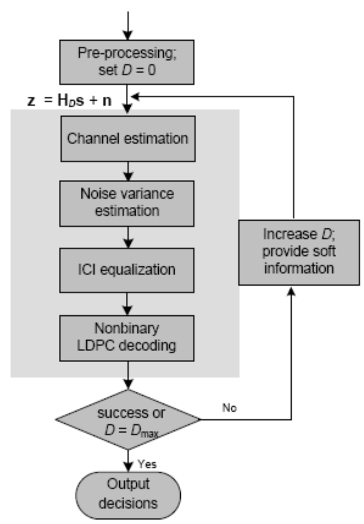
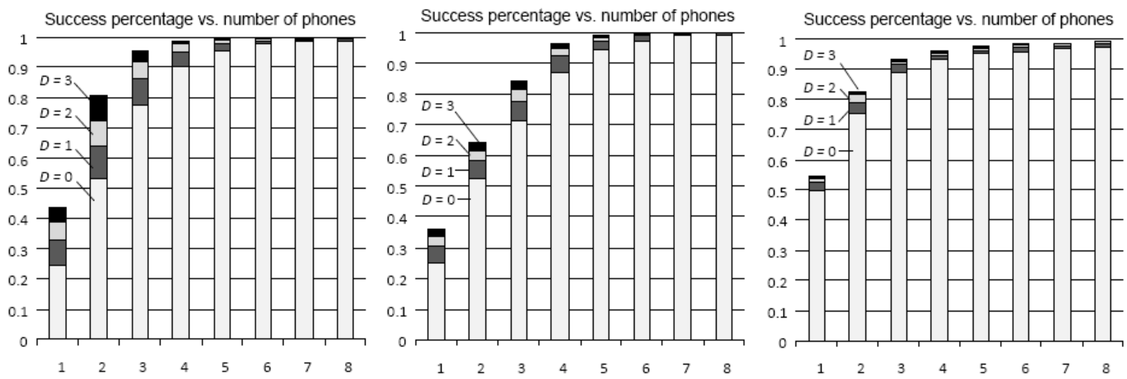


Figure 2: The progressive receiver structure.



(a) S1 (60 m) (b) S3 (200 m) (c) S5 (1000 m)

Figure 3: The block success percentage averaged over Julian dates 295-302, SPACE08 experiment, using the proposed progressive receiver structure.

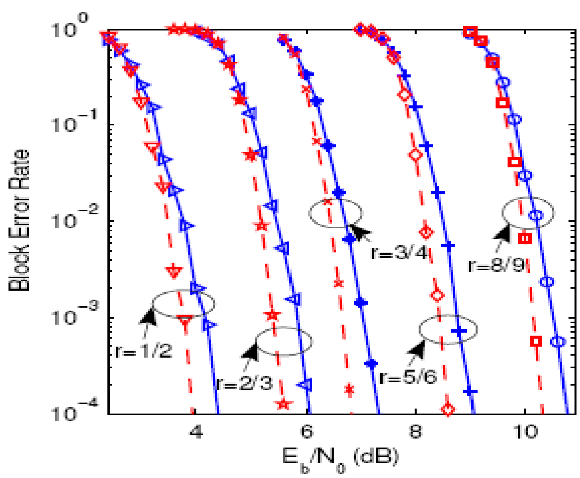


Figure 4. Performance of rate-compatible nonbinary QC-LDPC codes of various lengths over Rayleigh fading channel. Solid and dashed curves correspond to two sets of codes.

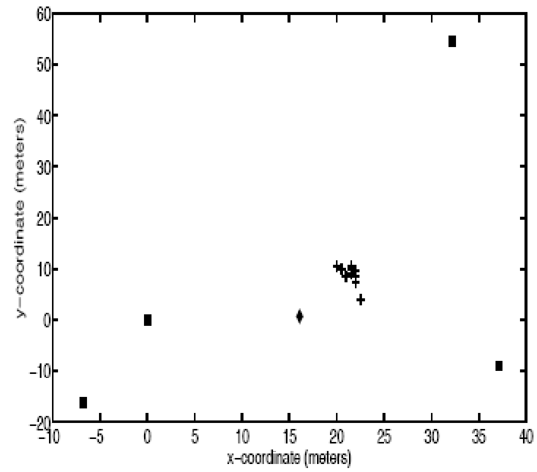


Figure 5. Node deployment in a local lake. The transmitters are denoted by squares and the receiver by the diamond. The scattered plus signs stand for the estimates.

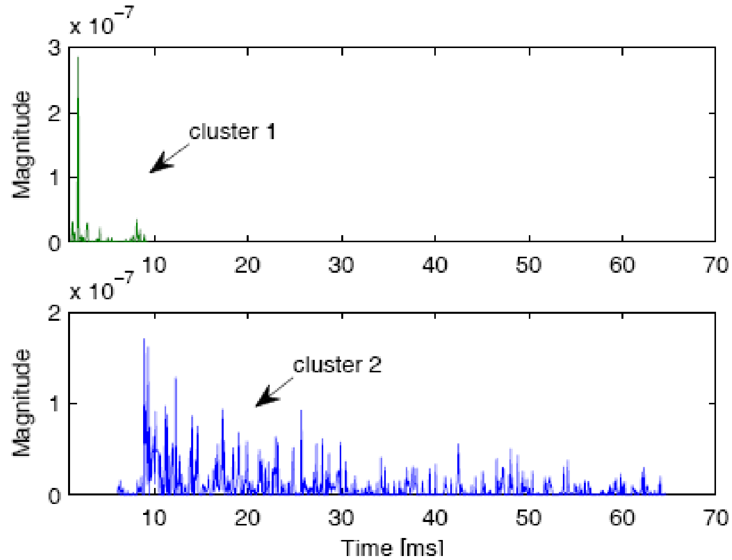


Figure 6. Channel estimation results at one sensor in the deep-water environment.