

# Towards A Practical Multicarrier Modem for Underwater Telemetry and Distributed Networks

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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 and build a practical multicarrier modem prototype. We have worked on four different aspects of this problem.

- Modulation: *Make OFDM work underwater.*
- Coding: *Drastically improve the system performance.*
- Detection, synchronization, and Doppler scale estimation: *Pave the way towards online receivers.*
- Prototype development: *Put our algorithms into practice.*

So far, excellent progress has been made, as summarized in the following.

## A. Modulation [1]–[12]

### 1) The achieved data rates in stationary testings.

In [5], 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 [2], [3].

### 3) *MIMO-OFDM.*

We have presented a MIMO-OFDM design with two transmitters in OCEANS'07, Vancouver [4]. With a 12-kHz bandwidth, a data rate of 12.18 kbps is achieved with QPSK modulation on two transmitters and rate 1/2 coding. The data is from an experiment at AUVFest, Panama City, FL, June 2007.

We have presented additional MIMO-OFDM results with two to four transmitters and high order modulation in OCEANS'08 [6]. A spectral efficiency of 3.52 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. In a VHF08 experiment conducted April 2008, a data rate of 125.7 kb/s was achieved with two transmitters, 16-QAM modulation, rate 1/2 coding, and a bandwidth of 62.5 kHz, as reported in [7].

### 4) *Sparse channel estimation and iterative receiver design.*

We exploited the sparse nature of underwater channels using both subspace methods from the array processing literature (e.g., MUSIC, ESPRIT) and compressive sensing methods (e.g., Orthogonal matching pursuit and basis pursuit) [10].

We presented an OFDM system design for underwater acoustic channels with large Doppler spread in [8], [9].

We will present a simple and effective noise-whitening approach for OFDM [11]. We will present an iterative receiver that couples sparse channel estimation, MIMO detection, and channel decoding for MIMO-OFDM [12].

- **Note 1:** Our JOE paper [3] is the first journal paper in IEEE Transactions on multicarrier underwater acoustic communications.
- **Note 2:** Our OCEANS-Vancouver paper [4] is the first conference paper in the literature that contains experimental results for MIMO-OFDM.

## B. **Channel coding:** [13], [14]

- Gallager's low-density-parity-check (LDPC) codes achieve Shannon capacity in additive-white-Gaussian-noise (AWGN) channels.
- **Note 3:** Our works in [4], [5], [13], [14] are the first in the literature that apply the advanced nonbinary LDPC codes in underwater applications.
- Our experience with real data is that whenever the uncoded BER is below 0.1, normally no decoding errors will occur for the rate 1/2 nonbinary LDPC codes used. Hence, *the goal of OFDM demodulation is to achieve an uncoded BER within the range of 0.1 and 0.01. Nonbinary LDPC coding will then boost the overall system performance.*

## C. **Detection, synchronization, and Doppler scale estimation:** [15], [16]

- Existing synchronization used in underwater telemetry are almost exclusively based on linearly frequency modulated (LFM) signals, also known as Chirp signals. This approach suffers from the following two

deficiencies: first, the noise level at the receiver has to be constantly estimated to achieve a constant false alarm rate (CFAR), usually accomplished using order statistics; second, its performance will degrade in the presence of dense and unknown multipath channels.

- We develop a novel method that utilizes multicarrier waveforms for detection, synchronization and Doppler scale estimation [15], [16]. 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) it leads to accurate Doppler scale estimation; (4) after coarse timing and resampling, it allows the use of fine timing algorithms developed for radio channels; (5) the algorithm can be implemented with very low complexity, as done in [17].
- 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.

#### D. Prototype Development: [17]–[19]

- 1) PC-based implementation as reported in [18]. See Fig. 1.

This implementation is based on Matlab programming on two laptops. Two laptops can communicate with each other via two-way acoustic links.

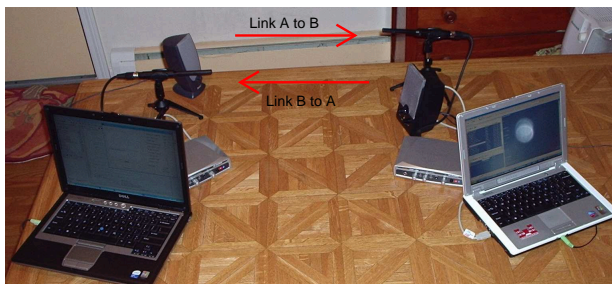


Fig. 1. The PC-based prototype with two-way communication

- 2) DSP-based implementation as reported in [17]. See Fig. 2.

This implementation 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 200 ms, and hence a *real-time* one-way communication is accomplished. The bandwidth is 5.5 kHz, and the overall data rate is 3.1 kbps after rate 1/2 convolutional coding.

These two prototypes were demonstrated at WUWNet, Montreal, Sept. 2007.

- 3) A three-node relay network as reported in [19]. See Fig. 3

Building upon the point-to-point data transmission, we have designed and experimented a three-node underwater relay network. We considered two scenarios for generating messages. In the first scenario, a



Fig. 2. The DSP-based prototype for real-time one-way communication

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.

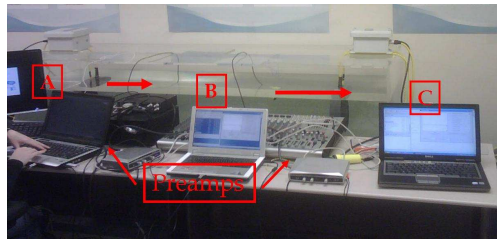


Fig. 3. The three-node testbed using the water tank

- 4) PC-based and DSP-based ( $2 \times 2$ ) MIMO-OFDM acoustic modem prototypes are demonstrated in WUWNet, San Francisco, CA, Sept. 15, 2008. QPSK modulation, rate 1/2 coding, bandwidth 5.5 kHz, and data rate 6.2 kb/s.



Fig. 4. The MIMO-OFDM prototypes (left) PC based and (right) DSP based implementation

**Note 4:** These two prototypes were demonstrated at WUWNet, San Francisco, CA, Sept. 2008 and won the first-prize in demo category, as voted by workshop participants.

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