

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. We have published the first IEEE journal paper on underwater OFDM. We have also presented the first

experimental result in the literature on underwater multi-input multi-output (MIMO) OFDM. As of now, the feasibility of OFDM for underwater acoustic communications is well accepted by the research community.

Over the past year, we have worked on the following aspects.

- 1) We continue to improve the receiver robustness through innovative algorithms.
- 2) We aim to increase the data rate through the deployment of MIMO techniques.
- 3) We continue our prototype development using both floating- and fixed-point DSP platforms.

We collaborate with Mr. Lee Freitag and Dr. James Preisig from WHOI who have conducted various underwater experiments for our designed signals. We discuss with Dr. Milica Stojanovic from MIT/Northeastern to improve understanding on OFDM receivers. We work with Dr. Peter Willett from UConn on receiver algorithms, and Drs. Zhijie Shi and Jun-Hong Cui from UConn on modem prototype development.

WORK COMPLETED

We have developed various receiver algorithms, and verified their performance using the data sets from the following three experiments.

- 1) RACE 08 experiment, Narragansett Bay, March 2008 (led by Dr. James Preisig)
- 2) SPACE08, Martha's Vineyard, MA, Oct. 2008 (led by Dr. James Preisig)
- 3) WHOI09, Buzzards Bay, Dec. 2009 (led by Mr. Lee Freitag)

We keep developing modem prototypes using both fixed- and floating-point DSP evaluation boards, for both single-transmitter OFDM and MIMO-OFDM.

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

Among various results that we have obtained, we will highlight the following: i) a noise-whitening approach, 2) an iterative receiver for MIMO OFDM, and 3) prototyping of OFDM modems.

1) A Simple and Effective Noise Whitening Method for Underwater OFDM.

Underwater acoustic OFDM enables simple frequency domain equalization, but its performance is often limited by inter-carrier-interference (ICI) that is induced by channel variation, in addition to the ambient noise. As the signal itself, the variance of the ICI is frequency dependent as i) the transmitter often has a non-ideal transmit voltage response (TVR), and ii) underwater acoustic propagation introduces frequency dependent attenuation (See illustration in Figure 1).

In this work, we proposed a simple method to account for the frequency-dependent spectrum of the ICI plus noise. Specifically, the power spectrum of the ICI plus noise is approximated using a low-order polynomial in the log-domain, by fitting the measurements on the null subcarriers embedded in each OFDM symbol. Prewhitening is then applied to each OFDM symbol before channel estimation and data demodulation. The proposed method is tested using experimental data collected from the SPACE08 and RACE08 experiments. Impressive performance gains are found whenever the signal is significantly colored. This is the case when either the TVR is not compensated or the transmission distance and bandwidth are large. Figure 2 illustrate the performance improvement using the SPACE08 data.

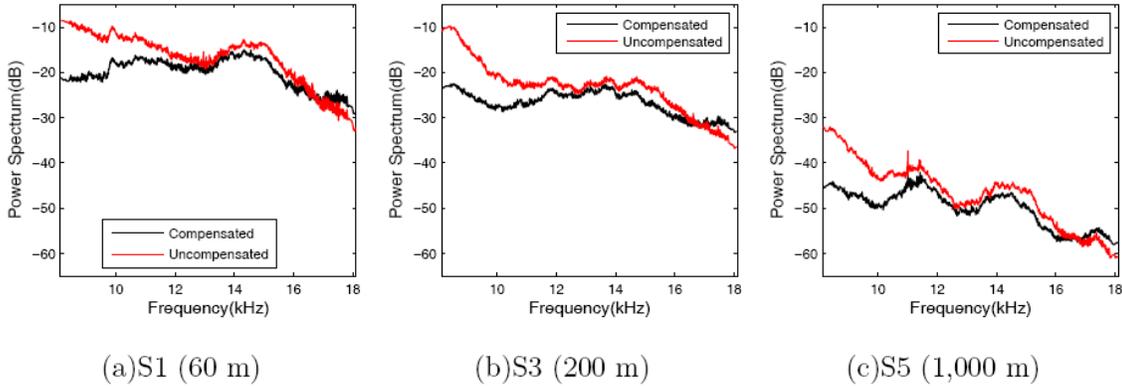


Figure 1 Experimentally measured signal spectrum at three receivers, Julian Date 292, SPACE08 Experiment. The spectrum is colored.

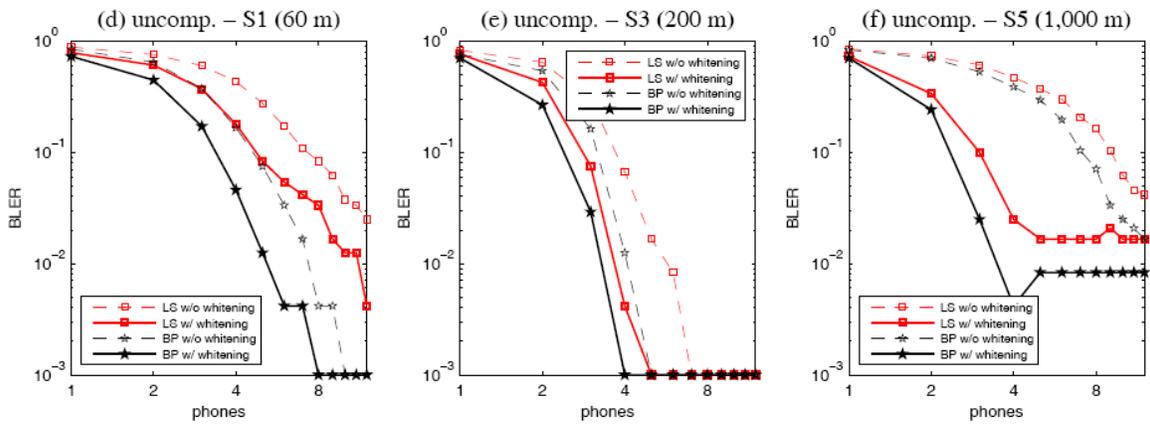


Figure 2. Performance comparison for compensated and uncompensated signals on Julian date 292 in the SPACE08 experiment, 16-QAM. For the transmissions that are not compensated at the transmitter side, much improved performance is observed when applying the noise-whitening approach based on the colored noise model.

2) Iterative Sparse Channel Estimation and Decoding for Underwater MIMO-OFDM. In this work we propose a block-by-block iterative receiver for underwater MIMO-OFDM that couples channel estimation with multiple-input multiple-output (MIMO) detection and low-density parity-check (LDPC) channel decoding. In particular, the channel estimator is based on a compressive sensing technique to exploit the channel sparsity, the MIMO detector consists of a hybrid use of successive interference cancellation and soft minimum mean-square error (MMSE) equalization, and channel coding uses nonbinary LDPC codes. See the diagram in Figure 3.

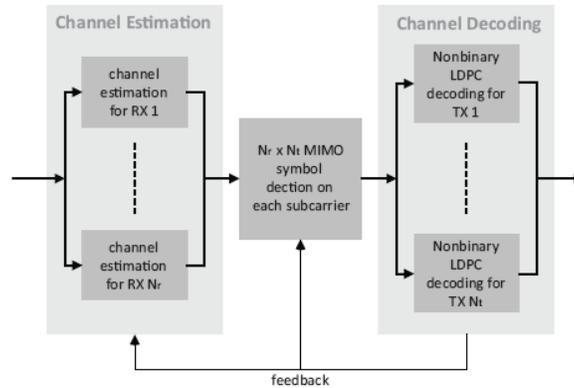


Figure 3: Iterative channel estimation and decoding for MIMO-OFDM

Various feedback strategies from the channel decoder to the channel estimator are studied, including full feedback of hard or soft symbol decisions, as well as their threshold-controlled versions. We find that iterative receiver processing including sparse channel estimation leads to impressive performance gains. These gains are more pronounced when the number of available pilots to estimate the channel is decreased, e.g., when a fixed number of pilots is split between an increasing number of parallel data streams in MIMO transmission. For the various feedback strategies for iterative channel estimation, we observe that soft decision feedback slightly outperforms hard decision feedback. See Figure 4 on performance results based on the RACE08 data.

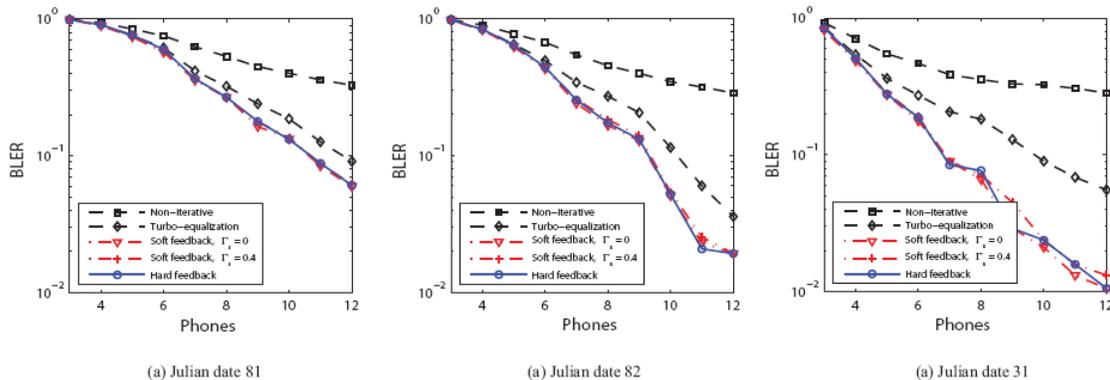


Figure 4: Experimental results from the RACE08 experiment on MIMO-OFDM with three transmitters and 16-QAM. The data rate is 15.6 kb/s using a 4.88 kHz bandwidth.

3) DSP based Receiver Implementation for OFDM Acoustic Modems. We have been consistently working on the improved OFDM modem prototypes. Here we report the implementation results of OFDM acoustic modems under different settings with either one or two parallel data streams transmitted, whose data rate is 3.2 kb/s or 6.4 kb/s, respectively, with QPSK modulation, rate-1/2 channel coding, and signal bandwidth of 6 kHz.

Real-time operation has been achieved with impressive margins, using a floating point TMS320C6713 DSP development board, running at 225 MHz. Specifically, with convolutional coding, the processing time for each OFDM block of duration 210 ms is about 38 ms and 77 ms for single-input single-output (SISO) and multi-input multi-output (MIMO) settings, respectively, where there are two transmitters and two receivers in the latter case. With nonbinary low-density parity-check (LDPC) coding, which gains about 2 dB in error performance relative to convolutional coding, the processing time per block increases to 50 ms and 101 ms for SISO and MIMO settings, respectively. We have also implemented the OFDM acoustic modems using a fixed-point TMS320C6416 DSP development board, where the DSP core runs at 1 GHz. The per-block processing time reduces by two thirds with negligible performance degradation.

Figure 5 shows an OFDM modem prototype. Multiple OFDM modems have been used to test an underwater localization solution recently in local lakes, in addition to testing the communication performance.

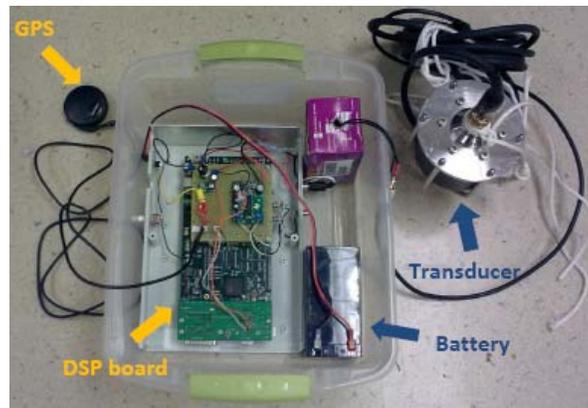


Figure 5: The OFDM modem prototype, connected with battery, transducer, and a GPS unit.

IMPACT/APPLICATIONS

The success of our projects will have a deep impact. Providing high-data-rate and reliable multicarrier modems with networking functionalities, our projects 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

The ONR project N00014-09-1-0704, entitled “Advancing Underwater Acoustic Communication for Autonomous Distributed Networks via Sparse Channel Sensing, Coding, and Navigation Support,”

4/1/2009-3/31/2014, PI: Shengli Zhou, aims to advance the research on multicarrier underwater acoustic communications, which was initiated from this reported project.

PUBLICATIONS

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3. B. Li, J. Huang, S. Zhou, K. Ball, M. Stojanovic, L. Freitag, and P. Willett, "MIMO-OFDM for High Rate Underwater Acoustic Communications," *IEEE Journal on Oceanic Engineering*, vol. 34, no. 4, pp. 634-644, Oct. 2009.
4. 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.
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7. J. Huang, J.-Z. Huang, C. R. Berger, S. Zhou, and P. Willett, "Iterative Sparse Channel Estimation and Decoding for Underwater MIMO-OFDM," in *Proc. of MITS/IEEE OCEANS Conference*, Biloxi, Mississippi, USA, Oct. 26-29, 2009.
8. C. R. Berger, S. Zhou, W. Chen, and J. Huang, "A Simple and Effective Noise Whitening Method for Underwater Acoustic OFDM," in *Proc. of MITS/IEEE OCEANS Conference*, Biloxi, Mississippi, USA, Oct. 26-29, 2009.