

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

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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.

WORK COMPLETED

In this year, we continue to develop advanced receiver algorithms, with real data sets from experiments done in previous years (SPACE08 and MACE10).

We have also participated an experiment near the Kaohsiung city, Taiwan, in May 2013, led by National Sun Yat-sen University and University of Connecticut.

We continue to interact with Dr. Josko Catipovic to develop receiver algorithms for interference cancellation to improve operations in the Atlantic Undersea Test and Evaluation Center (AUTEC). A data collection experiment was carried out in September 2013.

We have integrated advanced networking protocols to the OFDM modem prototypes.

We have supervised seven undergraduate students into research through their senior design projects:

- Project: “Field Tests and Comparisons of Underwater Network Localization Solutions”. Duration: Fall 2012-Spring 2013. Team Members: Tausif Shaikh, Johanna Thomas, Patrick Lazar, Kaleel Mahmood.
- Project: “Autonomous Underwater Vehicle Control Through Underwater Acoustics Communications”. Duration: Fall 2012-Spring 2013. Team Members: Connor Burns, Joseph Folz, Michael Daukas.

RESULTS

We next highlight our progresses made on the following topics, arranged in three different categories.

Receiver design:

- 1) Per-survivor processing for underwater direct-sequence spread spectrum communications;
- 2) Study of class-d power amplifiers for underwater acoustic OFDM transmissions;

- 3) Joint carrier frequency offset and impulsive noise estimation for underwater acoustic OFDM with null subcarriers;
- 4) Joint linear precoding and nonbinary LDPC coding for underwater acoustic OFDM.

Channel and network coding:

- 5) A New Iterative LT Decoding Algorithm for Binary and Nonbinary Galois Fields;
- 6) A Nonbinary LDPC Decoder Architecture with Adaptive Message Control;
- 7) Dynamic network coded cooperative OFDM for underwater data collection.

Localization, Networking, and Testbed:

- 8) On-demand collaborative localization for underwater sensor networks;
- 9) Outage performance of a distributed antenna system in underwater acoustic channels;
- 10) Dynamic block-cycling over a linear network in underwater acoustic channels;
- 11) Long Island Sound testbed and experiments.

1) Per-survivor processing for underwater acoustic direct-sequence spread spectrum communications.

This paper proposes a receiver for direct-sequence spread spectrum transmissions in underwater acoustic channels, which combines a per-survivor processing (PSP) structure with sparse channel estimation. Specifically, the PSP structure establishes the trellis on the symbol level to render a small to moderate number of states, thus reducing the computational complexity. Meanwhile, the sparse channel estimation is performed on the chip level, where the orthogonal matching pursuit algorithm is used and a two-dimensional grid of path delay and Doppler scaling factor is incorporated in the dictionary construction. The effective combination of the PSP detection and sparse channel estimation achieves a good tradeoff between performance and complexity. Simulation and experiment results show that the proposed receiver outperforms the conventional RAKE receiver considerably, and most importantly, the proposed PSP receiver with an exact wideband dictionary maintains an excellent performance even for challenging underwater acoustic channels with large Doppler disparities on different paths. A comparison can be found in Figure 1.

2) Study of class-d power amplifiers for underwater acoustic OFDM transmissions. In this work, we investigate the power amplifier design for underwater acoustic OFDM systems. Using the pilot signal to noise ratio (PSNR) of an OFDM signal as the design criterion, we study the impact of the modulation frequency and the number of quantization bits for the class-D power amplifiers. Experimental results, obtained using the setup shown in Figure 2, show that there is PSNR performance ceiling as the number of quantization bits increases.

3) Joint carrier frequency offset and impulsive noise estimation for underwater acoustic OFDM with null subcarriers. This work studies orthogonal-frequency-division-multiplexing (OFDM) transmissions over underwater acoustic channels in the presence of impulsive noise. Based on the measurements on the null subcarriers, we first present a non-iterative receiver that estimates the residual Doppler shift and the impulsive noise either separately or jointly. Based on the available channel estimate and tentative data symbol decisions, an iterative receiver is further developed with separate Doppler shift and impulsive noise estimation using measurements on null subcarriers, or with joint Doppler shift and impulsive noise estimation using measurements on all subcarriers. Simulation

and experimental results demonstrate that the proposed receivers are effective, considerably outperforming a benchmark receiver using the clipping method for impulsive noise reduction and the null-subcarrier based method for Doppler shift compensation; see e.g., Figure 3.

4) *Joint linear precoding and nonbinary LDPC coding for underwater acoustic OFDM.* Both channel coding over a finite field and linear precoding over a complex field can improve the system performance in wireless fading channels. In this work, we investigate the potential benefit of linear precoding in a nonbinary LDPC coded underwater acoustic OFDM system. Real precoders of small sizes are selected in different setups, in order to avoid any complexity increase at the receiver. Simulations and emulated experimental results demonstrate the benefits of linear precoding, particularly when the receiver has a small number of hydrophones; see e.g., Figure 4.

5) *A New Iterative LT Decoding Algorithm for Binary and Nonbinary Galois Fields.* Digital fountain codes are record-breaking codes for erasure channels. Most existing digital fountain codes operate over binary fields using an iterative belief-propagation (BP) decoding algorithm. In this work, we propose a new iterative decoding algorithm for both binary and nonbinary fields. The basic form of our proposed algorithm considers both degree-1 and degree-2 check nodes (instead of only degree-1 check nodes as in the original BP decoding scheme), and has linear complexity. Extensive simulation demonstrates that it outperforms the original BP decoding scheme, especially for a small number of source packets. The enhanced form of the proposed algorithm combines the basic form of the algorithm and a guess-based algorithm to further improve the decoding performance. Simulation results (e.g., Figure 5) demonstrate that it can provide better decoding performance than the guess-based algorithm with fewer guesses, and can achieve decoding performance close to that of the maximum likelihood decoder at a much lower decoding complexity.

6) *A Nonbinary LDPC Decoder Architecture with Adaptive Message Control.* A new decoder architecture for nonbinary low-density paritycheck (LDPC) codes is presented, as shown in Figure 6, to reduce the hardware operational complexity in VLSI implementations. The low decoding complexity is achieved by employing adaptive message control (AMC) that dynamically trims the message length of belief information to reduce the amount of memory accesses and arithmetic operations. To implement the proposed AMC, we develop the architecture of a horizontal sequential nonbinary LDPC decoder. Key components in the architecture have been designed with the consideration of variable message lengths to leverage the benefit of the proposed AMC. Simulation results demonstrate that the proposed nonbinary LDPC decoder architecture can significantly reduce hardware operations and power consumption as compared with existing work with negligible performance degradation.

7) *Dynamic network coded cooperative OFDM for underwater data collection.* This work considers an underwater data collection problem, where multiple underwater nodes need to send data to one common destination, as shown in Figure 7. With the conventional ARQ protocol, the destination requests retransmission from each node individually without any node cooperation. We propose two protocols, selective relay cooperation and dynamic network coded cooperation, utilizing the fact that underwater nodes can overhear the transmission of others. In the selective relay cooperation, one node can be selected as a relay to transmit the data from another undecoded node in the retransmission round. In the network coded cooperation, the selected relay nodes transmit network coded packets, combining the packets from several undecoded nodes to the destination. The relay nodes participating the cooperation are selected by the destination based on the measured pilot signal to noise ratio of the underlying OFDM modulation. Simulation results, as shown in Figure 7, based on one specific

underwater topology show that the proposed schemes can achieve significant gains compared with the conventional ARQ scheme.

8) *On-demand collaborative localization for underwater sensor networks.* This work considers the issue of localization in the context of underwater sensor networks which contain anchor nodes with perfect knowledge of their position, but asynchronous clocks. By taking advantage of a sequential broadcasting protocol the entire network can be localized simultaneously with minimal overhead. Additionally, it can be initiated by any node at any time. The localization protocol is illustrated in Figure 8. Through extensive simulation we have verified these claims, and further shown that both initiator and passive nodes can achieve low-error positioning.

9) *Outage performance of a distributed antenna system in underwater acoustic channels.* The distributed antenna system (DAS) has been known for providing a large coverage and throughput in terrestrial radio environments. This work investigates the benefits of DAS relative to the centralized antenna system (CAS) in underwater acoustic (UWA) environments. In particular, we analyze the outage performance in the wideband uplink transmissions. Based on theoretical derivation and numerical results, we show that in a medium transmission SNR regime, DAS outperforms CAS in both single-user and multiuser systems. To address the cochannel interference in the multiuser DAS, we suggest a multicell structure, which is shown having a lower outage error floor relative to the structure which takes the operational area as a single cell.

10) *Dynamic block-cycling over a linear network in underwater acoustic channels.* This work proposes a dynamic cooperative relaying protocol, termed dynamic block-cycling (DBC) protocol, for a UWA linear network. Considering large channel variations, we assume one node can hear from not only its direct but also several remote neighbors. A transmission package with multiple blocks is taken as one relay unit, where an erasure-correction code and an error-correction code are used for inter-block encoding and intra-block encoding, respectively. During the relaying process, each node in the proposed protocol starts relaying immediately after it decodes the relayed message, hence a reduced end-to-end transmission latency can be achieved. Meanwhile, to avoid the overhead for relay cooperation, the relays' transmissions are cyclically synchronized, such that in each time slot, the blocks arriving at the downstream receiving nodes from all the upstream transmitting nodes have the same block index. The DBC protocol is illustrated in Figure 10. Numerical results show that for a one-shot transmission, the proposed protocol achieves a reduced end-to-end delay relative to existing protocols while maintaining a decent outage performance.

11) *Long Island Sound testbed and experiments.* To effectively evaluate the performance of underwater wireless network and develop applications in real environments, an offshore testbed has been developed to conduct field experiments. The testbed consists of four nodes and has been deployed two times in Long Island Sound since Aug. 2012. The surface buoy is shown in Figure 11, and the locations of the two deployments are shown in Figure 12. Using this testbed, we evaluated and analyzed the performance of both link and physical layers of an underwater wireless network. The power consumptions of testbed components in different modes were also measured. From the testbed and field experiments, we learn lessons by first-hand experience which will be helpful in improving the testbed and for a better understanding of how underwater wireless networks work in real world scenarios.

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.

PUBLICATIONS

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2. J. Liu, Z.-H. Wang, M. Zuba, Z. Peng, J.-H. Cui, and S. Zhou, "DA-Sync: A Doppler Assisted Time Synchronization Scheme for Mobile Underwater Sensor Networks," *IEEE Transactions on Mobile Computing*, 2013 [In press].
3. X. Xu, S. Zhou, A. Morozov, J. Preisig, "Per-survivor processing for underwater acoustic direct-sequence spread spectrum communications," *Journal of Acoustical Society of America*, 2012. vol. 133, no. 5, May 2013.
4. J.-H. Huang, S. Zhou, Z.-H. Wang, "Performance Results of Two Iterative Receivers for Distributed MIMO-OFDM with Large Doppler Deviations," *IEEE Journal of Oceanic Engineering*, vol. 48, no. 2, pp. 3694 -- 3702, Apr. 2013.
5. Z.-H. Wang, S. Zhou, J. Catipovic, P. Willett, "Asynchronous Multiuser Reception for OFDM in Underwater Acoustic Communications," *IEEE Transactions on Wireless Communications*, vol. 12, no. 3, pp. 1050 -- 1061, Mar. 2013.
6. Z.-H. Wang, J. Huang, S. Zhou, and Z. Wang, "Iterative Receiver Processing for OFDM Modulated Physical-Layer Network Coding in Underwater Acoustic Channels," *IEEE Trans. on Communications*, vol. 61, no. 2, pp. 541 -- 553, Feb. 2013.
7. W. Tang, J. Huang, L. Wang, and S. Zhou, "A Nonbinary LDPC Decoder Architecture with Adaptive Message Control," *IEEE Transactions on Very Large Scale Integration Systems*, vol. 20, no. 11, pp. 2118 -- 2122, Nov. 2012.
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10. J. Song, S. Gupta, J. Hare, and S. Zhou, "Adaptive cleaning of oil spills by autonomous vehicles under partial information," in *Proc. of IEEE/MTS OCEANS conference*, San Diego, CA, Sept. 23-26, 2013.
11. X. Xu, S. Zhou, K. Mahmood, L. Wei, and J.-H. Cui, "Study of class-D power amplifiers for underwater acoustic ofdm transmissions," in *Proc. of IEEE/MTS OCEANS conference*, San Diego, CA, Sept. 23-26, 2013.
12. Z. Zhao, J.-H. C. P. Zhang, and S. Zhou, "Life-oriented control of tidal power generation," in *Proc. of IEEE/MTS OCEANS conference*, San Diego, CA, Sept. 23-26, 2013.

13. Z.-H. Wang, S. Zhou, Z. Wang, J. Catipovic, and P. Willett, "Outage performance of a distributed antenna system in underwater acoustic channels," in Proc. of the Asilomar Conference on Signals, Systems and Computers, Asilomar, California, Nov. 4-7, 2012.
14. Z.-H. Wang, S. Zhou, Z. Wang, B. Wang, and P. Willett, "Dynamic block-cycling over a linear network in underwater acoustic channels," in Proc. of the 7th ACM International Conference on UnderWater Networks and Systems (WUWNet), Los Angeles, CA, Nov. 5-6, 2012.
15. S. Gupta, J. Hare, and S. Zhou, "Cooperative coverage using autonomous underwater vehicles in unknown environments," in Proc. of IEEE/MTS OCEANS conference, Hampton Roads, Virginia, Oct. 14-19, 2012.
16. P. Carroll, S. Zhou, K. Mahmood, H. Zhou, X. Xu, and J.-H. Cui, "On-demand collaborative localization for underwater sensor networks," in Proc. of IEEE/MTS OCEANS conference, Hampton Roads, Virginia, Oct. 14-19, 2012.
17. H. Sun, W. Shen, Z.-H. Wang, S. Zhou, X. Xu, and Y. Chen, "Joint carrier frequency offset and impulsive noise estimation for underwater acoustic OFDM with null subcarriers," in Proc. of IEEE/MTS OCEANS conference, Hampton Roads, Virginia, Oct. 14-19, 2012.
18. Y. Chen, H. Sun, L. Wan, Z.-H. Wang, S. Zhou, and X. Xu, "Dynamic network coded cooperative OFDM for underwater data collection," in Proc. of IEEE/MTS OCEANS conference, Hampton Roads, Virginia, Oct. 14-19, 2012.
19. L. Wan, S. Hurst, Z.-H. Wang, S. Zhou, Z. Shi, and S. Roy, "Joint linear precoding and nonbinary LDPC coding for underwater acoustic OFDM," in Proc. of IEEE/MTS OCEANS conference, Hampton Roads, Virginia, Oct. 14-19, 2012.

HONORS/AWARDS/PRIZES

Shengli Zhou has been promoted to full professor, starting Fall 2013.

Dr. Zhaohui Wang, a former graduate student supported on this project, won the 2013 Woman of Innovation Award in the category of Collegian Innovation and Leadership by the Connecticut Technology Council.

Dr. Zhaohui Wang joined the faculty of the Department of Electrical and Computer Engineering at Michigan Technological University in August, 2013.

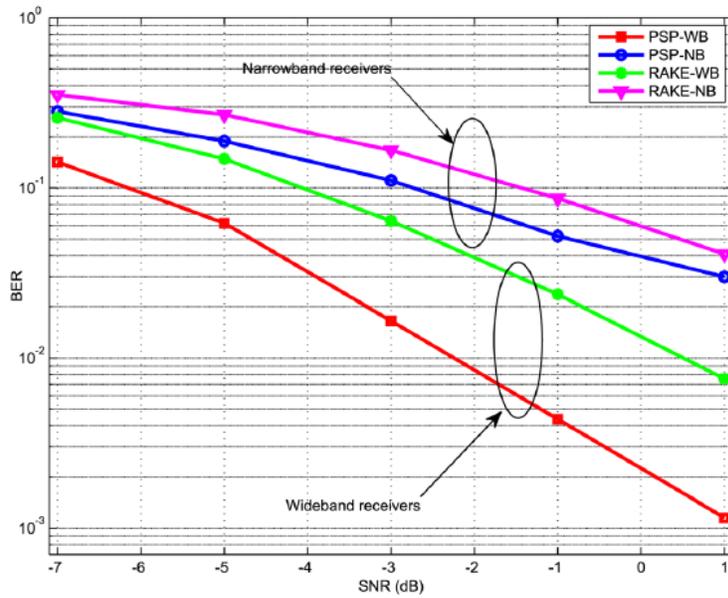


Figure 1. Experimental results: Performance comparison of receivers and narrowband receivers without Doppler scale estimation, with the resampled data having a relative Doppler speed 2 m/s.

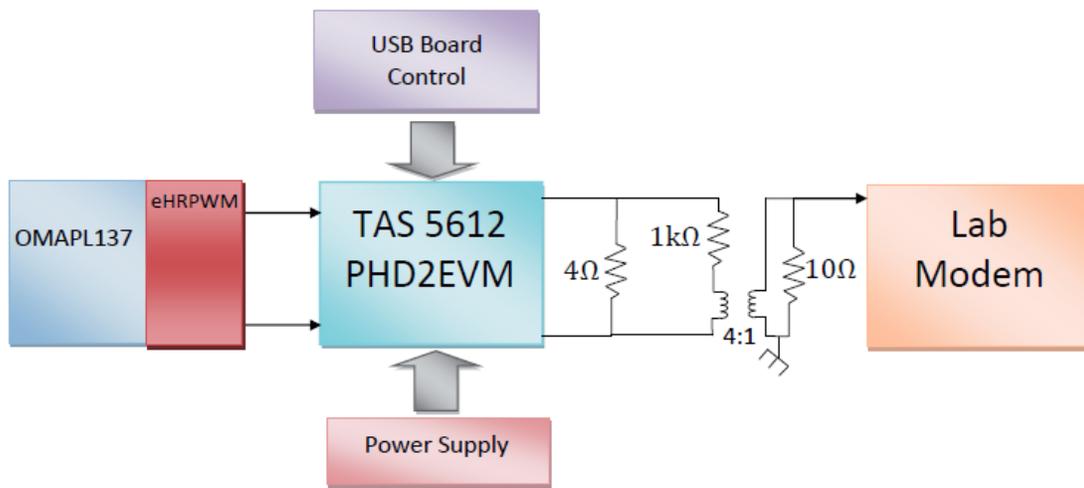


Figure 2. Experimental setup to study the class-D power amplifier.

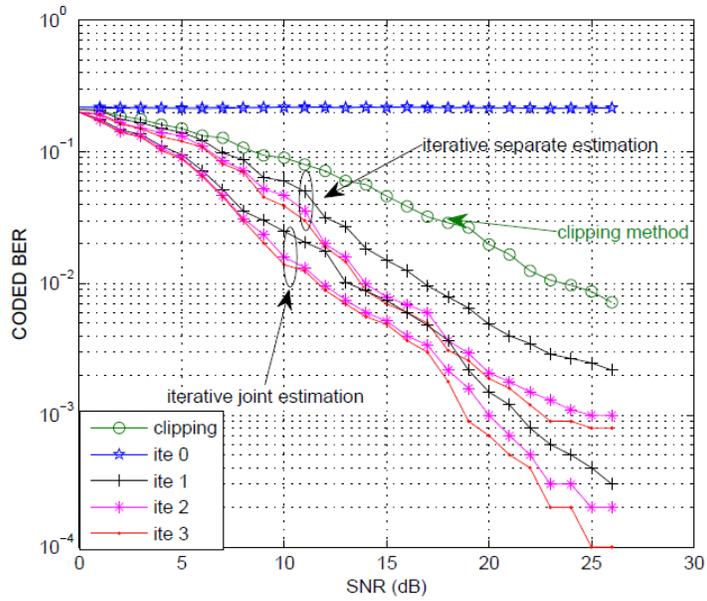


Figure 3. Bit error rate of the iterative separate and iterative joint estimation methods for Doppler shift compensation and impulse noise mitigation.

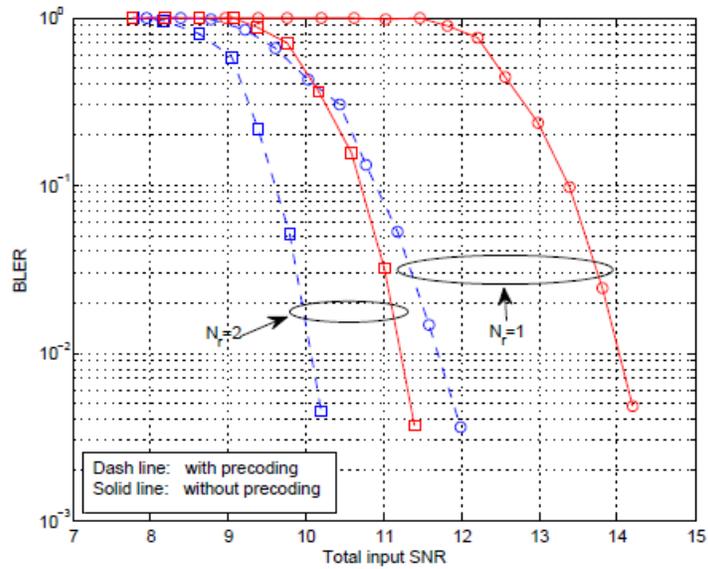


Figure 4. Performance comparison of OFDM system with and without linear precoding.

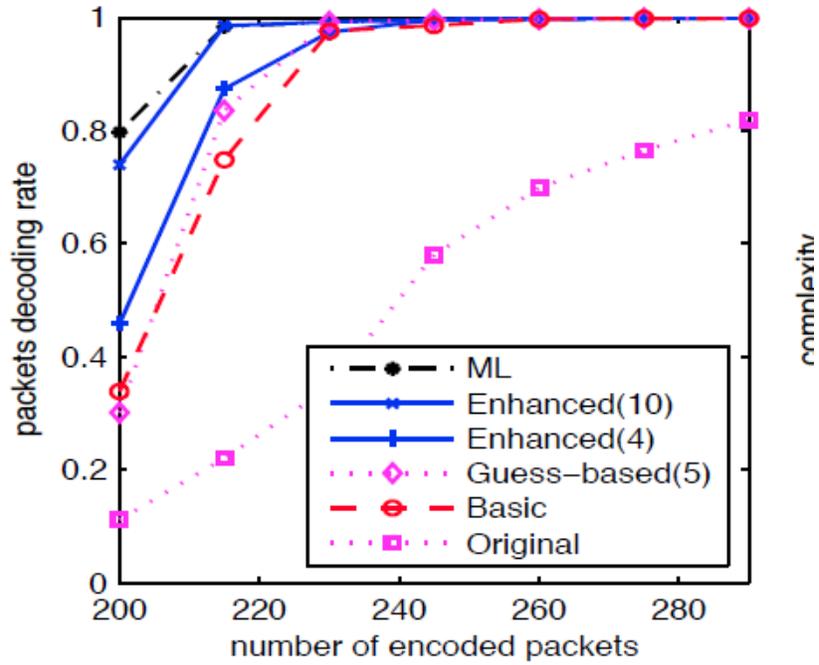


Figure 5. Performance of the proposed LT decoding algorithm and the guess-based algorithm in the binary field under the MBMS degree distribution, $k = 200$ and n is varied from 200 to 295.

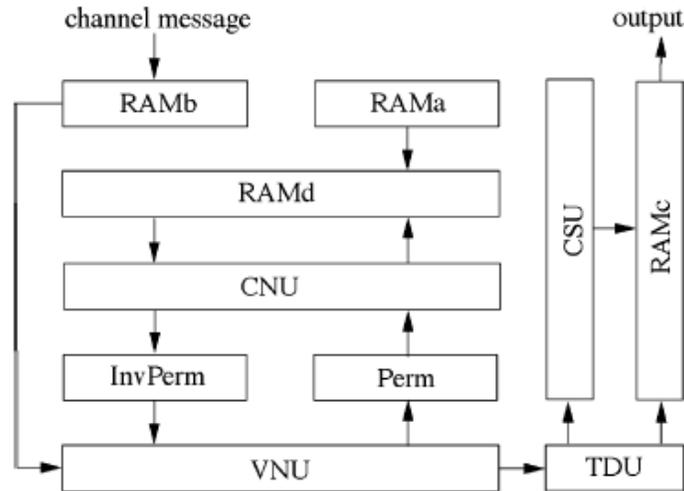


Figure 6. Top-level block diagram of the horizontal nonbinary LDPC decoder employing the adaptive message control (AMC).

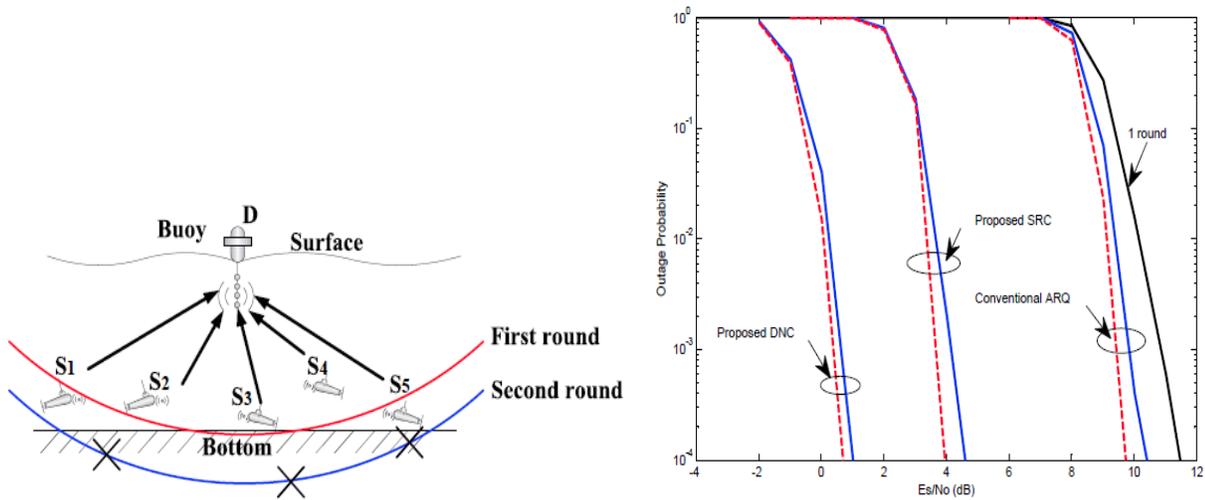


Figure 7. Left: The system setup for a surface buoy to collect data from bottom sensors. Right: The performance improvement for the proposed networked coded transmission.

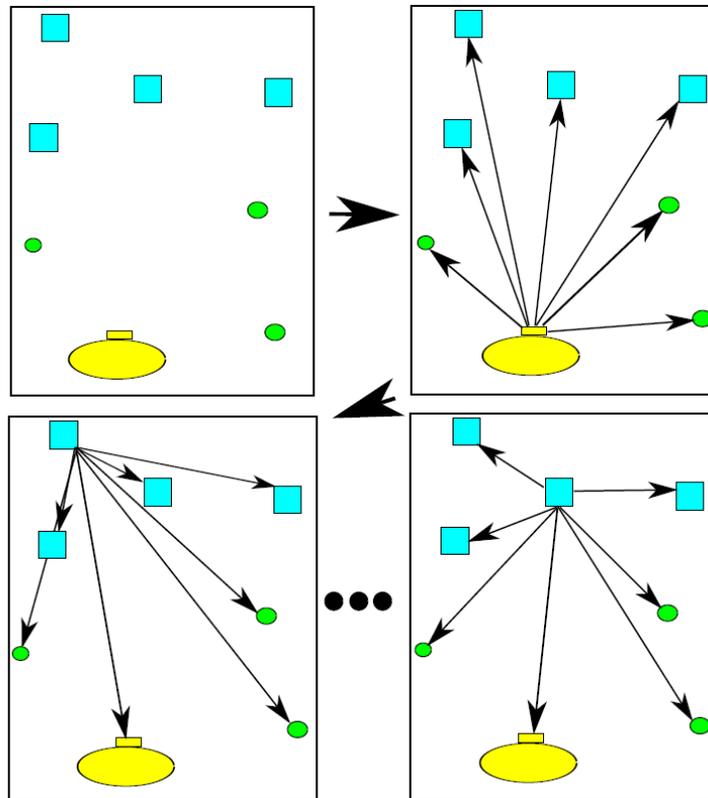


Figure 8. A brief overview of the transmission protocol in a sample network. The AUV initiates a transmission to all nodes, subsequently receiving a reply from the first anchor node. As time passes, all anchors reply sequentially until the AUV is finally localized.

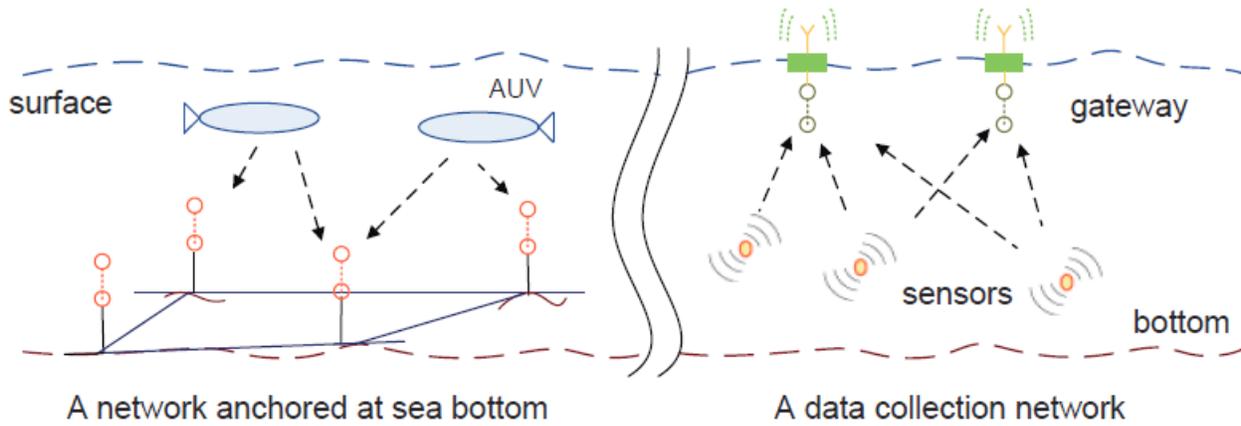


Figure 9. Two examples of underwater distributed antenna system (DAS) topologies. The nodes anchored at sea bottom in the first network are connected to a control center via cables. The gateways in the second network can communicate with each other using radios.

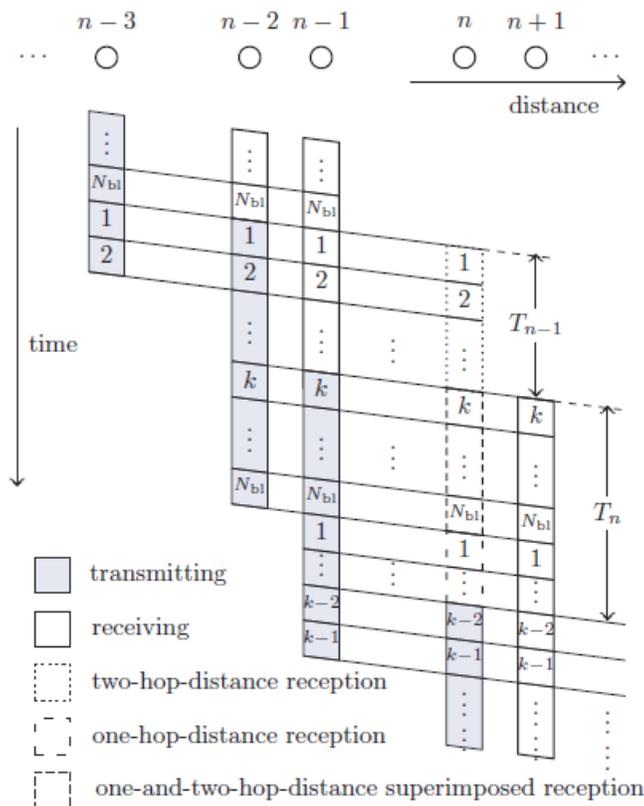


Figure 10. Illustration of the cyclically synchronized transmission over a non-equally spaced linear network at node n with three temporal progressive listening phases. Two-hop communication distance is assumed as an example.

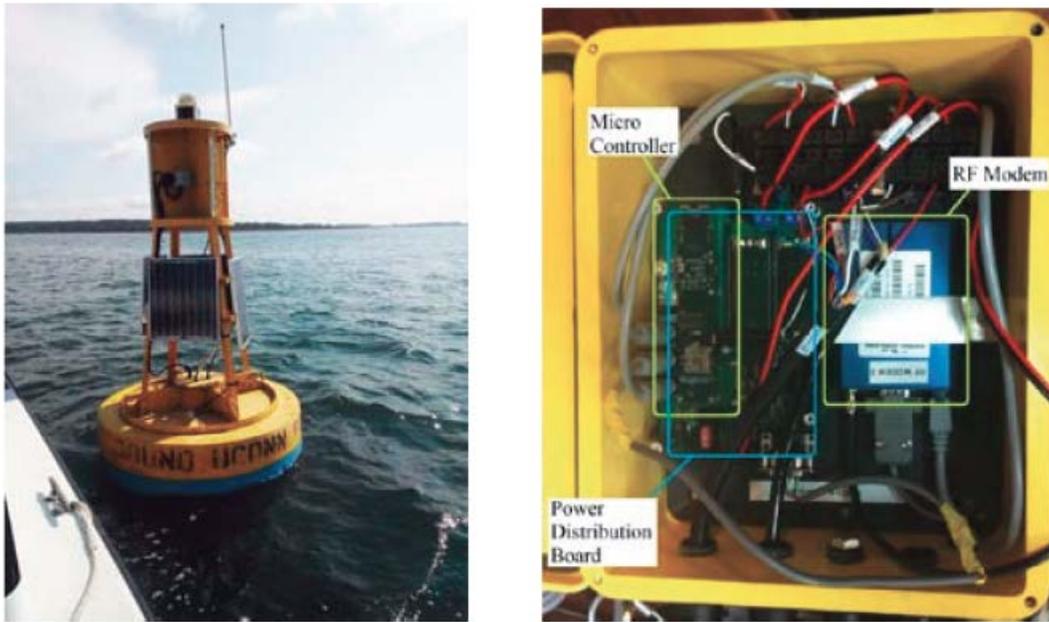


Figure 11 The buoy deployed for the network testbed. The yellow box contains various electronics.

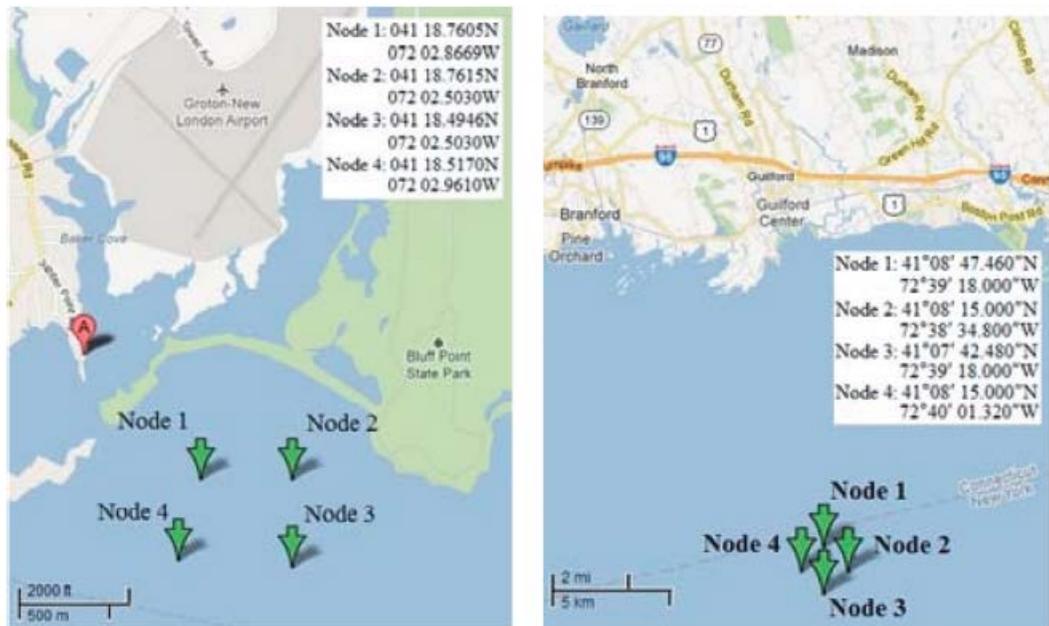


Figure 12 The locations of two deployments in the Long Island Sound, Aug. and Dec. 2012.