Exploitation of Environmental Complexity in Shallow Water Acoustic Data Communications

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LONG-TERM GOALS

Conduct feasibility experiments and associated algorithm design to explore how complexity of the shallow water acoustic environment can be used advantageously in acoustic data communications.

OBJECTIVES

Exploit environmental complexity through both real and synthetic aperture spatial processing to mitigate multipath-related fading and intersymbol interference in acoustic data communications.

APPROACH

The origin of this research is our experience with carrying out ocean acoustic time reversal experiments over a broad range of frequencies. Through a series of experiments conducted jointly between MPL and the NATO Undersea Research Centre (NURC), we have demonstrated that complexity of the ocean environment fundamentally is advantageous and facilitates rather than inhibits the resolution of physical processes, detection of targets, and acoustic telemetry of data. Furthermore, the time reversal experiments have illustrated that the ocean maintains a far greater inherent coherence than previously has been thought possible. Thus, the overall goal of this research is to take advantage of the self-adaptive nature of the complex ocean environment and learn how to exploit fluctuations, scattering, and variability.

Multiple-Input / Multiple-Output (MIMO) Acoustic Data Communications

The active time-reversal approach directly achieves spatial diversity through use of an array of sources. Source array diversity can be complemented with receive array diversity to enable transmitting independent communication sequences in parallel thus increasing the total data rate through the channel. The source array and receive array pair implements a multiple-input/multiple-output (MIMO) system. Although not optimized for overall communication system performance, the time-reversal approach is straightforward, results in relatively compact two-way channel responses, and yields high SNR at the focal depths of the communication sequences. Furthermore, the simple strategy of post-processing the communication sequence observed at a focal depth with a single-channel equalizer can prove effective.

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Synthetic Aperture Acoustic Data Communications

Here our objective is to exploit the dynamic propagation complexity arising from source-receiver motion to achieve the equivalent of an extended physical aperture with a single source-receiver pair. The underlying approach involves using distributed aperture time reversal to compensate for channel dispersion and the resulting problem of intersymbol interference (ISI). In order to fully understand medium complexity in the role of enhancing construction of the synthetic aperture, the focal region structure and temporal sidelobe characteristics obtained with a synthetic aperture array in the ocean medium needs to be explored. In addition, since we typically record transmissions on a vertical receive array, a direct comparison can be made between the synthetic aperture approach to a single receive array element and passive time reversal where a single transmission is received on multiple receive array elements – as well as combinations of the two. Essentially, we will be investigating how the medium complexity maps into spatial diversity between the source and receive array.

WORK COMPLETED

Experimental data collected during a joint experiment with the NATO Undersea Research Centre (NURC) has demonstrated the spatial diversity achieved by modest-aperture, two-dimensional source array for time-reversal acoustic communications transmissions. Post-processing of the received time series by a single-channel equalizer was shown effective in removing residual intersymbol interference (ISI) [4].

RESULTS

In active time reversal, the channel response from each source in a source array to a desired focal point in the ocean is obtained, time reversed, and retransmitted simultaneously from all sources. In the context of acoustic data communications, the time reversed channel response is used as the symbol waveform onto which the data bits are phase (and amplitude in the case of QAM) encoded. Although the symbols are heavily overlapped at the source array, they compress nicely in both time and space at the focal point [1-2].

During FAF-04 (Focused Acoustic Fields Experiment 2004), a modest-aperture, two-dimensional billboard array (BBA) was deployed in 50 m deep water SW of Elba Island off the west coast of Italy (see Fig. 1) [3]. A total of 14 source array elements were distributed over an aperture 8.4 m in the vertical and 0.6 m in the horizontal. The vertical receiving array (VRA) was located at 2 km range and consisted of 16 elements with 2 m spacing. The communications transmissions had a 1 kHz bandwidth at a center frequency 3.5 kHz.

The channel responses measured between the source array elements and the receiving array hydrophone at 34 m depth are illustrated in Fig. 2. The total spread is approximately 20 ms. In active time-reversal communications, the time-reversed version of the measured channel response is treated as one symbol. Using the principle of superposition, each symbol is copied and displaced by the symbol interval (2 ms in this case). Although there is substantial overlap of the transmitted symbols, the individual symbols are compressed back to their original 2 ms duration at the intended receiver. The quality of this compression is indicated by the summation of the autocorrelations of each channel response (denoted q(t) in [3]) and is shown in Fig. 3.

In addition to temporal compression, time-reversal also provides focusing in space as illustrated in Fig. 4. Spatial focusing thus enables the simultaneous transmission of independent communication sequences from the source array to multiple receiving elements on the VRA or multiple-input/ multiple-output (MIMO) data communications) [2,3].

As an illustration, Fig. 5 shows the result of an 8-PSK time-reversal communications transmission received at 34 m depth on the VRA. Some residual intersymbol interference (ISI) is apparent in Fig. 3 (temporal sidelobes) and results in some spreading of the symbol constellations in Fig. 5. Post-processing of the received time series using a single-channel decision feedback equalizer (DFE) results in improved performance as shown in Fig. 6.

IMPACT / APPLICATIONS

Acoustic data communications is of broad interest for the retrieval of environmental data from in situ sensors, the exchange of data and control information between AUVs (autonomous undersea vehicles) and other sensing systems and relay nodes (e.g. surface buoys), and submarine communications.

RELATED PROJECTS

This project is one of several sponsored by ONR Code 321OA and NRL which are exploring various aspects of high frequency channel characterization with specific applications to acoustic data communications and includes experimental work with the NATO Undersea Research Centre (NURC) and the recent KauaiEx (2003) and Makai (2005) experiments.

PUBLICATIONS

[1] G.F. Edelmann, H.C. Song, S. Kim, W.S. Hodgkiss, W.A. Kuperman, and T. Akal, "Underwater acoustic communications using time reversal," J. Oceanic Engr. 30: 852-864 (2006). [published, refereed]

[2] H.C. Song, R. Roux, W.S. Hodgkiss, W.A. Kuperman, T. Akal, and M. Stevenson, "Multiple-input/multiple-output coherent time reversal communications in a shallow water acoustic channel," IEEE J. Oceanic Engr. 31: 170-178 (2006). [published, refereed]

[3] H.C. Song, W.S. Hodgkiss, W.A. Kuperman, M. Stevenson, and T. Akal "Improvement of time-reversal communications using adaptive channel equalizers," IEEE J. Oceanic Engr. 31: 487-496 (2006). [published, refereed]

[4] H.C. Song, W.S. Hodgkiss, W.A. Kuperman, W.J. Higley, K. Raghukumar, T. Akal, and M. Stevenson, "Spatial diversity in passive time reversal communications, J. Acoust. Soc. Am. 120: 2067-2076 (2006). [published, refereed]

[5] J.F. Sifferlen, H.C. Song, W.S. Hodgkiss, W.A. Kuperman, and M. Stevenson, "An iterative equalization and decoding approach for underwater acoustic communication," IEEE J. Oceanic Engr. (submitted, 2006).

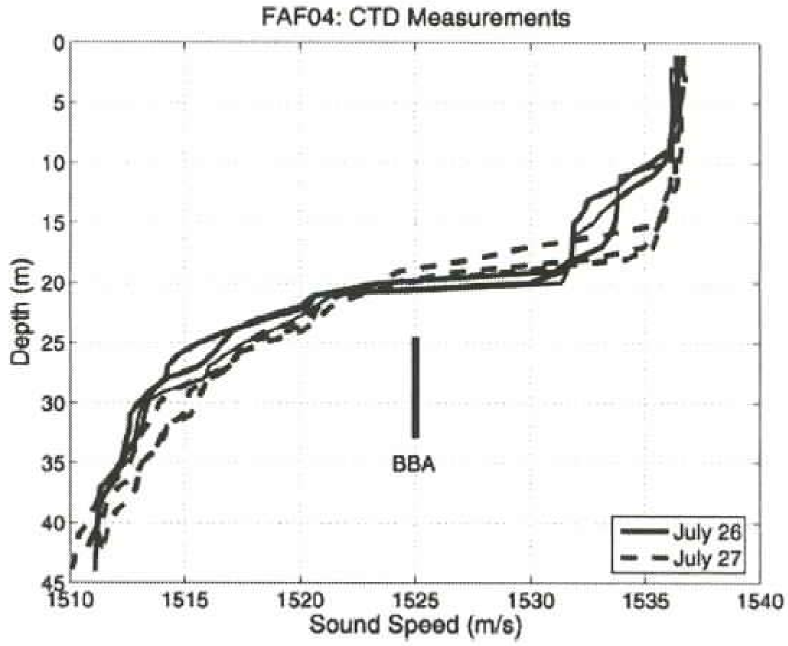

Figure 1. Sound speed profile measured during the communications transmissions along with an indication of the placement of the billboard array (BBA) in the lower half of the water column.

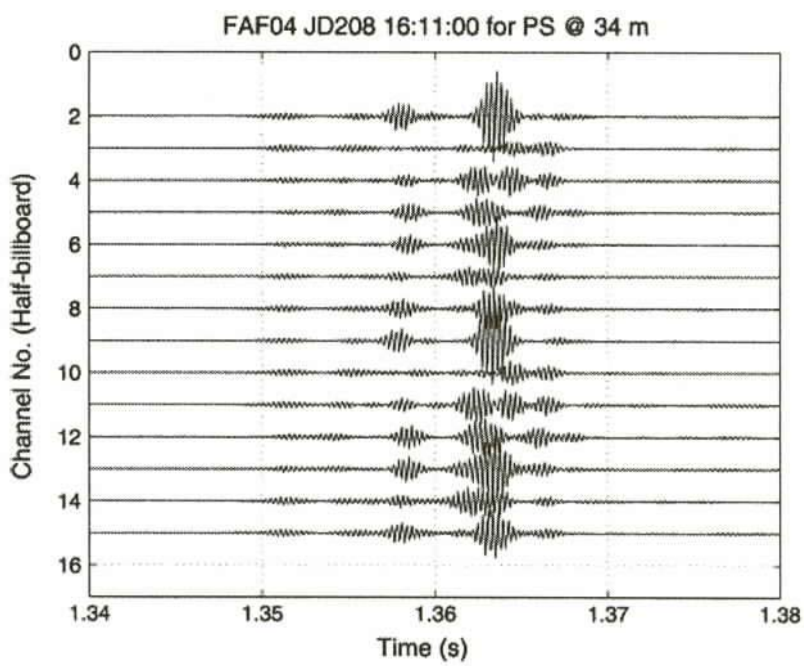

Figure 2. Example of the channel responses from the source array elements to the vertical receive array hydrophone at 34 m depth.

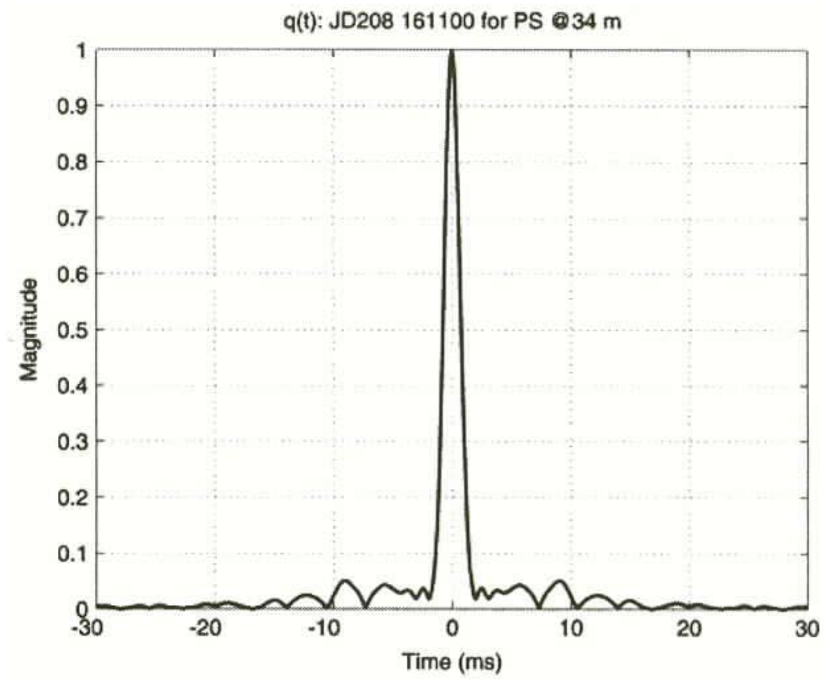

Figure 3. The quality of the time-reversal compression is indicated by the summation of the autocorrelations of each channel response and denoted by q(t).

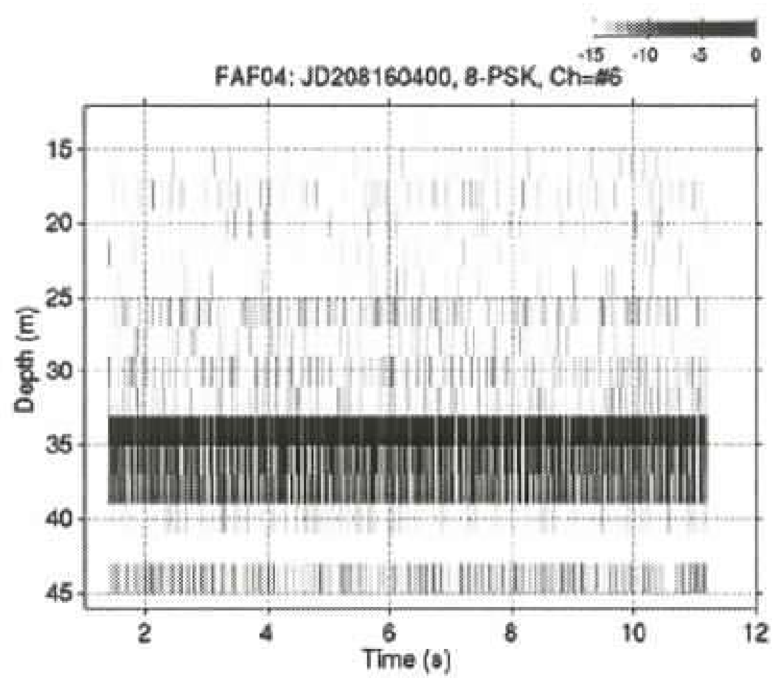

Figure 4. Spatial focusing of the time-reversal transmission at the 34 m depth hydrophone on the vertical receive array.

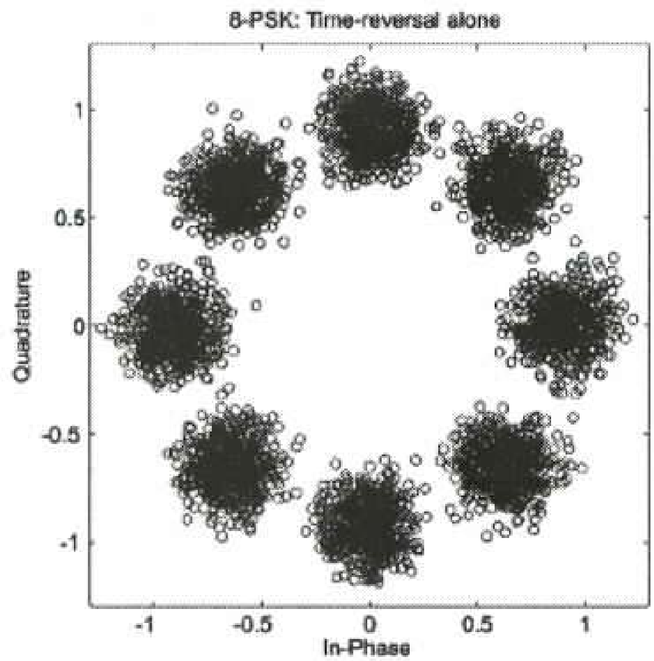

Figure 5. Reception of the time-reversal 8-PSK communications sequence.

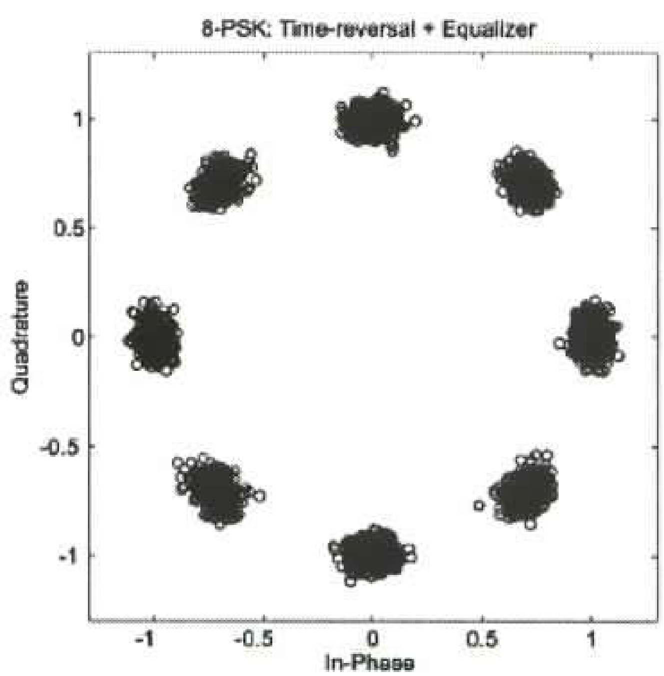

Figure 6. Results after post-processing of the received sequence with a single-channel decision feedback equalizer (DFE).