The Next Milestone: A Multicarrier Acoustic MODEM with Channel- and Network-Adaptivity for Underwater Autonomous Distributed Systems

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LONG-TERM GOALS

The long-term goal is to develop a practical multicarrier modem for underwater telemetry and distributed underwater sensor networks that can adapt to varying channel conditions and support advanced networking functionalities. This modem will be a major milestone on the path to a new era of underwater distributed networks.

OBJECTIVES

We have three objectives in this project.

1. ***Make OFDM work underwater.*** The success of multicarrier modulation in the form of orthogonal-frequency-division-modulation (OFDM) in radio channels illuminates a clear path one could take towards high-rate underwater acoustic communications. However, earlier work on the application of OFDM in underwater has only had limited success. We aim to *make OFDM work* in underwater environments.

2. ***Channel- and network-aware modulation, coding, and scheduling***. We aim to develop a layered coding structure with joint inter- and intra-packet coding. Intra-packet coding uses error-correction codes to deal with channel distortion and ambient noise, while inter-packet coding uses erasure-correction codes to cope with channel and network disruptions. This layered coding approach facilitates non-flow-based data delivery over single or multiple routing-paths, and can autonomously-adapt to channel and network conditions.

3. ***Prototype development.*** We aim to develop a stand-alone OFDM modem prototype that integrates the innovative algorithms developed in this project.

APPROACH

We aim to make OFDM work in underwater and build a practical multicarrier modem prototype. Over the past year, we have worked on four different aspects of this problem.

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14. ABSTRACT
The long-term goal is to develop a practical multicarrier modem for underwater telemetry and distributed underwater sensor networks that can adapt to varying channel conditions and support advanced networking functionalities. This modem will be a major milestone on the path to a new era of underwater distributed networks.

15. SUBJECT TERMS

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1) Modulation: ***Make OFDM work underwater***.
   Accounting for the wideband nature and fast time-variability of underwater acoustic channels, we have proposed a two-step approach to mitigating the frequency-dependent Doppler shifts: (1). Non-uniform Doppler compensation via resampling. This step converts a "wideband" problem into a "narrowband" problem. And (2). High-resolution uniform compensation of residual Doppler. This step fine-tunes the residual Doppler shift corresponding to the "narrowband" model for best inter-carrier-interference (ICI) reduction.

2) Coding: ***Drastically improve the system performance***.
   Gallager's low-density-parity-check (LDPC) codes achieve Shannon capacity in additive-white-Gaussian noise (AWGN) channels. Our works are the first in the literature that apply the advanced *nonbinary* LDPC codes in underwater applications.

3) Detection, synchronization, and Doppler scale estimation: ***Pave the way towards online receivers.***
   Existing synchronization used in underwater telemetry are almost exclusively based on linearly frequency modulated (LFM) signals. We developed a novel method using multicarrier waveforms for detection, synchronization and Doppler scale estimation.

4) Prototype development: ***Put our algorithms into practice***.
   We develop modem prototypes based on both PC and DSP implementations. This goal is to optimize our algorithms to meet real-time processing requirements.

We collaborate with Mr. Lee Freitag from WHOI who have conducted various underwater experiments for our designed signals. We discuss with Dr. Milica Stojanovic from MIT to improve understanding on OFDM receiver design in fast-varying underwater channels. We work with Dr. Peter Willett from UConn on nonbinary channel coding, synchronization, and Doppler scale estimation problems, and Drs. Zhijie Shi and Jun-Hong Cui from UConn on modem prototype development.

WORK COMPLETED

We have designed various muticarrier waveforms with advanced nonbinary LDPC channel coding and tested them in different experiments:

1) AUV Fest, June 2007 (through Mr. Lee Freitag)
2) Buzzards Bay, August 2007 (through Mr. Lee Freitag)
3) RACE 08 experiment, Narragansett Bay, March 2008 (led by Dr. James Preisig)
4) Buzzards Bay, April 2008 (through Mr. Lee Freitag).
5) GLINT08 test, Pianosa, Italy, July 2008 (through Mr. Lee Freitag)

We have analyzed the data sets, and reported our results through various venues.

We have developed the following modem prototypes

1) Single-input single-output (SISO) OFDM modem. We have used both PC and DSP boards as platforms for the prototypes. We have demonstrated these two implementations in the second ACM International Workshop on UnderWater Networks (WUWNet), Montreal, Canada, Sept. 2007.

2) Multi-input multiple-output (MIMO) OFDM modem. We have used both PC and DSP boards as platforms. We have demonstrated these two implementations in the third WUWnet Workshop, San Francisco, CA, USA, Sept. 2008.

We have involved undergraduate students into research through senior design projects:

1) Project: *An Underwater Acoustic Relay Network with Three Nodes.* Duration: Spring07 to Fall07. Team: Roy Behymer, Mary Hoyer, and Krenar Jusufi. The results from this project were presented at the National Conference on Undergraduate Research (NCUR), Maryland, April 2008.

2) Project: *A Hybrid DSP-FPGA Implementation of Underwater Acoustic Modem*. Duration: Fall07-Spring08. Team: Sanjiv Dinakar, Ajay Patel, Jamal Roache.

3) Project: *Prototyping and Real Time Testing of Underwater Acoustic Modem*. Duration: Spring08-Fall08. Team: J. Thengumthyil, Jason Thomas, Abbas Zaidi.

RESULTS

Modulation and coding: We have achieved very high data rates using multicarrier waveforms and advanced nonbinary LDPC channel coding.

1. *The achieved data rates in stationary tests.* We presented a scalable OFDM design that can scale the data rates with the bandwidth with minimal changes at the transmitter and the receiver. The achieved data rates are summarized in the following tables.

The results in the experiment at AUV Fest, June 2007

Modulation/Bandwidth	3 kHz	6 kHz	12 kHz
QPSK, rate 1/2 coding	1.5 kbps	3 kbps	6 kbps
16-QAM, rate 1/2 coding	3 kbps	6 kbps	12 kbps

The results in the experiment at Buzzards Bay, Aug. 2007

Modulation/Bandwidth	25 kHz	50 kHz
QPSK, rate 1/2 coding	12.5 kbps	25 kbps
16-QAM, rate 1/2 coding	25 kbps	50 kbps

2. *The achieved data rates in mobile tests.* With a 12-kHz bandwidth, a data rate up to 9.7 kbps is achieved with QPSK modulation and rate 2/3 convolutional coding. The algorithm works even when the transmitter and the receiver moved at a relative speed up to 10 knots. The data is from an experiment at Buzzards Bay, MA, Sept. 2006.

3. *MIMO-OFDM.* Based on the data from RACE08, we have presented MIMO-OFDM results with two to four transmitters and high order modulation. A spectral efficiency of *3.5 bits/sec/Hz* is approached in this experiment with two parallel 64-QAM data streams, or three parallel 16-QAM data streams, or four parallel 8-QAM data streams.

Detection, synchronization, and Doppler scale estimation: We developed a novel method that utilizes multicarrier waveforms for detection, synchronization and Doppler scale estimation. Compared with the LFM-preamble based approach, the proposed method has the following advantages: (1) the detection threshold is between 0 and 1, and doesn't depend on the channel or operating SNR; (2) it has a very good detection performance, which is based on the signal energy from *all* paths rather than only a single path; (3) the algorithm can be implemented with very low complexity. The proposed method can start decoding when each OFDM block comes in (no need to buffer a data packet of multiple OFDM blocks). This *paves the way* towards online receiver operation for multicarrier underwater acoustic communication.

Prototype development: Our DSP implementation of the OFDM modem is
is based on a TMS320C6713 DSP board. For an OFDM block duration of 230 ms, the demodulation-plus-decoding time at the receiver is about 40 ms, as of April 2008, and hence a *real-time* one-way communication is accomplished.

IMPACT/APPLICATIONS

The success of this project will have a deep impact. First, it will solve the long-standing problem of realizing OFDM in underwater environments. Second, it will directly contribute to the development of UWSNs for a variety of aquatic applications, by providing a high-rate and reliable multicarrier modem with networking functionalities.

RELATED PROJECTS

I am a PI on the project "A Multicarrier Underwater Acoustic Modem with Precise-Ranging Capability," 9/1/2007-8/31/2009, from National Science Foundation. This project is also related to OFDM modem development, but it has a different emphasis which is to provide the precise-ranging capability (for localization) to the OFDM modem.

PUBLICATIONS

Journal Papers

1. S. Mason, C. R. Berger, S. Zhou, and P. Willett, "Detection, synchronization, and Doppler scale estimation with multicarrier waveforms in underwater acoustic communication," *IEEE JSAC Special Issue on Underwater Wireless Communications and Networks,* Dec. 2008 [in press].

2. J. Huang, S. Zhou, and P. Willett, "Nonbinary LDPC coding for multicarrier underwater acoustic communication," *IEEE JSAC*, Dec. 2008 [in press].

3. L. Liu, S. Zhou, and J. Cui, "Prospects and Problems of Wireless Communications for Underwater Sensor Networks," *Wireless Communications and Mobile Computing*, Oct. 2008 [in press].

4. C. R. Berger, S. Zhou, Y. Wen, P. Willett, and K. Pattipati, "Optimizing Joint Erasure- and Error-Correction Coding for Wireless Packet Transmissions," *IEEE Transactions on Wireless Communications*, 2008 [in press].

5. C. R. Berger, S. Zhou, P. Willett, and L. Liu, "Stratification Effect Compensation for Improved Underwater Acoustic Ranging," *IEEE Transactions on Signal Processing*, vol. 56, no. 8, August 2008 [published].

6. B. Li, S. Zhou, M. Stojanovic, L. Freitag, and P. Willett, "Multicarrier communication over underwater acoustic channels with nonuniform Doppler shifts," *IEEE J. of Oceanic Engineering*, vol. 33, no. 2, Apr. 2008 [published].

Conference Papers

1. B. Li, J. Huang, S. Zhou, K. Ball, M. Stojanovic, L. Freitag, and P. Willett, "Further results on high-rate MIMO-OFDM underwater acoustic communications," in *Proc. of OCEANS*, Sept. 15-18, 2008 [published].

2. S. Mason, S. Zhou, W.-B. Yang, and P. Gendron, "A comparative study of differential and noncoherent direct sequence spread spectrum over underwater acoustic channels with multiuser interference," in *Proc. of MTS/IEEE OCEANS conference*, Quebec City, Canada, Sept. 15-18, 2008 [published].

3. K. Jusufi, R. Behymer, M. Hoyer, and S. Zhou, "Designing a three-node underwater acoustic relay network," in *Proceedings of the National Conference On Undergraduate Research (NCUR)*, April 10–12 2008 [published].

4. J. Huang, S. Zhou, and P. Willett, "Nonbinary LDPC coding for multicarrier underwater acoustic communication," *Proc. of OCEANS*, Apr. 2008 [published].

5. S. Mason, C. R. Berger, S. Zhou, and P. Willett, "Detection, synchronization, and Doppler scale estimation with multicarrier waveforms in underwater acoustic communication," in *Proc. of OCEANS*, April 8-11, 2008 [published].

6. B. Li, S. Zhou, J. Huang, and P. Willett, "Scalable OFDM design for underwater acoustic communications," in *Proc. of Intl. Conf. on ASSP*, Las Vegas, NV, Mar. 30 – Apr. 4, 2008 [published].

7. B. Li, S. Zhou, M. Stojanovic, L. Freitag, J. Huang, and P. Willett, "MIMO-OFDM over an underwater acoustic channel," in *Proc. of OCEANS*, Vancouver, BC, Canada, Sept. 29 - Oct. 4, 2007 [published].

8. H. Yan, S. Zhou, Z. Shi, and B. Li, "A DSP implementation of OFDM acoustic modem," in *Proc. of WUWNet*, September 14, 2007 [published].

PATENTS

1. "Stable Wideband OFDM Receiver for Underwater Acoustic Communications," U.S. Provisional Patent Application Number 60/936,167, filed on 18th June 2007, (S. Zhou, B. Li, M. Stojanovic, L. Freitag, P. Willett), [pending].

2. "Nonbinary LDPC Coding for Multicarrier Underwater Acoustic Communications," UConn Invention Disclosure reference number 08-016, (S. Zhou, J. Huang, P. Willett).

3. "A Novel Method on Detection, Synchronization, and online Doppler Scale Estimation for Underwater Acoustic Communication Based on Multicarrier Waveforms," UConn Invention Disclosure reference number 08-017 (S. Zhou, S. Mason, C. R. Berger, P. Willett).

HONORS/AWARDS/PRIZES

Our demo in the third WUWNET workshop, Sept. 2008, *won the first prize in the demo competition.* Title: "Demonstration of PC-based and DSP-based Implementations of a MIMO-OFDM Acoustic Modem". Team members: Hai Yan, Juanjuan Liao, Xiao Zhou, Shengli Zhou, Zhijie Shi, and Jun-Hong Cui.

Photos of The Multicarrier Modem Prototypes Developed at UConn

Figure 1: Single-input single-output (SISO) OFDM modem prototypes: (left) PC based implementation, (right) DSP based implementations. With bandwdith 5.5 kHz, QPSK modulation, and rate ½ coding, the achieved data rate is 3.1 kb/s. For a block duration of 200ms, the decoding time is only 40 ms on the DSP board, hence, real-time decoding is achieved. These prototypes were demonstrated at WUWNet, Montreal, Canada, Sept. 2007.

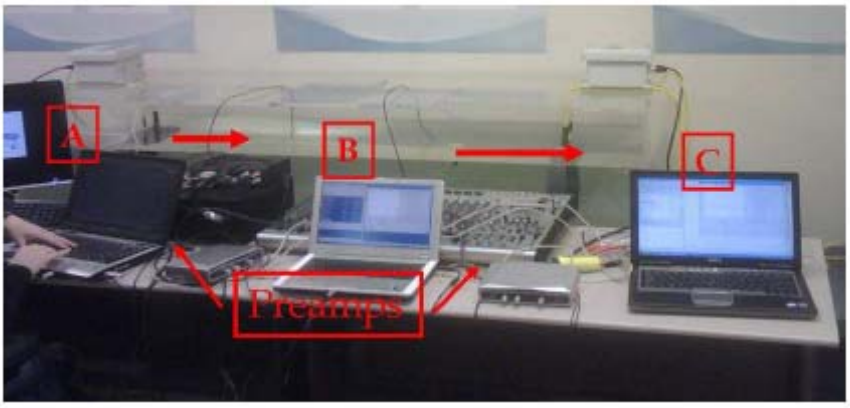

Figure 2: Building upon the point-to-point data transmissions, we have designed and experimented a three-node underwater relay network. We considered two scenarios for generating messages. In the first scenario, a message input from the graphic user interface can be transmitted to any specified destination in the network. In the second

scenario, a motion sensor is attached to one node for continuous motion monitoring. Once an event is detected, an alert message is generated and broadcast to the whole network. We have tested the three-node network in a water tank and in a lake.

Figure 3: Multi-input multi-output (MIMO) OFDM prototypes: (left) PC based implementation, (right) DSP based prototypes. Two speakers and two microphones are used for transmission and reception, respectively. With bandwidth of 5.5 kHz, QPSK modulation, and rate ½ coding, the achieved data rates are 6.2 kb/s. These two prototypes are demonstrated at WUWNet, San Francisco, CA, Sept. 2008.

Figure 4: The MIMO-OFDM demo setup at WUWNet, San Francisco, CA, Sept. 2008. This demo won the first-prize in the demo category, as voted by workshop participants.