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Nulling Crosstalk in Underwater Communication with an Adaptive Time-Reversal Mirror

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1. Introduction

A time-reversal mirror (TRM) uses the signals received from a probe source to refocus the signal at the probe source location by backpropagating the time-reversed version of the received signal. The effectiveness of a TRM has been demonstrated in ultrasonics[1)] and ocean acoustics[2)]. Since the concept of adaptivity was introduced to TRM and referred to as an adaptive time-reversal mirror (ATRM)[3)], the applicability of ATRM has been demonstrated in selective focusing onto a weak scatterer among two scatterers[3)], as well as in multiple focusing[4)] with applications to underwater communication for self-equalization at multiple receiving locations. In the present study, ATRM was extended to independent multiple focusing in an ocean waveguide by imposing a set of constraints in the formulation to determine the weight vectors. Subsequently, the developed algorithm was, via simulation, appli ed to the self-equalization process at multiple receiving locations without crosstalk in long-range underwater acoustic communication, where the characteristics of the channel are dispersive and multi-pathed, resulting in severe signal distortion.

2. Adaptive Time Reversal Mirror

As described in **Fig. 1**, the phase-conjugate field at the field location $\vec{r}$ in a frequency domain can be written as

$$p(\vec{r}) = \mathbf{g}^{+}(\mathbf{r}_{\text{arr}} \,|\, \vec{r}_{\text{ps}})\mathbf{g}(\vec{r} \,|\, \mathbf{r}_{\text{arr}}), \qquad (1)$$

where $\mathbf{g}(\mathbf{r}_{\text{arr}} \,|\, \vec{r}_{\text{ps}})$ and $\mathbf{g}(\vec{r} \,|\, \mathbf{r}_{\text{arr}})$ represent the vector form of Green's function for the received acoustic pressure at the *i*-th array element location $\vec{r}_i$ from the probe source position $\vec{r}_{\text{ps}}$ and the field propagated from the *i*-th array element location $\vec{r}_i$ to the arbitrary receiver location $\vec{r}$, respectively, as shown in Fig. 1. The array element positions are expressed as $\mathbf{r}_{\text{array}}$, $(N \times 1)$ column vectors. N is the number of array elements. Superscript $()^{+}$ denotes the Hermitian transpose.

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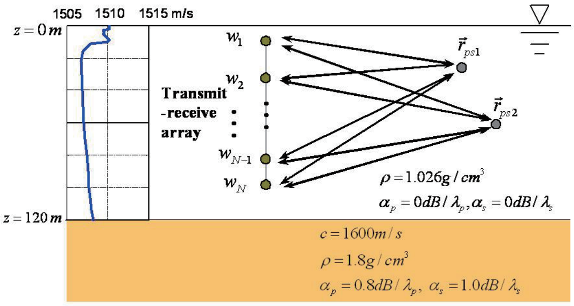

Fig. 1 Description of the ATRM and simulation

By introducing a signal vector for backpropagation $\mathbf{w} = [w_1 \;\; w_2 \;\; \dots \;\; w_{N-1} \;\; w_N]^T$, eqation (1) can, be expressed more generally as

$$p(\vec{r}) = \sum_{i=1}^{N} \mathbf{w}^{+}\mathbf{g}(\vec{r} \,|\, \mathbf{r}_{\text{array}}), \qquad (2)$$

where $\mathbf{w}$ reduces to $\mathbf{g}(\mathbf{r}_{\text{array}} \,|\, \vec{r}_{\text{ps}})$ in a conventional time-reversal mirror. Based on the minimum variance distortionless response (MVDR) of the adaptive beamformer[5)], the weight vector for adaptive TRM can be derived as

$$\mathbf{w} = \frac{\mathbf{K}^{-1}\mathbf{d}_{\text{ps1}}}{\mathbf{d}^{+}_{\text{ps1}}\mathbf{K}^{-1}\mathbf{d}_{\text{ps1}}} \qquad (3)$$

where $\mathbf{d}_{\text{ps1}}$ is the steering vector for the look direction, or the signal vector from $\vec{r}_{\text{ps1}}$ to the array location $\mathbf{r}_{\text{array}}$ in the context of a TRM. To steer a null to $\vec{r}_{\text{ps2}}$, the cross-spectral density matrix (CSDM) in (3) is defined as[3)]

$$\mathbf{K} = \mathbf{d}_{\text{ps1}}\mathbf{d}^{+}_{\text{ps1}} + \mathbf{d}_{\text{ps2}}\mathbf{d}^{+}_{\text{ps2}} \qquad (4)$$

with the constraint, $\mathbf{w}^{+}\mathbf{g}(\vec{r}_{\text{ps1}} \,|\, \mathbf{r}_{\text{array}}) = 1$.

3. Simulation

TRM and ATRM were used to focus at A: (8400 m, 50 m) and focus at A with nulling at B: (8600 m, 70 m). Fig. 2(a) and (b) show the acoustic fields for these cases at 3.5 kHz, respectively. Fig. 2(c) and 2(d) shows the focused field at A and the null at B while maintaining the focus at A, respectively, which indicates a solid line for TRM and a dotted line for ATRM. In the numerical experiment for Fig. 3, the

BPSK and FSK signal sequences were used as probe signals to focus (or, self-equalization) at A and B, respectively. The depth-stacked time series are shown in Fig. 3(a) at ranges of 8600 m without nulling A. As shown in Fig. 3(b), there is unwanted crosstalk, BPSK sequences in this case. With nulling A by ATRM, only the FSK sequences appear in Fig. 3(c) and (d) at a depth of 70 m as expected.

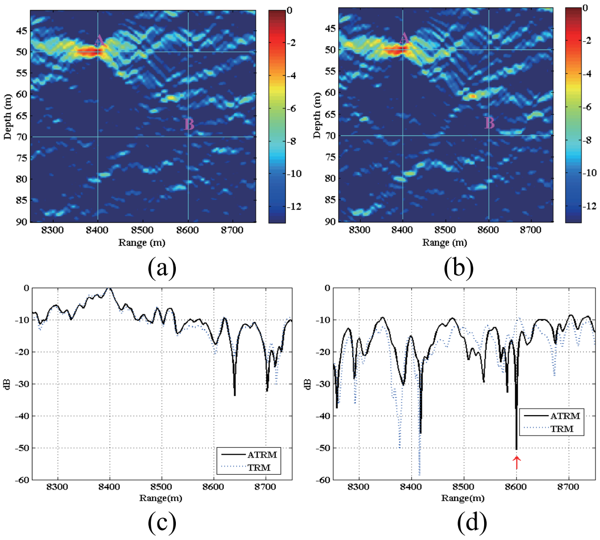

Fig. 2 Contour plot of focusing at A by (a) TRM, (b) ATRM with the null steered at B, and range vs. dB plot at (c) focal point A, (d) null point B.

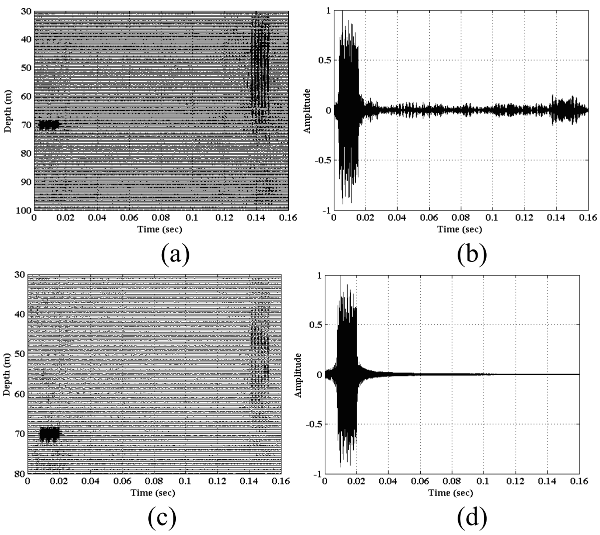

Fig. 3 Signals received at B: (a) depth-stacked signals, (b) signals at 70 m depth with crosstalk, and (c) depth-stacked signals, (d) signals at 70 m depth without crosstalk.

The Green's function obtained from the ocean experimental data[6] was applied to crosstalk nulling in practice. The range between the transmit/receive array and probe source was 8600 m, and the FSK and QPSK symbols are transmitted to the receivers located at depths of 84 m and 70 m, respectively. The performance of the underwater communication was inspected in a simulation using the transfer function for an actual ocean environment. Figure 4 shows the constellation plot of the QPSK sequences by (a) TRM and (b) ATRM. When TRM was used, crosstalk scatters the constellation of the QPSK symbols. However, the use of ATRM effectively removes crosstalk resulting in the convergence of the QPSK symbols to the corresponding points. For the numerical demonstration, noise was not considered to emphasis the crosstalk nulling by the ATRM. However, this study employed the CSDM calculated using the white noise constraint method, which has been shown to be robust[5] in a noisy environment.

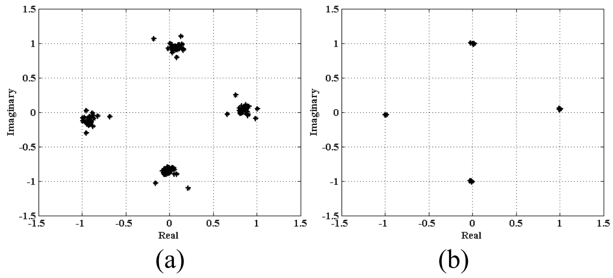

Fig. 4 Constellation plot of the QPSK signal with (a) crosstalk, and (b) nulling crosstalk.

4. Summary

Based on the ATRM, an underwater acoustic communication algorithm to cancel crosstalk between multiple receiving locations was developed and demonstrated through a simulation. The developed algorithm can transmit the different symbol sequences independently and simultaneously to different receiver locations. By crosstalk cancellation, the performance was improved significantly due to the improved SNR.

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