Development of High Data Rate Acoustic Multiple-Input/Multiple-Output Modems

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LONG-TERM GOALS

The long-term goal of the project is to enhance communication capabilities of underwater platforms and facilitate real-time adaptive operations in the ocean.

OBJECTIVES

The primary objective is to develop an acoustic modem prototype based on proven communication methods that we have developed: multiple transducer signaling at the transmitter and low-complexity time reversal processing at the receiver.

APPROACH

Underwater acoustic (UWA) communication is useful in a variety of industrial and scientific applications such as ocean observation and exploration, subsea telemetry, marine security and defense, etc. The UWA channel poses a challenge for high-frequency communication systems due to its severe multipath delay spread and rapid time fluctuations. The substantial inter-symbol interference (ISI) produced by the extensive multipath is difficult to remove, therefore, restricting achievable data rates.

Several methods have been developed to mitigate the time-varying ISI in the underwater acoustic environment. The use of decision feedback equalizer (DFE) for coherent underwater communications has been studied in [1]. An alternative method is time reversal [2]. Time reversal can achieve temporal focusing and compression, thus reducing the ISI. Time reversal followed by equalization has been developed in several studies [3-5]. This technique allows for complexity reduction at the equalization stage. Additionally, this type of systems can handle severe ISI effects.

In this project, we implemented the time reversal DFE receiver from [6] on digital signal processors (DSPs). We utilized a purchased Acoustic Modem Development Platform (AMDP) for implementation. The communication receiver used time reversal multi-channel combining followed by a single-channel DFE. Periodic channel estimation was employed to track the channel fluctuations. Various optimization tasks were performed to reduce the receiver computational complexity. Field tests were conducted to demonstrate the effectiveness of our implementation.

WORK COMPLETED

During the project period, we performed the following tasks:

1) We purchased and fabricated multiple acoustic instruments. Figure 1 shows the purchased AMDP hardware, which consists of a transmitter box, two transducers, a receiver box, and an 8-element hydrophone array.

(a)	(b)
(c)	(d)
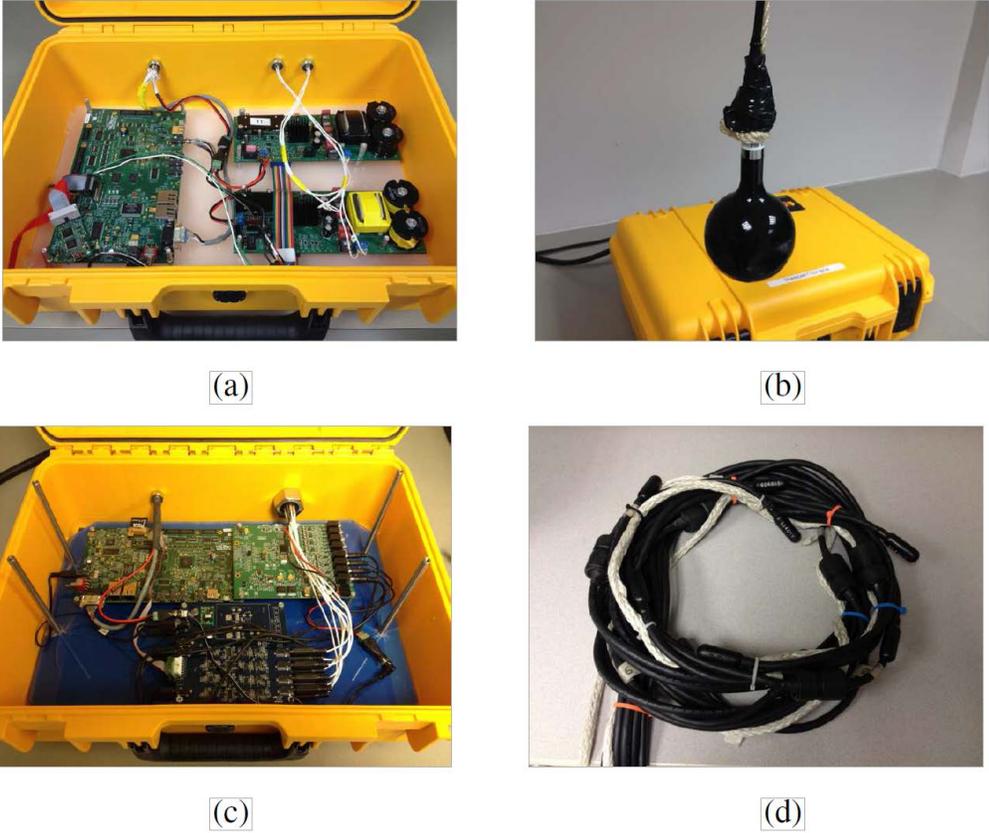
Figure 1. AMDP hardware. A) Transmitter box, b) Transducer, c) Receiver box, and d) Receiving array.

Because of the price saving from the purchase of the AMDP, we were able to purchase two units of passive acoustic recorders. Multiple environmental sensors were also purchased. These instruments were deployed in the local Delaware Bay tests.

2) Using the AMDP, we developed a time reversal acoustic modem prototype for shallow water environments.

3) We conducted multiple field tests in the local Delaware Bay to test the TR receiver implementation.

RESULTS

1) Development of acoustic modem prototype. A pair of AMDPs were used for transmission and reception in our implementation. These are two programmable devices, shown in Fig.1. The AMDPs are controlled by OMAP-L137 evaluation boards, with Texas Instruments OMAP-L137 as its main processors. The transmitter and receiver boxes operate on finite state machines (FSMs). Our implementation was programmed in C language on the OMAP-L137 chip, in each state of the FSMs.

In the transmitter box shown in Fig.1 (a), the DSP evaluation board performs two functions: communication with a host computer and control of the transmission function. It connects with the host computer through the RS232 serial port. In the transmission mode, it receives instructions from the host computer through the serial port. The DSP loads the modulated passband signal, which is sent to the digital-to-analog converter (DAC) to generate the analog signal. Then the analog signal is amplified by the power amplifier to drive the acoustic transducer (shown in Fig. 1(b)).

At the receiver side as shown in Fig. 1(c) and 1(d), an array of 8 hydrophones serve as the receiving antennas. The received signal is pre-amplified and fed into the analog-to-digital converter (ADC). The DSP acquires the digitized signals and then proceeds to demodulation. The results of the demodulation can be sent to a computer via the RS232 serial port.

In time reversal receivers, channel estimation accounts for a significant portion of the receiver complexity since channel estimation needs to be performed at each receiving element, repeatedly at the channel update interval. In the receiver configuration TR, the channel estimation operations account for more than ninety percent of the computation. We reduce the complexity of this process by a fast implementation of the sparse channel estimator, which is referred to as the FMP algorithm. We approximate the matrix-vector multiplication in the BMP by FFT operations. The fast implementation assumes that the data Toeplitz matrix can be approximated by a circulant one.

The FMP algorithm is much faster than the BMP one, especially for large channel lengths. With larger channel lengths, the execution time reduction becomes more significant. For instance, when channel length is L=2056, we show in Table 1 that the FMP algorithm is about 174 times faster than the BMP algorithm.

Table 1. Execution time comparison between the FMP and BMP algorithms

L	FMP time (ms)	BMP time (ms)	Speed Increase Factor
128	1.6	7.5	4.6
256	3.7	53.6	14.2
512	11.4	431.5	37.7
1024	39.9	3386.2	84.7
2056	153.8	26859.8	174.7

2) Local test results. Multiple field tests were conducted in the local Delaware Bay. We here show the results from a shallow water site near the Roosevelt Inlet, Delaware Bay during September, 2014. During the experiment, the transmitter and receiver boxes were deployed 400 m away from each other. The water depth was about 3 m. The hydrophone spacing was 0.25 m. BPSK signals with a duration of 1.5 s were transmitted for three symbol rates: 1, 2, and 4 kHz.
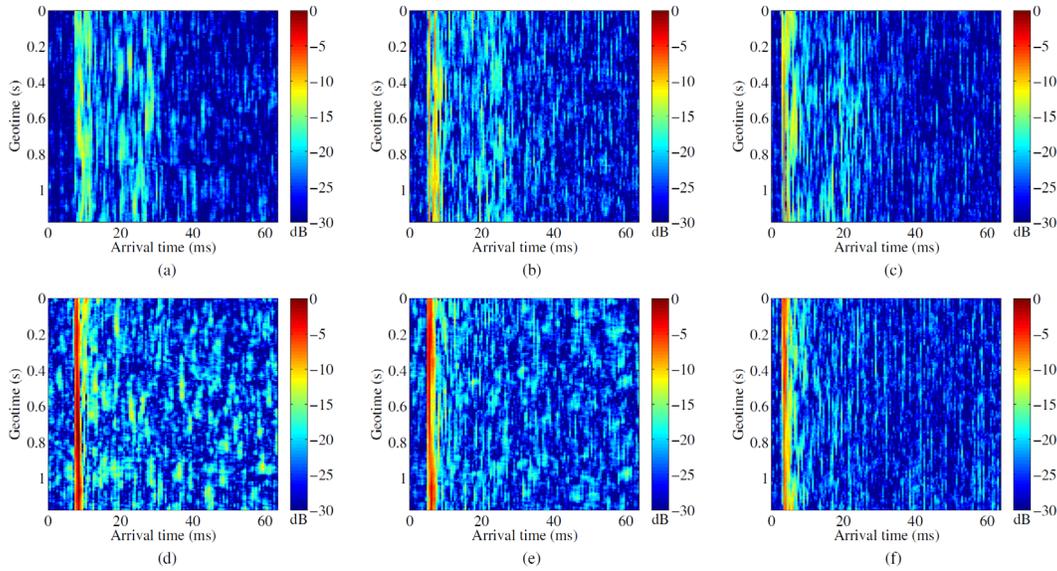
Figure 2. Estimated CIRs for different symbol rates at two hydrophone channels. (a) 1 kHz, (b) 2 kHz, and (c) 4 kHz at channel 2. (d) 1 kHz, (e) 2 kHz, (f) 4 kHz at channel 8.

The least squares (LS) algorithm is utilized to calculate the non-sparse version of the channel impulse responses (CIRs). The CIR estimates are shown in Fig.3. The signal power of channel 2 was lower than that of channel 8. In addition, strong channel fluctuations can be observed. For example, in Fig.2(b), the CIR intensity changed during the geotime of 0.2 to 0.6 s. Similarly, in Fig.2(f), the CIR intensity decreased around the geotime of 0.8 s, compared with that of 0.4 s. Figure 3 shows the scatter plot of the demodulated symbols at the three different symbol rates. At the symbol rates of 1 and 2 kHz, there were no demodulation errors. At 4 kHz, the bit-error-rate (BER) was still low, 0.13%.

The receiver execution time is significantly reduced when the FMP algorithm is used. For the same symbol rate, the receiver using the FMP algorithm is about 4 times faster. If we just use time reversal (no subsequent DFE), at symbol rates of 1 and 2 kHz, the receiver execution time is shorter than the duration of the BPSK data, which is 1.5 s. That means the receiver can approach real-time processing of communication packets in this mode for these two rates.
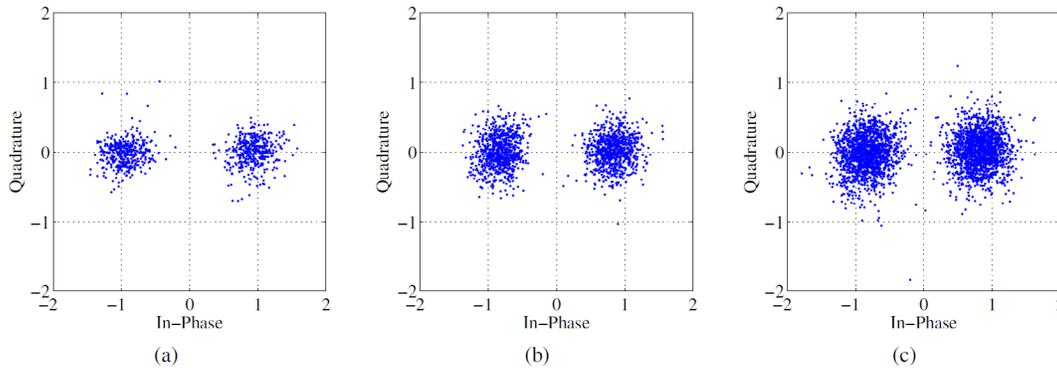
Figure 3. Demodulation results of three symbol rates: (a) 1 kHz, (b) 2 kHz, and (c) 4 kHz, using the time reversal implementation.

The AMDP provides two transmission channels and two transducers. Transmissions via two transducers were implemented. Receiver algorithms for two transducer transmissions were not implemented due to the low computational capacity provided by OMP-L137. However, the transceiver extension to a multi-transducer configuration should be straightforward, based on the existing TR-DFE implementation, for more powerful DSP platform.

In sum, we implemented high frequency time reversal receivers on a DSP platform for the UWA environment. Several optimizations were carried out to reduce the receiver computation cost. For example, the FMP algorithm, as a fast implementation of the BMP algorithm, was developed and tested on the DSP platform. In comparison with the BMP algorithm, the FMP algorithm led to significant speed increase at the DSP platform. The low BERs obtained during our experiment at the different symbol rates demonstrated the effectiveness of our DSP implementation.

IMPACT/APPLICATIONS

The developed acoustic modem prototype can perform robust, high data rate digital communications in shallow water environments. The advancement has direct impacts on defense appliations since underwater acoustic modems are critical to a number of naval operations.

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PUBLICATIONS

[1] S. Matiz, A. Song, and M. Badiey, "DSP Implementation of Time Reversal Acoustic Communication Receivers," Physical Communication, 2015 [Submitted].