Acoustic Communication Using Time-Reversal Signal Processing: Spatial and Frequency Diversity

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Abstract. Time-reversal signal processing can be viewed as a form of matched filtering that operates both in time and in space. Acoustic communication represents a promising potential application of the processing. In designing a communications system, constraints are imposed by the available bandwidth and by the geometry of the time-reversal array. In the present paper, the interplay between bandwidth and array geometry is examined. If the bandwidth is large relative to the symbol rate, time-reversal processing can be successful with sparse arrays. If the array is well populated, the required bandwidth can be reduced. Results from experiments and data-driven simulations are presented.

INTRODUCTION

The principle of acoustic time-reversal can be used to design both elegant physics experiments but also practical devices [1]. In active time-reversal, also called phase conjugation [2], a measured acoustic signal is rebroadcast but in a time-reversed fashion. Ideally, the backpropagated field will focus at the location of the original source. Invoking reciprocity, Dowling [3] showed how similar pulse compression could be achieved passively using a receive-only array. Acoustic communications represents a plausible application of time-reversal processing in the ocean. Both active[4-6] and passive [7-9] versions of the processing have been tested in experiments.

In the present paper, we consider three interrelated factors relevant in designing an acoustic communications scheme based on passive time-reversal signal processing. We first outline how a decision-directed technique can be used to update the matched filters. Updating the matched filters is necessary to compensate for a changing environment. The role of spatial diversity is then studied. Data from an experiment are processed using different subsets of a 14-element receiving array with the communications performance quantified in terms of the resulting bit-error rate. Finally, a form of frequency diversity is studied. Results from a broadband experiment are used to predict communications performance at reduced bandwidths and with different modulation schemes.

DECISION-DIRECTED PASSIVE PHASE CONJUGATION

As implemented in Rouseff et al. [7], passive phase conjugation processing begins by transmitting a single probe pulse. The response to this probe pulse is recorded at each element in the distant receiving array. The data stream is then transmitted. The measured probe responses serve as the matched filters; at each array element, the associated probe response is cross-correlated with the received data stream. The cross-correlation is done in parallel at each element with the outputs then combined across the array. The combined signal is then detected to infer the transmitted data.

At the high frequencies relevant to acoustic communication, the measured probe responses might accurately characterize the acoustic channel for only a fraction of a second. Small changes in the oceanographic environment from factors like internal waves, turbulence or surface waves can change the acoustic environment sufficiently to render the measured probe responses obsolete. Changes in the source or receiver positions can have a similar effect. One approach to compensating for these changes is to break a long data stream into small sections and intersperse additional probe pulses. While this approach has been applied successfully [7], the method is inefficient, as no data can be transmitted while the environment is being reprobed.

Flynn et al. [10,11] proposed an alternative method for inferring the matched filters. Rather than send an isolated probe, the procedure begins by sending an extended probing sequence that is known at the receiver. Combining this knowledge with the observed responses, an initial estimate for each channel's matched filter is generated. These matched filters are then applied to the subsequent data stream. After combining across the array, the demodulator output is quantized to give symbol estimates that are then fed back into a channel estimation algorithm. The estimation algorithm updates the matched filters that are then used to process the next block of data. In this way, past decisions for the symbols direct the form of the matched filters.

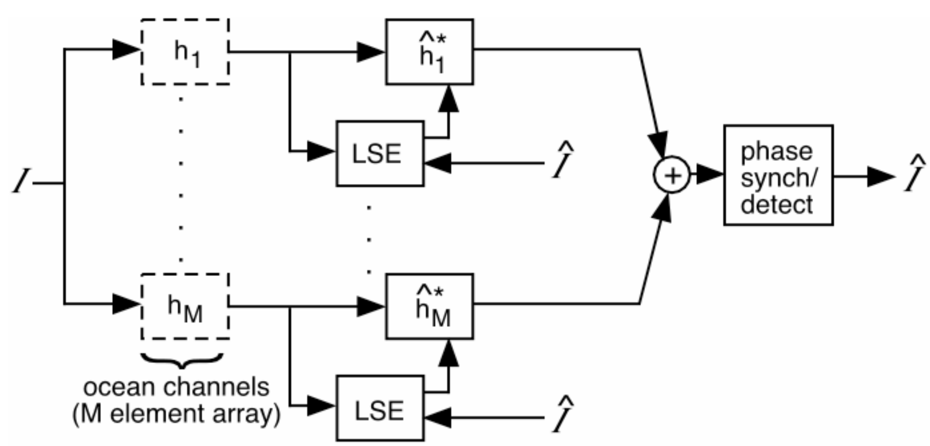

FIGURE 1. Baseband-equivalent of decision-directed passive phase conjugation processing. Data symbols represented by *I* and carets used for estimated quantites.

Figure 1 sketches the baseband-equivalent of decision-directed passive phase conjugation. The sequence of data is represented by I and h_m is the channel response for the m^{th} element in the receiving array. Carets are used to denote estimated quantities. The LSE blocks represent the channel estimation step. Note that each channel is estimated independently from the other channels. This implies that the processing burden scales only linearly with the number of array elements M and suggests significant computational savings compared to joint equalization as M gets large. In practice, the LSE step can be efficiently implemented using a fast iterative method; see the references for the mathematical details [10,11].

As a byproduct, the algorithm produces an estimate for the time-varying channel response at each element in the array. Figure 2 is a sample result for the "drifting source" data set described previously [7]. The figure shows how the channel response evolves over a 5 s window for the deepest element in the receiving array. The bulk time shift is due to the increasing range as the source moves away from the array. A horizontal slice through the figure shows the channel response at a moment in time. Strong multipathing is evident with the later arriving paths typically showing the most variability. The data stream extends over the band from 5-18 kHz while the symbol rate is 2.17 kilosymbols/s. In this example, the channel response was modeled as being 35 symbols in duration corresponding to a delay spread of 16 ms. The channel was updated every 50 symbols, and 100 symbols were used to do the estimation. Communications performance for this case is discussed in the following section.

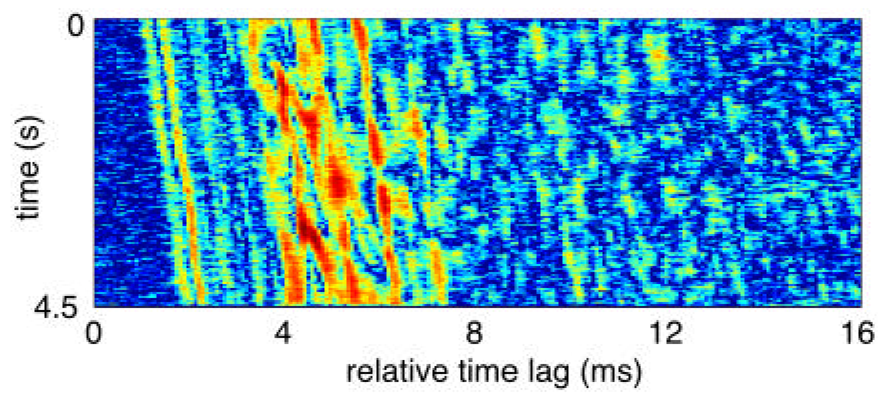

FIGURE 2. Evolving impulse response from Puget Sound experiment. Estimated as byproduct of decision-direct passive phase conjugation processing using full available bandwidth

SPATIAL DIVERSITY: EXPERIMENTAL RESULTS

Time-reversal signal processing exploits spatial diversity by using an array of receivers. The number of array elements and the spacing between elements are important considerations in designing an experiment. At moderate frequencies, it may be practical to assemble a vertical array that spans the water column with elements spaced every half-wavelength. Such a configuration is relatively easy to analyze because the orthogonality of the acoustic modes supported by the ocean waveguide can be exploited [12,13]. At the higher frequencies relevant to acoustic communications, however, a long array with densely spaced elements is unrealistic.

To quantify the effect of spatial diversity at communications frequencies, data from the May 2000 Puget Sound experiment [7] were reexamined. The experiment featured a 14-element receiving array with adjustable spacing between the elements. Five second long sections of Binary Phase Shift Keying (BPSK) data were sent over a 13 kHz bandwidth at 2.17 kilosymbols/s. Measurements were made at various ranges and water depths. In reprocessing the data, communications performance was assessed using subsets of the full 14-element array. The results were quantified in terms of the Bit Error Rate (BER).

Figure 3 shows a typical result plotting the BER versus time for various sized arrays. The range is 4.6 km and the array elements are spaced at 2 m in water 28 m deep. Results are for the same case that was considered in Fig. 2. When all 14 elements are used, the communication is error free. For a reduced number of channels, some errors are apparent. Only when the array is reduced to a single channel, however, is the tracking lost and does the method fail completely. Even with just three elements, the BER is less than 10^{-2} without any error-correction coding. It should be observed that the error rates are relatively stable; the method tolerates erroneous feedback symbols I (Fig. 1) up to error rates beyond the regime typically accepted for data links. The results shown in Fig. 3 represent averages over different combinations of array elements. For example, the seven-channel result is an average of using the top seven, the middle seven, and the bottom seven elements in the array. Interestingly, the BER is relatively insensitive to which array elements are used. The number of array elements is more important than their precise spatial distribution in depth.

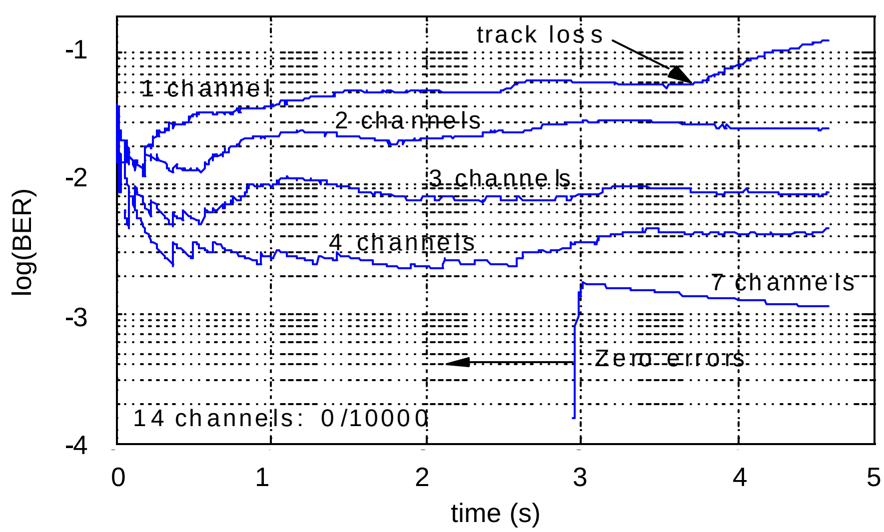

FIGURE 3. Communications performance for Puget Sound experiment. Bit error rate versus time using various subsets of full 14 element array.

FREQUENCY DIVERSITY: DATA-DRIVEN SIMULATIONS

Derode et al. [14] conducted laboratory demonstrations of active time-reversal processing in strongly multiple-scattering environments. If the signal has a wide bandwidth, strong refocusing of the backpropagated signal could be achieved using a single element without need for an array. In a subsequent paper [15], they discussed the implication of this result for communications. The results presented in Fig. 3 can be interpreted in a similar light; because the bandwidth (13 kHz) is large compared to the data rate (2.17 kilosymbols/s), decision-directed passive phase conjugation can be successful with a modest number of hydrophones. The drawback to such an approach for communications is that it is inefficient as a better use of the available bandwidth might allow the data rate to be increased.

Using a bandwidth that is large relative to the data rate represents a form of frequency diversity [16]. Using an array of hydrophones represents a form of spatial diversity. In the present section, we examine the interplay between these two forms of diversity on passive phase conjugation processing. Our approach is to use the results from broadband experiments to predict performance at reduced bandwidths. The mathematical details [17] are beyond the scope of the present short communication; here, we merely sketch how these data-driven simulations are performed and present numerical results.

As noted earlier, a byproduct of decision-directed passive phase conjugation is an estimate for the time-evolving channel response. Figure 2 is an example generated using the full 13 kHz bandwidth of the experiment. These estimates for the channel are used as input to the simulator. For the purposes of the simulator, the estimates generated using the full bandwidth data are treated as being the true time-evolving channel responses. The simulator is then driven using novel synthetic data streams having a bandwidth less than what was actually used in the experiment. Gaussian noise is added to produce a time series for each element in the array. The processor shown in Fig. 1 is applied yielding the synthetic demodulation output. Simulation parameters that can be varied include the bandwidth, the modulation scheme, the SNR and the number of array elements used in the processing. For a fixed set of parameters, the simulations are repeated many times for different realizations of the noise and the data with the results then averaged.

Figure 4 shows the predicted BER as a function of SNR for four combinations of bandwidth and modulation scheme. In Fig. 4(a) and 4(b), the bandwidth is 5.4 kHz while in Fig. 4(c) and 4(d) it has been reduced to 2.7 kHz. In Fig. 4(a) and 4(c), BPSK modulation has been simulated while Fig. 4(b) and 4(d) are QPSK. Because QPSK has two bits per symbol, it represents a doubling of the data rate as compared to BPSK. For each combination, the calculations are repeated using different subsets of the full 14 array elements.

Several observations can be made from Fig. 4. For the case in Fig. 4(a), a BER of 10^{-2} can be achieved at zero SNR if all 14 array elements are used. Similar performance can be achieved with fewer array elements at higher SNR. The results in Figs. 4(b) and 4(c) are similar to one another. This might be expected since the efficiency (defined as the ratio of the data rate to the bandwidth) is the same for the two cases. The case shown in Fig. 4(c) is four times as efficient as that shown in Fig.

4(a). The price paid for this improved efficiency is an error floor; increasing the SNR has little or no effect on the observed BER. The performance in this case is limited by the intrinsic intersymbol interference (ISI) produced by the processor, not by the noise.

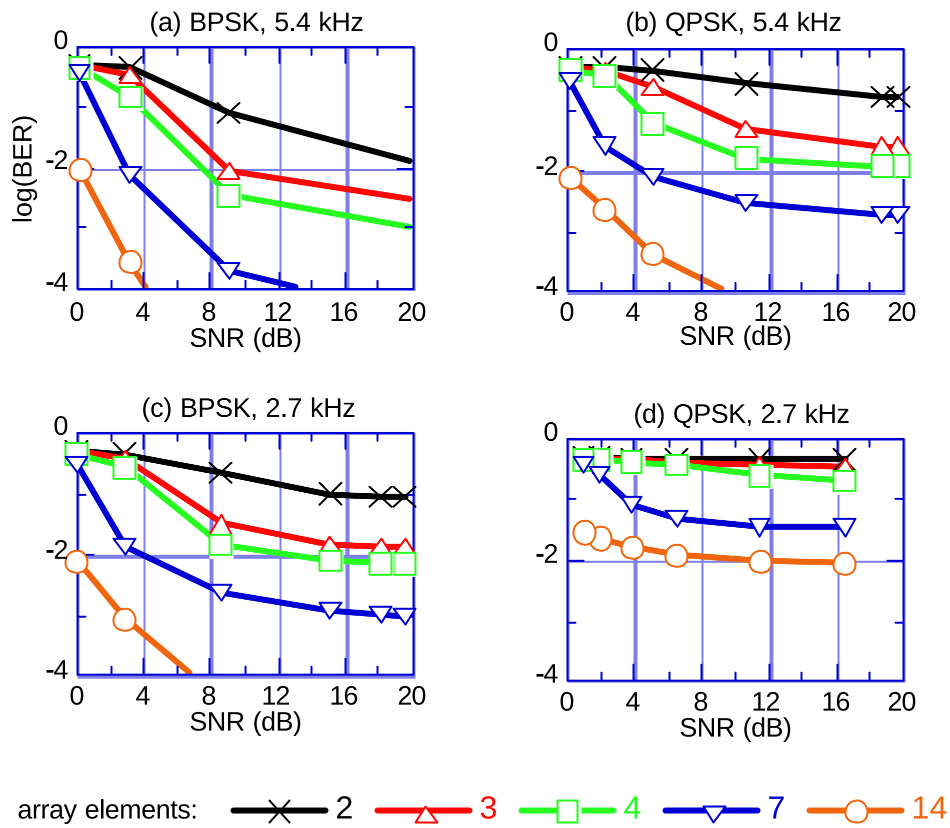

FIGURE 4. Effect of spatial and frequency diversity on communications performance. Bit error rate versus SNR for various modulation schemes (BPSK and QPSK) and bandwidths (5.4 and 2.7 kHz). The data rate in all cases is 2.17 kilosymbols/s. Results are from data-driven simulations.

SUMMARY

Passive phase conjugation is a form of time-reversal processing that uses a multi-element, receive-only array to do acoustic communication. At each array element, the received signal is matched filtered. The decision-directed version of passive phase conjugation outlined in this paper gives a method for updating the matched filters to compensate for the changing environment. A key point is that the computational burden scales only linearly with the number of elements in the array.

Results from field experiments and data-driven simulations demonstrate the interplay between spatial and frequency diversity in time-reversal processing. For our communications problem, an acceptable bit error rate can be achieved with a relatively small number of array elements provided that the bandwidth is large compared to the data rate. As the bandwidth is reduced, however, more array elements are necessary to achieve the same level of communications performance.

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REFERENCES

1. Fink, M., Cassereau, D., Derode, A., Prada, C., Roux, P., Tanter, M., Thomas, J-L, Wu, F., "Time reversed acoustics," *Reports on Prog. in Physics*, **63**, 1933-1995 (2000).
2. Jackson, D. R. and Dowling, D. R., "Phase conjugation in underwater acoustics," *J. Acoust. Soc. Am.*, **89**, 171-181 (1991).
3. Dowling, D. R., "Acoustic pulse-compression using passive phase-conjugate processing," *J. Acoust. Soc. Am.* **95**, 1450-1458 (1994).
4. Akal, T., Edelmann, G., Kim, S., Hodgkiss, W.S., Kuperman, W.A., and Song, H-C., in Proc. 5th European Conf. on Underwater Acoustics, 2000, pp. 989-994.
5. Edelmann, G. F., Akal, T., Hodgkiss, W. S., Kim, S., Kuperman, W. A., and Song, H. C., "An initial demonstration of underwater acoustic communication using time reversal," *IEEE J. Oceanic Eng.* **27**, 602-609 (2002).
6. Heinemann, M., Larraza, A., Smith, K.B., "Experimental studies of applications of time-reversal acoustics to noncoherent underwater communications," *J. Acoust. Soc. Am.* **113**, 3111-3116 (2003).
7. Rouseff, D., Jackson, D. R., Fox, W. L. J., Ritcey, J. A. and Dowling, D. R., "Underwater acoustic communication by passive-phase conjugation: theory and experimental results," *IEEE J. Oceanic Eng.* **26**, 821-831 (2001).
8. Hursky, P., Porter, M.B., Rice, J.A., and McDonald, V.K., "Passive phase-conjugate signaling using pulse-position modulation," in IEEE Oceans Conf. Record **4**, 2001, pp. 2244-2249.
9. Silva, A.J. and Jesus, S. M., "Underwater communications using virtual time reversal in a variable geometry channel," in IEEE Oceans Conf. Record **4**, 2002, pp. 2416-2421.
10. Flynn, J. A., Ritcey, J. A., Fox, W. L. J., Jackson, D. R. and Rouseff, D., "Decision-directed passive phase conjugation: equalisation performance in shallow water," *Elect. Let.* **37**, 1551-1553 (2001).
11. Flynn, J. A., Ritcey, J. A., Fox, W. L. J., Jackson, D. R. and Rouseff, D., "Decision-directed passive phase conjugation for underwater acoustic communications with results from a shallow-water trial," Conference Record of 35th Asilomar Conf. on Sig., Sys. and Comp., vol 2, 2002, pp.1420-1427.
12. Siderius, M., Jackson, D.R., Rouseff, D., and Porter, R.P., "Multipath compensation in shallow water environments using a virtual receiver," *J. Acoust. Soc. Am.* **102**, 3439-3449 (1997).
13. Kuperman, W. A., Hodgkiss, W. S., Song, T. Akal, H. C., Ferla, C. and Jackson, D. R., "Phase conjugation in the ocean: Experimental demonstration of an acoustic time-reversal mirror," *J. Acoust. Soc. Am.*, **103**, 25-40 (1998).
14. Derode, A., Tourin, A., and Fink, M., "Time reversal versus phase conjugation in a multiple scattering environment," *Ultrasonics* **40**, 275-280 (2002).
15. Derode, A., Tourin, A., de Rosny, J., Tanter, M., Yon, S., and Fink, M., "Taking advantage of multiple scattering to communicate with time-reversal antennas," *Phys. Rev. Let.* **90**, 014301 (2003).
16. Proakis, J. G., Digital Communications, New York: McGraw Hill, 1995, pp.777-806.
17. Flynn, J.A., Ritcey, J. A., Fox, W.L.J., and Rouseff, D., *Technical Report UWEETR-2004-0003*, Dept. of Elect. Eng., Univ. of Washington, Box 32500, Seattle, WA 98195-2500.