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

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## 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 collected in the following two major experiments.

1) SPACE08 experiment, Martha's Vineyard, MA, Oct. 2008 (led by Dr. James Preisig)
2) MACE10 experiment, Martha's Vineyard, MA, July 23, 2010. (led by Mr. Lee Freitag).

We have also participated an experiment held by Naval Research Laboratory, Sept. 4-12, 2012, near New Jersey.

We continue to interact with Dr. Josko Catipovic to develop receiver algorithms for OFDM in deep water channels with very large delay spread and external interference. 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 and March 2010.

We have started to integrate advanced networking protocols to the OFDM modem prototypes. Initial tests have been conducted in the water tank and swimming pools.

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

- Project: "Communication Over Non-Ideal Signal Channels". Duration: Fall 2011-Spring 2012. Team Members: Tyler Avery, Tim Jakubiak, and Andre Silva.
- Project: "Underwater Sensor Networks". Duration: Fall 2011-Spring 2012. Team Members: Andrew Mueller, Francis Obst, and Jason Prosco.

## RESULTS

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

***OFDM receiver design:***

1) Robust Initialization with Reduced Pilot Overhead for Progressive OFDM Receivers.
2) Frequency-Domain Oversampling for Zero-Padded OFDM Receivers.
3) Parameterizing both path amplitude and delay variations of underwater acoustic channels for block decoding of orthogonal frequency division multiplexing
4) Performance Comparison of Doppler Scale Estimation Methods for Underwater OFDM
5) Two Iterative Receivers for Distributed MIMO-OFDM with Large Doppler Deviations.
6) Asynchronous Multiuser Reception for OFDM in Underwater Acoustic Communications,

***Channel and netowrk coding:***

7) Computing the Minimum Distance of Nonbinary LDPC Codes --
8) Nonbinary Multiple Rate QC-LDPC Codes With Fixed Information or Block Bit Length,
9) Design of nonbinary quasi-cyclic LDPC codes by maximising the minimum distance
10) A Joint Network-Channel Coding Scheme for Reliable Communication in Wireless Networks

***Networking:***

11) A Time Synchronization Scheme for Mobile Underwater Sensor Networks

*1) Robust Initialization with Reduced Pilot Overhead for Progressive Underwater Acoustic OFDM Receivers.* In the past years, we have proposed a progressive receiver to mitigate the intercarrier interference (ICI) in orthogonal-frequency-division-multiplexing (OFDM) transmissions over underwater acoustic (UWA) channels, where the ICI span gradually increases during the receiver iterations. Operating on a block-by-block basis, the progressive receiver is initialized by measurements on pilot subcarriers inserted in each OFDM block. In this work, we propose an initialization method that exploits channel correlation across blocks to reduce the number of pilots needed, as shown in Figure 1. Performance results based on data recorded in SPACE08 and MACE10 experiments demonstrate the robust system performance with reduced number of pilots, where the transmitter in SPACE08 was stationary and that in MACE10 was slowly moving; see Figure 2. Extension to the progressive receiver for multi-input multi-output (MIMO) OFDM is also pursued, where it is shown that the proposed hybrid initialization enables drastically improved receiver performance with a small number of pilots per transmitter.

*2) Frequency-Domain Oversampling for Zero-Padded OFDM in Underwater Acoustic Communications.* Although time-domain oversampling of the received baseband signal is common for single-carrier transmissions, the counterpart of frequency-domain oversampling is rarely used for multicarrier transmissions. This is because frequency-domain oversampling cannot be taken advantage of, when using the commonly used low-complexity receiver that assumes orthogonal subcarriers. In this work, we explore frequency-domain oversampling to improve the system performance of zero-padded orthogonal frequency division multiplexing transmissions over underwater acoustic channels with large Doppler spread. On these channels intercarrier interference has to be addressed explicitly via frequency-domain equalization, which enables inclusion of additional frequency samples at little increased complexity. Based on both simulation and experimental results, e.g., as shown in Figure 3, we observe that the receiver with frequency-domain oversampling outperforms the conventional one considerably, where the gain increases as the Doppler spread increases.

*3) Parameterizing both path amplitude and delay variations of underwater acoustic channels for block decoding of OFDM.* There are no commonly-agreed mathematical models for the input-output relationship of underwater acoustic channels. For each path in a time-varying multipath channel within a short period of time (e.g., one short data block), this work proposes to use one polynomial to approximate the amplitude variation and another polynomial up to the first order to approximate the delay variation within a block duration. Under such a channel parameterization, the discrete-time channel input-output relationship tailored to zero-padded OFDM transmissions is then derived, based on which an OFDM receiver is validated using experimental data collected during the SPACE08 experiment. For channels with a short coherence time, the numerical results show that incorporating both the amplitude and delay variations improves the system performance; see Figure 4.

*4) Performance Comparison of Doppler Scale Estimation Methods for Underwater Acoustic OFDM.* Doppler scale estimation is one critical step needed by the resampling operation in acoustic communication receivers. In this work, we compare different Doppler scale estimation methods using either cyclic-prefixed (CP) or zero-padded (ZP) orthogonal-frequency division-multiplexing (OFDM) waveforms. For a CP-OFDM preamble, a self-correlation method allows for blind Doppler scale estimation based on an embedded repetition structure while a cross-correlation method is available with the knowledge of the waveform. For each received ZP-OFDM block, the existence of null subcarriers allows for blind Doppler scale estimation, while a cross-correlation based approach can use either a template constructed from pilot subcarriers only or from all subcarriers after data decoding. This paper carries out extensive comparison among these methods using both simulated and real experimental data; see one example plot in Figure 5. Further,the applicability of these methods to distributed multiuser systems are investigated.

*5) Two Iterative Receivers for Distributed MIMO-OFDM with Large Doppler Deviations.*
This work studies a distributed system with multiple quasi-synchronous users, where different users may transmit different numbers of parallel OFDM data streams. The distinction from most existing work is that the multipath channels for different users have significantly different Doppler scales. Such a setting with two single-transmitter users was first studied in a recent publication by Tu et al, 2010. This work presents two iterative receivers, termed as multiuser detection (MUD)-based and single-user detection (SUD)-based receivers, respectively. The MUD-based receiver in Figure 6 adopts a frequency-domain oversampling front-end on each receive element, then performs channel estimation and data detection jointly for all data streams. The SUD-based receiver in Figure 7 adopts conventional single-user processing modules, but adds a critical step of multiuser interference (MUI) cancellation, where the MUI reconstruction explicitly considers different resampling factors used by different users. Experimental data sets from MACE10 and SPACE08 are used to emulate a distributed OFDM system with different numbers of users and different numbers of data streams per user. Performance results in different settings validate the effectiveness of the proposed iterative receivers; see e.g., Figure 8.

*6) Asynchronous Multiuser Reception for OFDM in Underwater Acoustic Communications.* Recently significant progress has been made on point-to-point underwater acoustic communications, and the interest has grown on the application of those techniques in multiuser communication settings, where the asynchronous nature of multiuser communication poses a grand challenge; see e.g., Figure 9. This work develops a time-asynchronous multiuser reception approach for orthogonal frequency division multiplexing (OFDM) transmissions in underwater acoustic channels. The received data burst is segmented and apportioned to multiple processing units in an overlapped fashion, where the length of the processing unit depends on the maximum asynchronism among users on the OFDM block level, as shown in Figure 10**.** Interference cancellation is adopted to reduce the interblock interference between overlapped processing units. Within each processing unit, the residual inter-block interference from multiple users is aggregated as one external interference which can be parameterized. Multiuser channel estimation, data detection, and interference mitigation are then carried out in an iterative fashion. Simulation and emulated experimental results demonstrate the robustness of the proposed receiver with signal asynchronism among multiple users in both time-invariant and time-varying environments, see e.g., Figure 11.

*7) Computing the Minimum Distance of Nonbinary LDPC Codes.* Finding the minimum distance of low-density-parity-check (LDPC) codes is an NP-hard problem. Different from all existing works that focus on binary LDPC codes, we in this work aim to compute the minimum distance of nonbinary LDPC codes, motivated by the fact that operating in a large Galois field provides one important degree of freedom to achieve both good waterfall and error-floor performance. Our method is based on the existing nearest nonzero codeword search (NNCS) method, but several modifications are incorporated for nonbinary LDPC codes, including the modified error impulse pattern, the dithering method, and the nonbinary decoder. Numerical results on the estimated minimum distances show that a code's minimum distance can be increased by careful selection of nonzero elements of the parity check matrix, or by increasing the mean column weight, or by increasing the size of the Galois field; see e.g., Figure 12.

*8) Nonbinary Multiple Rate QC-LDPC Codes With Fixed Information or Block Bit Length.* In this work, we consider nonbinary quasi-cyclic low-density parity-check (QC-LDPC) codes and propose a method to design multiple rate codes with either fixed information bit length or block bit length, tailored to different scenarios in wireless applications. We show that the proposed codes achieve good performance over a broad range of code rates, see e.g., Figure 13.

*9) Design of nonbinary quasi-cyclic low-density parity-check codes by maximising the minimum distance.* In this work, we propose a construction method of nonbinary quasi-cyclic low-density parity-check (QC-LDPC) codes. The shift offset values of the circulant permutation sub-matrices are selected to maximize the minimum distance upper bound instead of girth. The proposed method provides a more rational optimization way than maximizing the girth, as shown in e.g., Figure 14.

*10) A Practical Joint Network-Channel Coding Scheme for Reliable Communication in Wireless Networks.* In this work, we propose a practical scheme, Non-Binary Joint Network-Channel Coding (NB-JNCC), for reliable multi-path multi-hop communication in arbitrary large-scale wireless networks. NB-JNCC seamlessly couples channel coding and network coding to effectively combat the detrimental effect of fading of wireless channels. Specifically, NB-JNCC combines non-binary irregular low-density parity-check (LDPC) channel coding and random linear network coding through iterative joint decoding, as shown in Figure 15, which helps to fully exploit the spatial diversity and redundancy residing in both channel codes and network codes. Through both analysis and simulation, we demonstrate the significant performance improvement of NB-JNCC over other schemes.

*11) A Time Synchronization Scheme for Mobile Underwater Sensor Networks.* Time synchronization plays a critical role in distributed network systems. In this work, we investigate the time synchronization problem in the context of underwater sensor networks (UWSNs). We propose a pairwise, cross-layer, time synchronization scheme for mobile underwater sensor networks, called TSMU, with the message exchange shown in Figure 16. Facilitated by the Kalman Filter, the proposed method greatly improves the dynamic propagation delay estimation by exploring the Doppler effect. Simulation results show hat TSMU outperforms existing synchronization schemes in both accuracy and energy efficiency, in e.g., Figure 17.

## 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

1. 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. [submitted].
2. 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, 2012. [submitted].
3. Z.-H. Wang, S. Zhou, B. Wang, Z. Wang, P. Willett, ``Dynamic Block Cycling Over a Linear Network in Underwater Acoustic Channels," IEEE Transactions on Wireless Communications, 2012. [submitted].
4. Z.-H. Wang, S. Zhou, J. Catipovic, P. Willett, ``Asynchronous Multiuser Reception for OFDM in Underwater Acoustic Communications," IEEE Transactions on Wireless Communications, 2012. [submitted].
5. Y. Mao, J. Huang, B. Wang, J. Z. Huang, W. Zhou, and S. Zhou, ``A New Iterative LT Decoding Algorithm for Binary and Nonbinary Galois Fields", Journal of Communications and Networks, 2012. [submitted].
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, 2012. [in press].
7. Z.-H. Wang, S. Zhou, J. Catipovic, and J. Huang, "Factor-Graph Based Joint IBI/ICI Mitigation For OFDM in Underwater Acoustic Multipath Channels with Long-Separated Clusters", Journal of Oceanic Engineering, 2012. [in press].

8. L. Liu, W. Zhou, and S. Zhou, ``Design of nonbinary quasi-cyclic low-density parity-check codes by maximising the minimum distance,"  Transactions on Emerging Telecommunications Technologies, Aug. 2012, doi:10.1002/ett.2564. [published].
9. L. Liu, W. Zhou, and S. Zhou, ``Nonbinary Multiple Rate QC-LDPC Codes With Fixed Information or Block Bit Length," Journal of Communications and Networks, vol. 14, no. 4, pp. 429--433, Aug. 2012. [published].
10. L. Liu, J. Huang, W. Zhou, and S. Zhou, ``Computing the Minimum Distance of Nonbinary LDPC Codes," IEEE Transactions on Communications, 2012, vol. 60, no. 7, pp. 1753--1758, July 2012. [published].
11. P. Carroll, S. Zhou, H. Zhou, X. Xu, J.-H. Cui and P. Willett,  "Underwater Localization and Tracking of Physical Systems," Journal of Electrical and Computer Engineering, Special Issue on Underwater Communications and Networks, 2012 , doi:10.1155/2012/683919; [published].
12. L. Wan, Z.-H. Wang, S. Zhou, TC Yang and Z. Shi, ``Performance Comparison of Doppler Scale Estimation Methods for Underwater Acoustic OFDM," Journal of Electrical and Computer Engineering, Special Issue on Underwater Communications and Networks, 2012, doi:10.1155/2012/703243. [published].
13. X. Xu, Z.-H. Wang, S. Zhou, and L. Wan, "Parameterizing both path amplitude and delay variations of underwater acoustic channels for block decoding of orthogonal frequency division multiplexing," Journal of the Acoustical Society of America, vol. 131, no. pp. 4672- 4679, June 2012. [published].
14. Z. Guo, J. Huang, B. Wang, S. Zhou, J.-H. Cui, and P. Willett, "A Practical Joint Network-Channel Coding Scheme for Reliable Communication in Wireless Networks," Transactions on Wireless Communications, vol. 11, no. 6, pp. 2084 - 2094, June 2012. [published].
15. Z.-H. Wang, S. Zhou, J. Preisig, K. R. Pattipati, and P. Willett, "Clustered Adaptation for Estimation of Time-Varying Underwater Acoustic Channels", IEEE Transactions on Signal Processing, vol. 60, no. 6, pp. 3079-3091, June 2012. [published].
16. Z.-H. Wang, S. Zhou, J. Catipovic, and P. Willett, ``Parameterized cancellation of partial-band partial-block-duration interference for underwater acoustic OFDM," IEEE Transactions on Signal Processing, vol. 60, no. 4, pp. 1782-1795, Apr. 2012. [published].
17. J.-Z. Huang, S. Zhou, J. Huang, J. Preisig, L. Freitag, and P. Willett, ``Progressive Intercarrier and Co-channel Interference Mitigation for Underwater Acoustic MIMO-OFDM," Wireless Communications and Mobile Computing, Feb 2012, doi:10.1002/wcm.1251. [published].
18. M. Zuba, Z. Shi, Z. Peng, J.-H. Cui, and S. Zhou, ``Vulnerabilities of Underwater Acoustic Networks to Denial-of-Service Jamming Attacks", Security and Communication Networks, Feb. 2012, doi:10.1002/sec. [published].
19. Z.-H. Wang, S. Zhou, G. B. Giannakis, C. R. Berger, and J. Huang, ``Frequency-Domain Oversampling for Zero-Padded OFDM in Underwater Acoustic Communications," IEEE Journal of Oceanic Engineering, vol. 37, no. 1, pp. 14 - 24, Jan. 2012. [published].
20. J.-Z. Huang, S. Zhou, J. Huang, C. Berger, P. Willett, ``Progressive Inter-carrier Interference Equalization for OFDM Transmission over Time-varying Underwater Acoustic Channels," IEEE Journal of Selected Topics in Signal Processing, vol. 5, no. 8, pp. 1524 -- 1536,  Dec. 2011. [published].

21. Z.-H. Wang, S. Zhou, J. Catipovic, and P. Willett, "Asynchronous Multiuser Reception for OFDM in Underwater Acoustic Communications," Proc. of IEEE/MTS OCEANS conference, May 21-24, 2012. [published].
22. J. Liu, Z.-H. Wang, Z. Peng, M. Zuba, J.-H. Cui, and S. Zhou, ``TSMU: A Time Synchronization Scheme for Mobile Underwater Sensor Networks," Proc. of GLOBECOM, Houston, TX, Dec. 5-9, 2011. [published].
23. Z.-H. Wang, S. Zhou, J. Catipovic, and P. Willett, ``Parameterized cancellation of partial-band partial-block-duration interference for underwater acoustic OFDM," in Proc. of the ACM International Workshop on UnderWater Networks (WUWNet), Seattle, Washington, USA, Dec. 1 - 2, 2011. [published].
24. J.-Z. Huang, S. Zhou, and Z.-H. Wang, ``Robust Initialization with Reduced Pilot Overhead for Progressive Underwater Acoustic OFDM Receivers," Proc. of MILCOM Conference, Baltimore, Maryland, Nov. 7-10, 2011. [published].

**HONORS/AWARDS/PRIZES**

The senior design project on "Underwater Sensor Networks" won the second-prize award of senior design competition in the Department of Electical and Computer Engineering at the University of Connecticut, April 30, 2012.

Shengli Zhou received the Charles H. Knapp Associate Professorship in Electrical Engineering, starting Fall 2012.

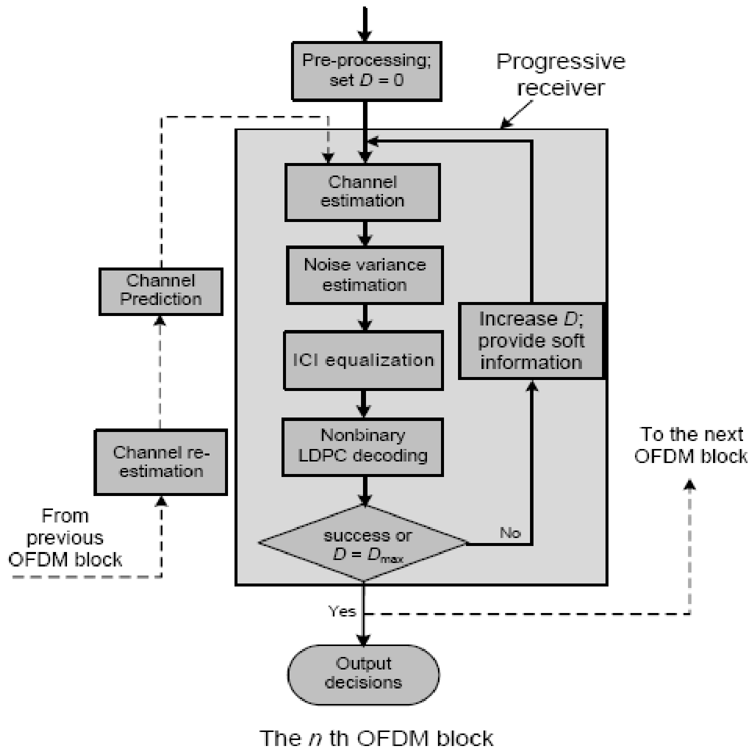


***Figure 1: The progressive receiver for underwater acoustic OFDM systems with robust initialization.***

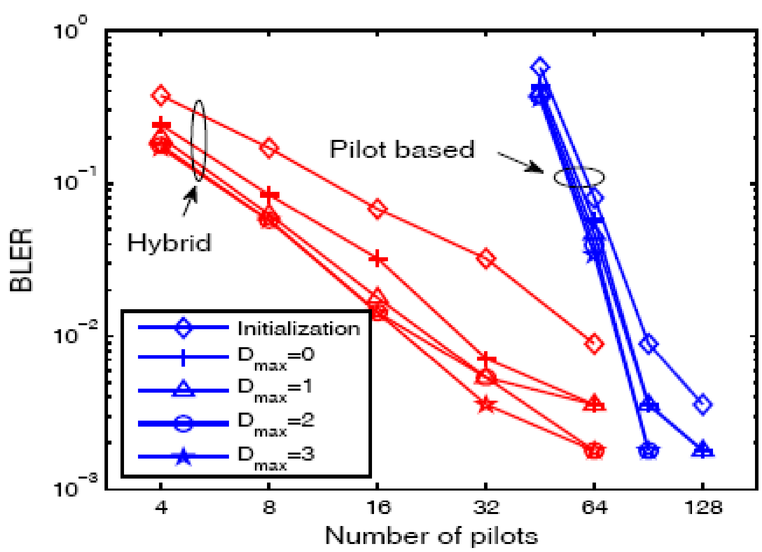


***Figure 2. Block-error-rate performance of 16QAM in MACE10, 1 phone used. (Progressive receiver with robust initialization)***

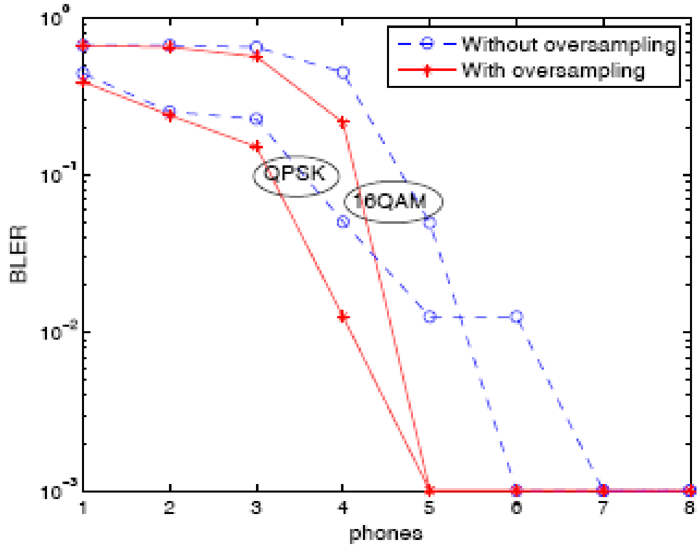


***Figure 3. Block error rate performance with or without frequency-domain resampling, using SPACE08 data sets.***

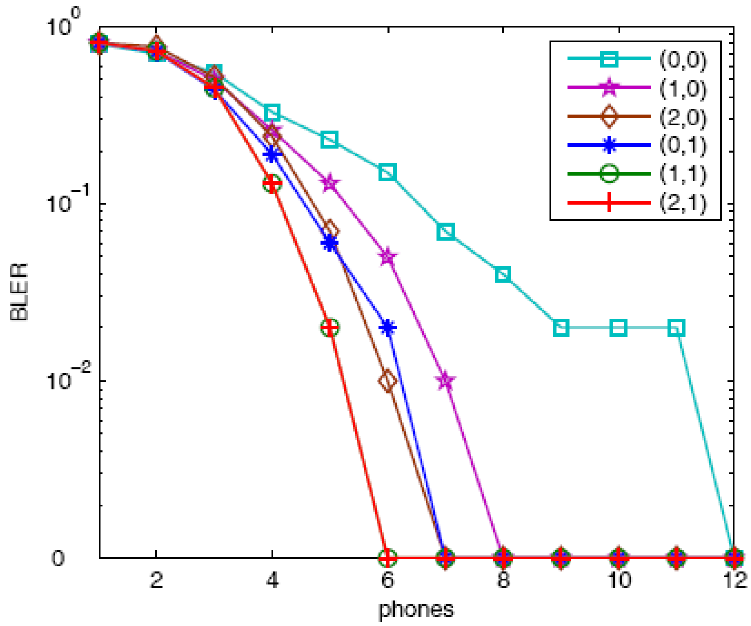


***Figure 4. The decoding results with data collected in Julian date 300. Receiver S3, 16-QAM, SPACE08 experiment. The legend (a,b) means that an ath-order polynomial is used to parameterize amplitude variation and a bth-order polynomial is used to parameterize the delay variation.***

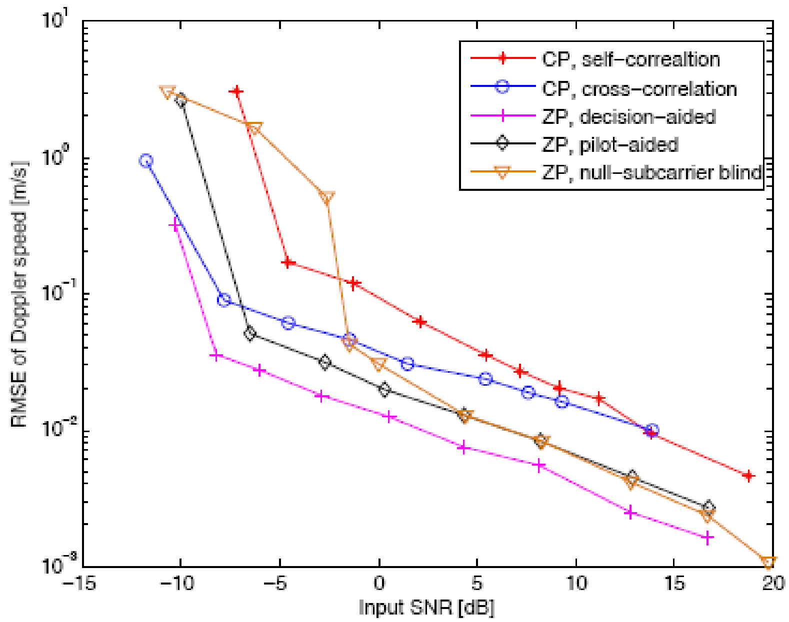


***Figure 5. Performance comparison of Doppler estimation approaches, file ID: 1750155F1954_C0_S5 from the MACE10 experiment.***

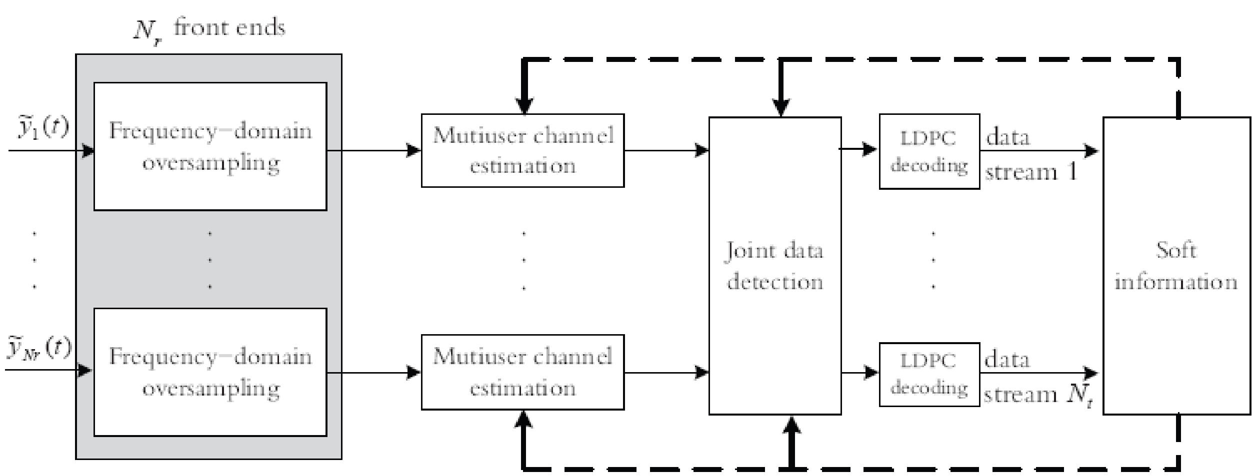


***Figure 6. Multiuser detection (MUD) based iterative receiver with multiuser channel estimation and joint data detection. The a posteriori probabilities (APP) of the data symbols and the extrinsic information from the channel decoders are fed back to the channel estimation and data detection modules, respectively, for performance improvement in an iterative fashion.***

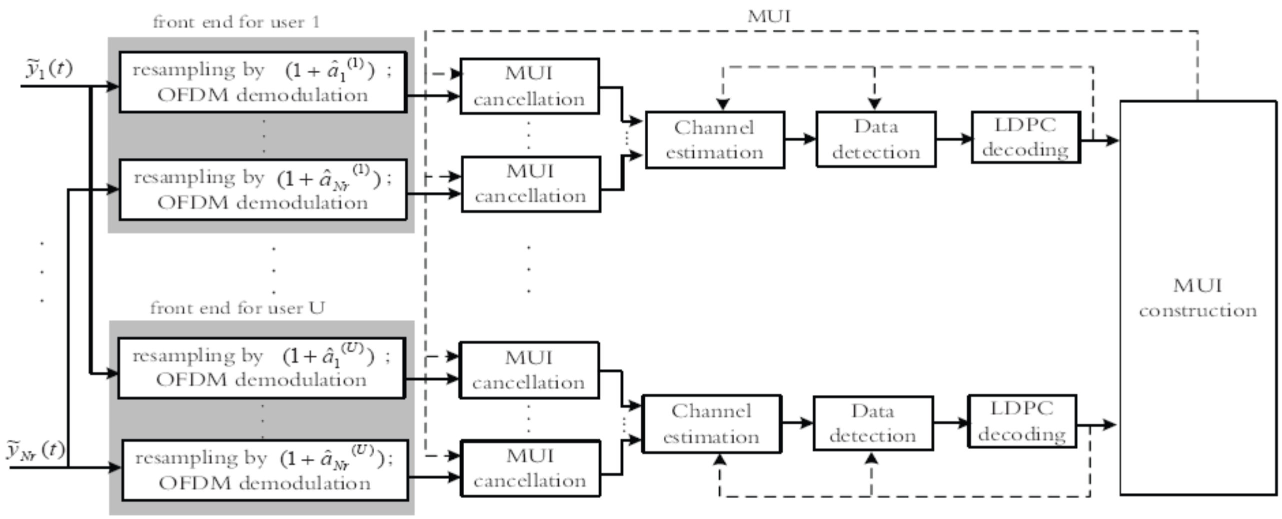


*Figure 7. Single user detection (SUD) based iterative receiver with multiuser interference (MUI) cancellation. In each iteration, the channel and symbol estimates from the previous iteration are used for MUI reconstruction and cancellation, and the soft information from the channel decoder is used to improve channel estimation and data detection.*

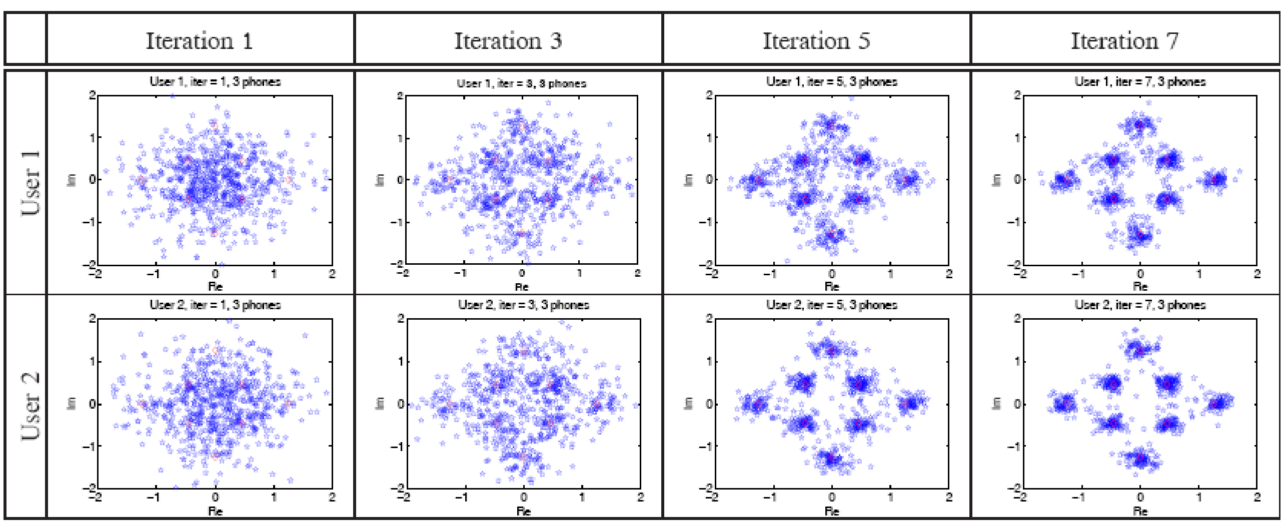


*Figure 8. Constellation scattering plots at the output of the MMSE detector for users 1 and 2 with the single user detection (SUD) based receiver, 3 phones are combined.*

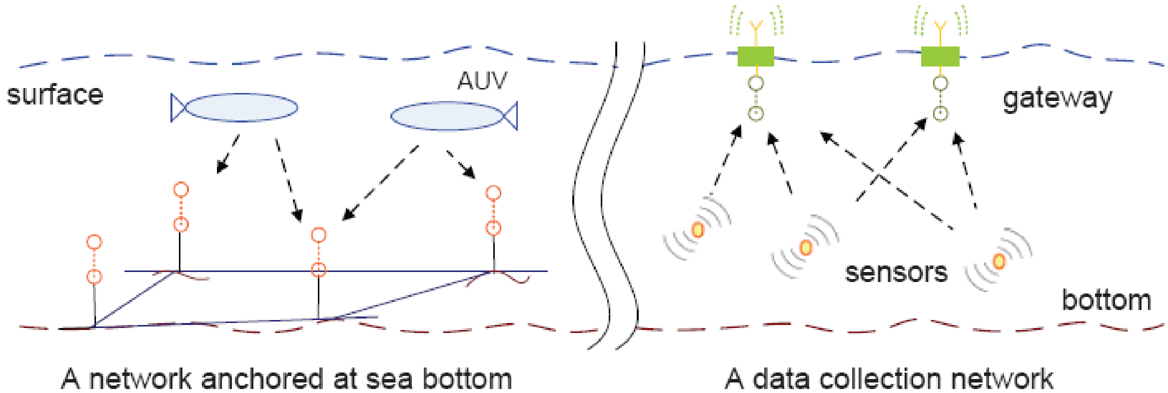


***Figure 9. Two example underwater networks. The nodes anchored at sea bottom in the first network are connected to a control center via cables. The gateways in the second network can communicate with satellites or ships using radio waves.***

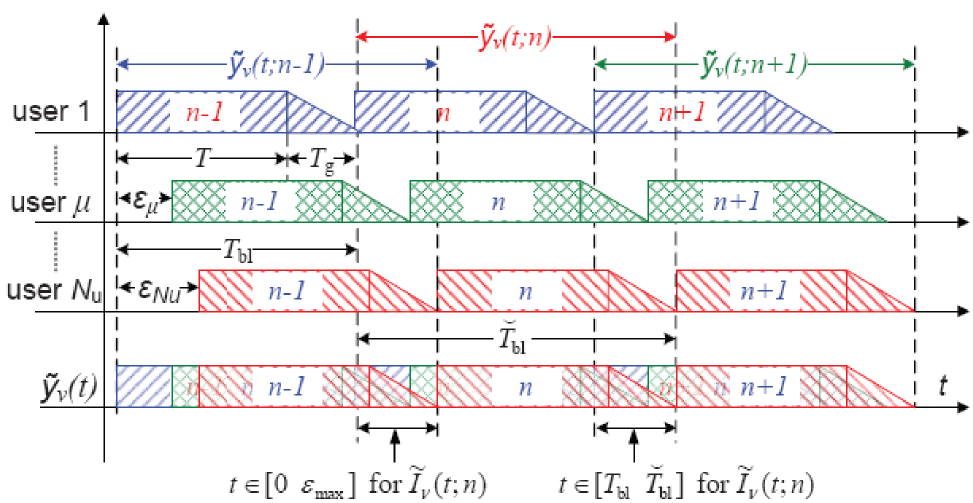


***Figure 10. Illustration of the overlapped partition of the received signal and the aggregated interference in an asynchronous Nu-user system.***

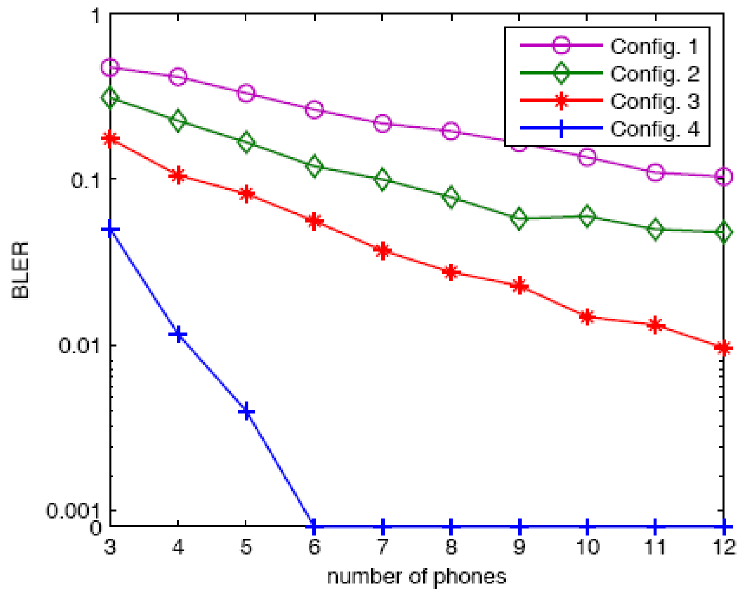


***Figure 11. Block-error-rate performance of four receiving configurations, MACE10 data sets. Configuration 4 corresponds to the proposed burst-by-burst receiver with multiple rounds of forward and backward processing, which outperforms other existing approaches.***

| | | | | | | |
|---|---|---|---|---|---|---|
| **GF(2)** | | | | | | |
| mean column weight | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
| minimum distance | **10** | **11** | **12** | **19** | **27** | **50** |
| multiplicity | **2** | **1** | **1** | **1** | **2** | **1** |
| **GF(8)** | | | | | | |
| mean column weight | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
| minimum symbol weight | **12** | **14** | **32** | **46** | **65** | **76** |
| minimum bit weight | **17** | **19** | **44** | **75** | **100** | **119** |
| multiplicity | **1** | **1** | **1** | **1** | **1** | **1** |
| **GF(16)** | | | | | | |
| mean column weight | 2.5 | 2.6 | 2.7 | 2.8 | 2.9 | 3.0 |
| minimum symbol weight | **13** | **24** | **40** | **52** | **62** | **68** |
| minimum bit weight | **24** | **45** | **77** | **98** | **120** | **133** |
| multiplicity | **1** | **1** | **1** | **1** | **1** | **1** |

***Figure 12. Estimated minimum distance of some nonbinary LDPC codes by the proposed method.***

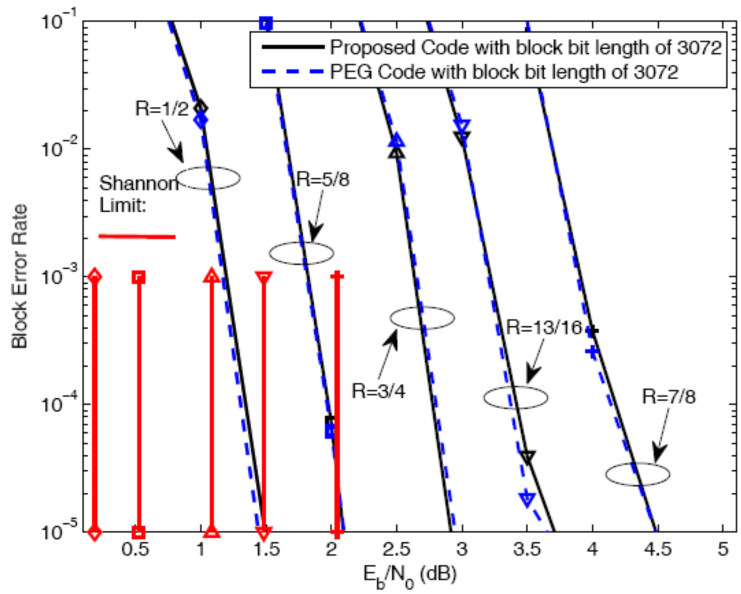


***Figure 13. Performance comparison between the proposed codes and the separate PEG codes of a fixed block bit length 3072.***

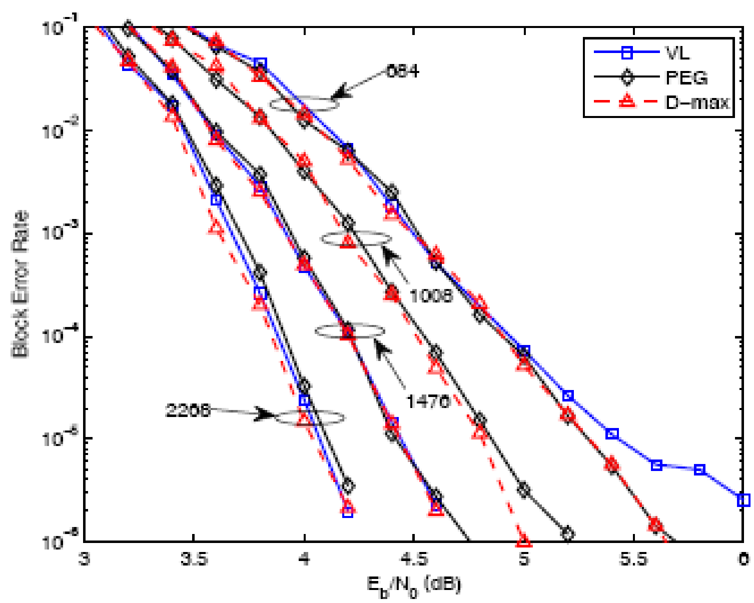


***Figure 14. Performance of codes over Rayleigh fading channel. The proposed method based on maximizing the minimum distance leads to good codes.***

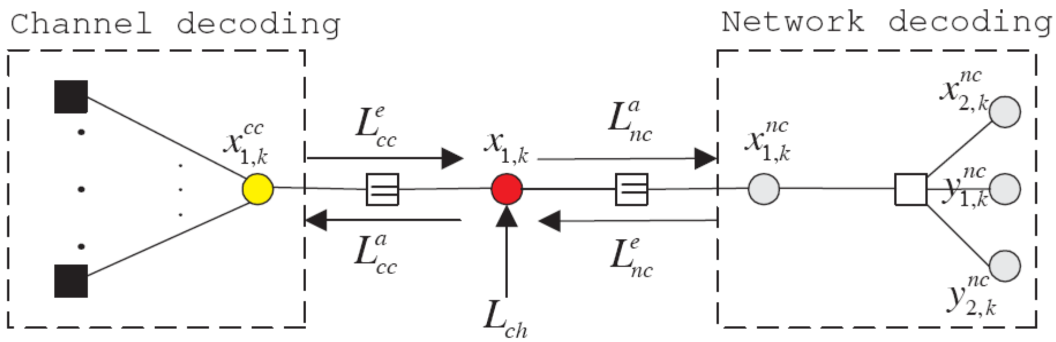


***Figure 15. Message exchange illustration for the k-th symbol x1,k of packet x1 between channel decoding and network decoding in the proposed iterative joint decoding of nonbinary joint network and channel coding (NB-JNCC).***

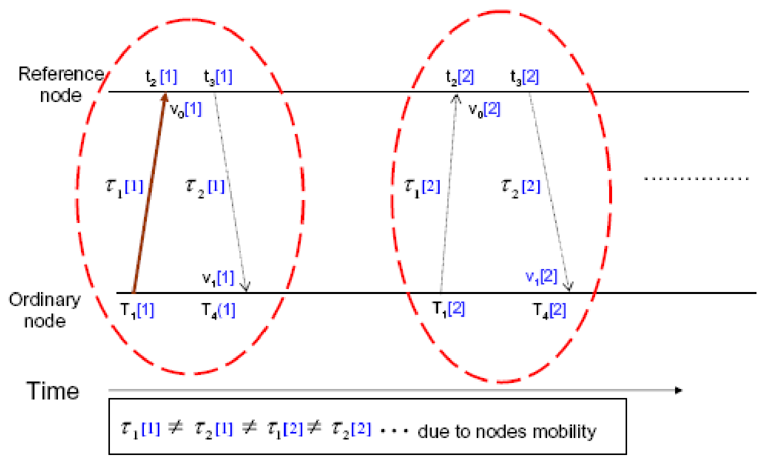


***Figure 16. Illustration of message exchange process for sensor node time synchronization.***

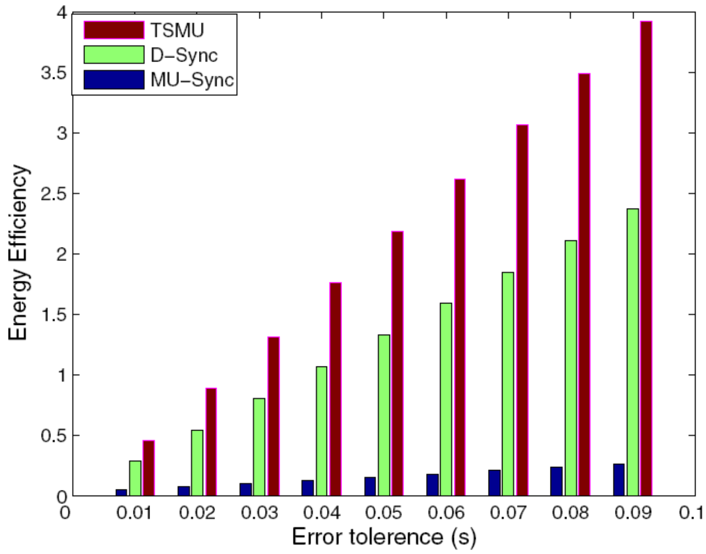


***Figure 17. Energy efficiency versus error tolerance***