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Proceedings of Symposium on Ultrasonic Electronics, Vol. 37 (2016)

16-18 November, 2016

MIMO underwater acoustic communication using adaptive time reversal in deep ocean

Time reversal による MIMO 水中音響通信

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1. Introduction

Recently, there has been an increasing interest in multiple-input/multiple-output (MIMO) and multiuser communication in the research field of underwater acoustic communication, for high-rate communication or communication with multiple underwater vehicles [1,2].

Time reversal is a promising solution for such MIMO or multiuser communication by realizing space division multiplexing (SDM) based on its spatial focusing effect without sacrificing data transmission rate. In the previous studies, it was revealed that adaptive time reversal (ATR) is very effective for multiuser communication especially in case that sources are very close [3,4]. In this study, ATR is applied to MIMO communication and its performance is evaluated and compared with orthogonal frequency-division multiplexing (OFDM) as a conventional method with experiment data.

2. Theory of Adaptive Time Reversal

Time reversal for single-input/multiple-output (SIMO) communication is named passive time reversal, in which channel response estimated from received probe signal is cross-correlated with received information-bearing signal, and summed over channels. By spatial and temporal focusing effect, in addition to removing intersymbol interference, signals from different sources can be separated. Thus, passive time reversal can be applied to communication from multiple sources.

Additionally, ATR is used to enhance ability to suppress interstream interference. In ATR, the channel response is replaced to ATR probe signal, which is derived as below [5]. Supposing the channel response, $h_j^i(t)$, received at the jth element of the receiver array from the ith source, and its expression in the frequency domain, $H_j^i(f)$, ATR probe signal is given by,

$$\mathbf{w}_i = \mathbf{R}^{-1}\mathbf{d}_i / \mathbf{d}_i^{\dagger}\mathbf{R}^{-1}\mathbf{d}_i \,, \qquad (1)$$

where

$$\mathbf{R} = \sum_i \mathbf{d}_i\mathbf{d}_i^{\dagger} + \sigma^2\mathbf{I} \,, \quad \mathbf{d}_k = \left[H_1^k(f)\cdots H_M^k(f)\right]^T \qquad (2)$$

subject to the constraint that $\mathbf{w}_i^{\dagger}\mathbf{d}_i = 1$. Here, † denotes the complex conjugate transpose, M is the total number of receivers, and $\sigma^2\mathbf{I}$ is a small diagonal loading for a matrix inversion with an identity matrix **I**. Using ATR, the signal from ith source is preserved while signals from other sources are suppressed, that is, null-focusing is created to interfering source points. After ATR combining, a single channel decision feedback equalizer (DFE) is appended as in the previous studies [3,4].

3. Experimental Set-up

An at-sea experiment was carried out in the 1000-m-deep area in the inner part of Suruga-bay. A source, whose frequency band is from 450 to 550 Hz, and a twenty-channel receiver array were used. The source was suspended from R/V Kaiyo with changing the depth from 594 to 956 m at the interval of 20 m. Thus, signals were transmitted from nineteen points. The received signals from multiple sources were synthesized in the post processing to create test signals for MIMO communication. The receiver array was moored at the range of 10 km away from the point of the suspended source. The receiver aperture was spanning at the depth from 848 to 962 m at the interval of 6 m. The sound speed profile at the experiment site and the arrangement of source and receiver array are shown in **Fig. 1**.

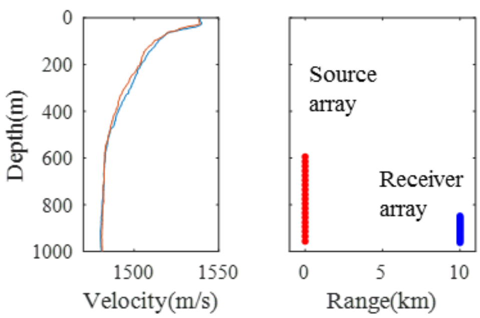

Fig. 1. Sound velocity profile at experiment site and source and receiver arrangements.

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4. Performance Analysis

As mentioned above, signals modulated with binary phase shift keying (BPSK) were transmitted from nineteen points, and the received signals were synthesized to create MIMO communication signals.

Fig. 2 shows output SNRs in case that the number of synthesizing, that is, the channel number of the virtual source array is four. A group of four dot markers connected with dot line indicates a synthesized four channel source array. The horizontal axis is the depth of each source. Thus, source arrays are allocated in turn at the step of 20 m. As shown in this figure, ATR is better than only passive time reversal, and its performance is not dependent on the source array depth. In results of ATR, there occurs no bit error in all the packets.

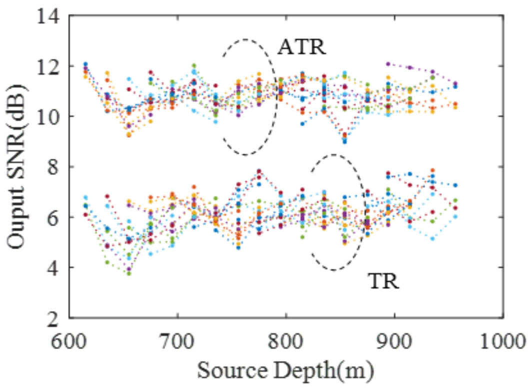

Fig. 2. Output SNRs in case of four channel source array.

Fig. 3 shows one of demodulated results when the number of sources is four, which are demodulated symbols on the constellation map. The source depths are 934.5, 913.5, 894.5 and 874.5 m, respectively, as Tx1 to Tx4 in Fig.3. The upper panels are the results with ATR while the lower panels are the results with zero-forcing (ZF) OFDM. In case of OFDM, MIMO test signals are created using channel responses obtained with chirp signals transmitted from each depth. Channel responses of two packets sequentially transmitted from the same depth convoluted with a pilot symbol and an information bearing symbol of OFDM, respectively. These signals are treated as received pilot and information-bearing symbols. From the received pilot symbol, $H_j^i(f)$, is estimated and ZF detector is given by,

$$\boldsymbol{W} = (\boldsymbol{H}^H \boldsymbol{H})^{-1} \boldsymbol{H}^H \text{, where } H_{ij} = H_j^i(f). \qquad (3)$$

Note that time variance during receiving each OFDM symbol is not included in this analysis. In the meantime, in case of ATR, actual received signals are processed including time variance. It is known that OFDM is weak to time variance during each symbol because its modulation/demodulation is based on IFFT/FFT. Thus, a big advantage is given to OFDM in this comparison, which is not fair to ATR. However, demodulation results of ATR are better than ZF-OFDM as shown in Fig. 3.

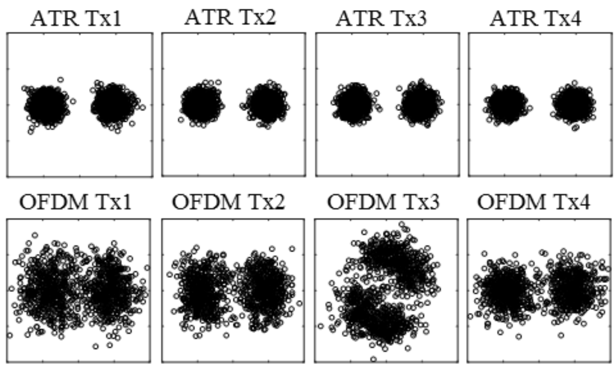

Fig. 3. Demodulated results comparing ATR and ZF-OFDM in case of four channel source array.

In this experiment data, it is possible to achieve demodulation with no error up to eight channel source array with ATR.

5. Summary

The performance of MIMO communication with adaptive time reversal is investigated with real data. As results, it is proved that adaptive time reversal has better performance than ZF-OFDM and it is possible to increase the number of multiplexing source channel up to eight in this experiment data.

Acknowledgment

We deeply thank the crews of the R/V Kaiyo and the research assistants of Marine Works Japan Ltd. We sincerely appreciate Heechun Song who was a host researcher for the first author's visiting research program at the Scripps Institute of Oceanography.

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