Shallow Water Fluctuations and Communications

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LONG TERM GOALS

The central effort of this research will be the development of robust algorithms for reliable, high data rate, acoustic communications in a dynamic ocean environment and demonstration of their use with data collected in a shallow water environment.

OBJECTIVE

We will study shallow water fluctuation physics and the enhancement of performance of broad area acoustic communications in shallow water by building on developments in adaptive channel equalizers in conjunction with the time reversal approach.

APPROACH

We have shown in recent work [1] that the time reversal approach exploiting the *a priori* knowledge of the channel is applicable to underwater communications due to its spatial and temporal focusing capability. Temporal focusing (compression) mitigates the intersymbol interference (ISI) resulting from multipath propagation, while spatial focusing achieves a high SNR at the intended receiver with a low probability of interception (LPI) elsewhere. The spatial focusing property enables a straightforward extension to multi-user/multi-access communications.

However, there are two major limitations in the time reversal (TR) approach. First, there always is some residual ISI which results in saturation of the performance. Second, time reversal assumes that the channel is time-invariant while the channel continues to evolve over time in a fluctuating ocean environment, resulting in a mismatch between the measured channel responses and the actual channel responses. To overcome these limitations, the time reversal approach will be combined with adaptive channel equalization which simultaneously eliminates the residual ISI and compensates for the channel fluctuations [2]. In fact, it has been confirmed recently [3] that the time reversal approach combined with channel equalization offers nearly optimal performance in theory when the receiver array provides appropriate spatial diversity.

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14. ABSTRACT
The central effort of this research will be the development of robust algorithms for reliable, high data rate, acoustic communications in a dynamic ocean environment and demonstration of their use with data collected in a shallow water environment.

15. SUBJECT TERMS

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WORK COMPLETED

The impact of spatial diversity in passive time reversal communications [4] has been addressed using at-sea experimental data from transmissions between a single transmitter and a multiple receiver array [see Fig. 1(a)]. The performance of two different approaches was investigated in terms of output SNR versus the number of receiver elements M: (1) time reversal alone (TR) and (2) time reversal combined with channel equalization (TR+EQ). Earlier, Stojanovic [5] developed theoretical performance bounds for various approaches including (1) and (2), under the assumption that the time-invariant channel transfer functions are known to the receiver, an infinite number of taps are used for linear equalization, and no phase tracking is required. The objective of research is to compare the performance between theory and data.

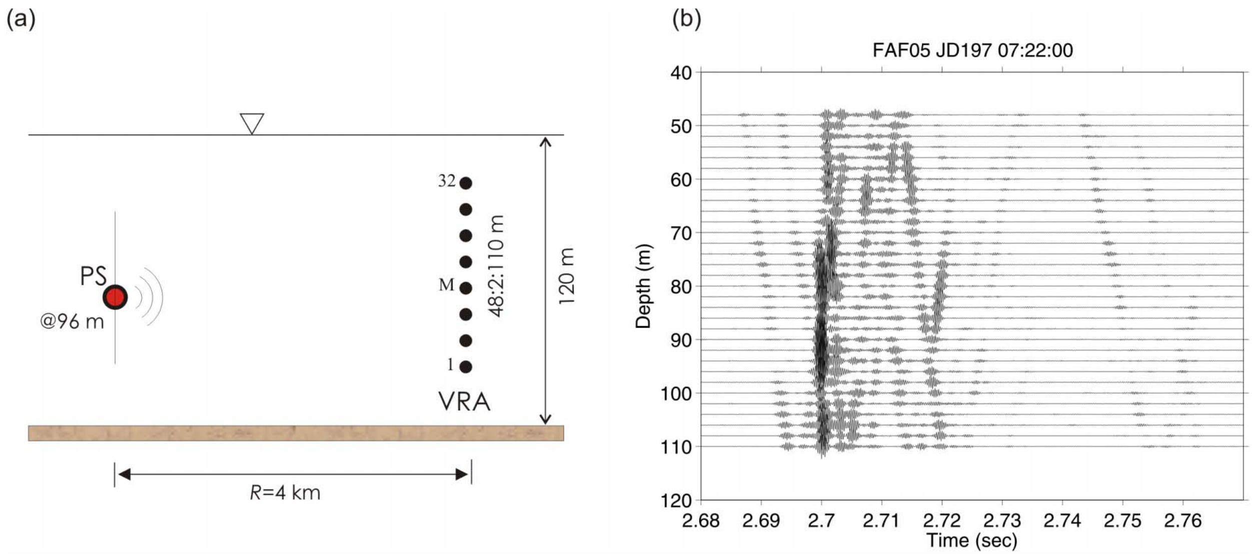


Figure 1. (a) Schematic of passive time reversal communication. (b) The channel impulse responses (CIR) observed by a 32-element vertical array (VRA) from a probe source (PS) at 96-m depth at 4 km range in 120-m deep water.

RESULTS

To achieve the objective, we have selected data from a recent time reversal experiment (FAF-05) conducted in a shallow region of the Mediterranean Sea [6] for two specific reasons. First, the data exhibit a high input SNR across the array (e.g., 12-19 dB), allowing for a clean capture of the channel impulse response (CIR) from a probe signal preceding a communication data packet. Second, the environment was very stable such that the channel remained relatively time invariant during the transmission of each data packet (about 10 s) with both transmitter and receivers fixed, except that there is a small Doppler shift due to mismatch in sampling rate [4] ($f_d = -0.054$ Hz). As a result, the data can be evaluated under conditions similar to those assumed in the theory. An example of the CIR from a probe at 96-m depth in a flat region of 120-m deep water received to a 32-element vertical receiver array (VRA) at 4 km range is displayed in Fig. 1(b). The delay spread is about 80 ms, resulting in an intersymbol interference (ISI) of 40 symbols when the symbol rate is $R = 1/T = 500$ Hz. The complexity of the channel is beneficial for time reversal communications.

Experimental Data

We begin with analysis of the at-sea experimental data [7]. The experimental setup is the same as the one described in [4] for the stationary case and we briefly review the basic signaling scheme. The source level was 179 dB and the shaping pulse was a 15-ms, 2.5-4.5 kHz chirp with a Hanning window, resulting in an effective 100-ms, 3-4 kHz chirp. The duration of the chirp after compression (matched filtering) is $T = 2$ ms equivalent to the symbol period. Since the signal bandwidth is $B = 1$ kHz, the excess bandwidth is 100% ($\alpha = 1$).

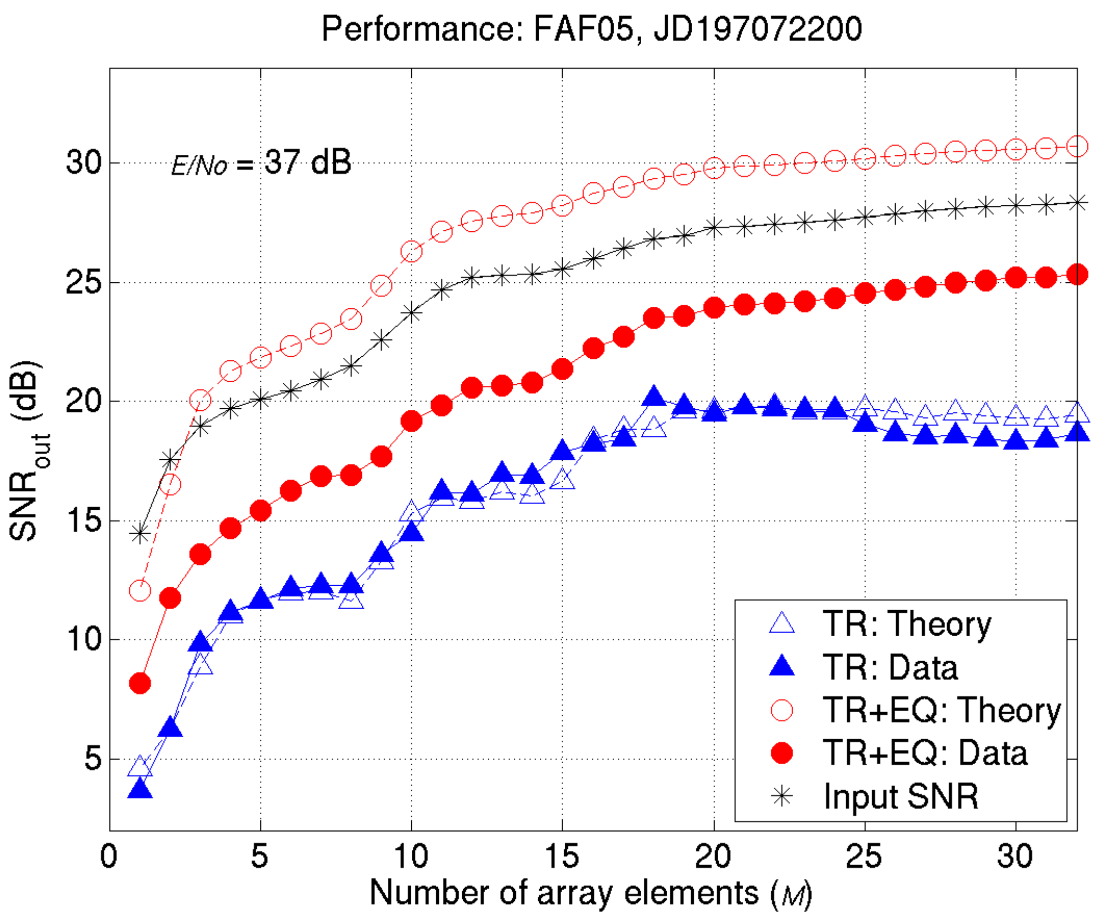


Figure 2. Performance comparison between data (filled) and theory (hollow) versus the number of receiver elements M: (1) time reversal (TR, triangles) and (2) time reversal combined with equalization (TR+EQ, circles). The receiver elements are selected from the bottom. The input SNR (*) is superimposed as a reference.

The resulting performance of time reversal communications from the data using quadrature phase-shift keying (QPSK) modulation is illustrated in Fig. 2: (1) TR (▲) and (2) TR+EQ (●). Figure 3 shows a block diagram of passive time reversal communications to be implemented. The *M* elements are selected from the bottom. A fractionally spaced decision-feedback equalizer (DFE) with tap spacing of $(1/4)T$ is applied to approach (2). The number of taps for the feed-forward and feedback portions of the DFE is 20 and 10, respectively. Overall, approach (2) outperforms approach (1) by 3-5 dB, consistent with the results reported in [4]. It also is interesting to observe the performance of approach (2) follows closely the characteristics of the input SNR (*) in Fig.2. Figure 4 shows an example of scatter plots when $M = 2$.

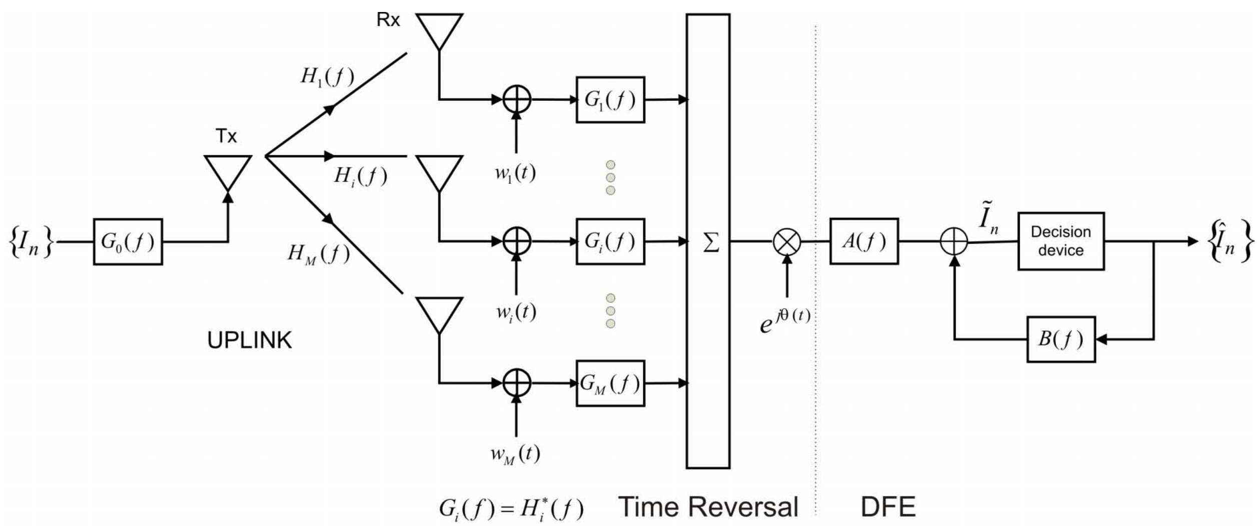
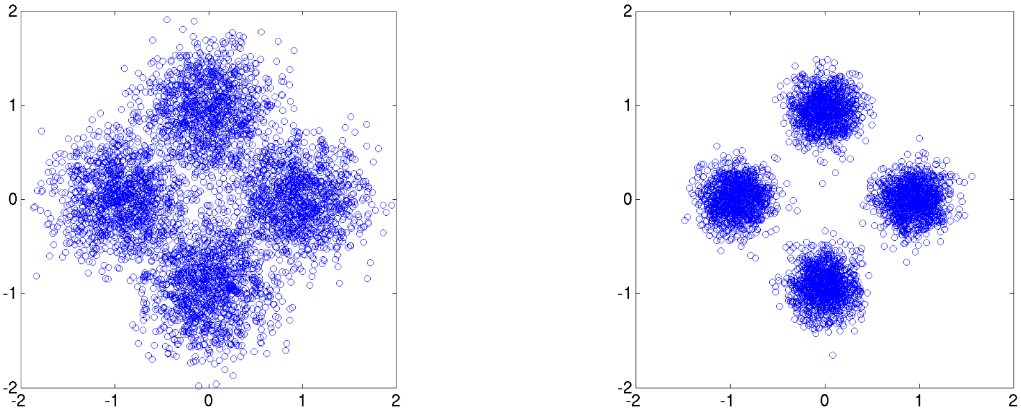


Figure 3. Block diagram for passive time reversal combining followed by a DFE.

Theory

Now the theoretical performance bounds are evaluated from the analytical expressions developed in [5]: Eq. (33) for TR (Δ) and Eq. (46) for TR+EQ (○). The numerical computation involves three components: (i) the CIR of Fig. 1(b) represented by $\gamma(f)$ defined in Eq. (12) of [5], (ii) a raised cosine spectrum $X(f)$ with an excess bandwidth of $\alpha = 1$, and (iii) $E/N_0 = 37$ dB which is described in the Appendix of [5]. The resulting theoretical performance bounds are superimposed in Fig. 2 for comparison purposes. Two important observations can be made. First, approach (1) shows a good agreement between theory and data. Second, in contrast with approach (1), the performance of data using approach (2) is below the theory by approximately 3-5 dB. This is not surprising because the theory assumes perfect knowledge of the channel, infinite number of linear equalizer taps to remove the ISI, and no need for phase tracking. Taking these into considerations, the theoretical performance bounds can provide a useful upper bound for predicting performance of time reversal communications.



(a) **(b)**

Figure 4. Performance of QPSK modulation: (a) time reversal alone (left) and (b) time reversal in conjunction with an adaptive DFE (right). The output SNR is 6.3 dB and 11.7 dB, respectively.

IMPACT/APPLICATIONS

Time reversal mirrors, either active [1,2,8] or passive [4,6,9], exploit spatial diversity to achieve spatial and temporal focusing, a useful property for communications in an environment with significant multipath. Taking advantage of spatial diversity involves using a number of receivers distributed in space. Our recent paper [4] presented the impact of spatial diversity in passive time reversal communications for two different approaches: (1) time reversal alone and (2) time reversal combined with channel equalization (TR+EQ). Earlier, Stojanovic [5] developed theoretical performance bounds including (1) and (2). Furthermore, recently it has been confirmed that approach (2) offers nearly optimal performance in theory when the receiver array provides appropriate spatial diversity [3].

One of the important questions is "Can we predict the performance of time reversal communications from measured channel impulse responses (CIR) for a given geometry (spatial distribution of the receiver array elements)?" The performance comparison between theory and data [7] suggests that the theoretical performance can provide a useful upper bound (3-5 dB above data), taking into account that the theory assumes perfect knowledge of the channel, infinite number of linear equalizer taps to remove the ISI, and no need for phase tracking.

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