MIMO Communication Based on Adaptive Passive Time Reversal in Deep Water

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Abstract**—** In underwater acoustic communication, the multi input multi output (MIMO) technique is used to increase the data rate. However, the MIMO communication performance is reduced by crosstalk. Here, to mitigate the crosstalk, we applied the adaptive time reversal-technique, which was verified using data from an underwater communication experiment conducted in the East Sea in October 2018. The water depth at the experiment site was in the range of 950–1,500 m. The communication signals, modulated with quadrature phase shift keying, were transmitted at ranges of 26 and 30 km and synthesized to generate a multiuser communication sequence.

Keywords—communication; adaptive passive time reversal; multi input multi output; deep water

I. Introduction

Research has recently been performed on multi input multi output (MIMO) communication to increase the data rate in underwater acoustic communication under unfavorable conditions [1-5]. In particular, to realize long-range communication, the data rate is reduced using low frequencies. MIMO communication can be effective in such cases because signals are transmitted simultaneously from multiple users. However, the received signals transmitted through the waveguide are distorted by inter-symbol interference (ISI) due to the multipath. Further, in the case of multiuser communication, the received signals are affected by crosstalk among users. Thus, to realize MIMO communication, an approach is required to remove the influence of the ISI. In this study, to mitigate the crosstalk we applied adaptive passive time reversal (PTR) based on the minimum variance distortionless response (MVDR) to maintain the distortionless response of the desired signal and minimize the response of interference signals [2, 4-6].

The remainder of this paper is organized as follows. In Section II, the conventional and adaptive PTR techniques are briefly reviewed. Section III describes a recent deep-water experiment conducted in the East Sea to demonstrate the proposed approach.

II. Theory

Here, we review the theoretical formulation of the conventional and adaptive PTR techniques.

A. Conventional Approach

In the frequency domain, conventional PTR can be defined as follows:

$$\boldsymbol{P}(\omega) = \boldsymbol{G}^H(\omega)\boldsymbol{R}(\omega) = \boldsymbol{G}^H(\omega)\boldsymbol{G}(\omega)S(\omega) = Q(\omega)S(\omega) \quad (1)$$

where $S(\omega)$ and $R(\omega)$ represent the source and received signals obtained from the vertical line array (VLA), respectively, and G is the Green's function from the source to the VLA.

If a multipath exists and the number of receivers increases, $Q(\omega)$ in Eq. (1) approaches 1. This implies that the source signal is restored through the PTR, enabling demodulation.

B. Adaptive Approach

In order to eliminate the crosstalk between users, an adaptive TR based on MVDR was proposed. Equation (2) expresses the adaptive PTR. Equation (3) expresses an adaptive weight vector used to maintain a distortionless response toward the user j and to minimize the output power.

$$P(\omega) = \boldsymbol{W}^H(\omega)\boldsymbol{R}(\omega) = \boldsymbol{W}^H(\omega)\boldsymbol{G}(\omega)S(\omega) \quad (2)$$

$$\boldsymbol{W}^H(\omega) = \frac{\boldsymbol{K}^{-1}\boldsymbol{G}(\omega)}{\boldsymbol{G}^*(\omega)\boldsymbol{K}^{-1}\boldsymbol{G}(\omega)} \quad (3)$$

where G is the Green's function from the source to the VLA and K is a cross-spectral density matrix (CSDM), which exploits the knowledge of channel impulse responses.

If the number of users is assumed to be 2, the signal for user 2 is removed using the adaptive weight vector for user 1. Similarly, if the adaptive weight vector for user 2 is used, the signal for user 1 is removed.

III. BLAC18 Experiment

In October 2018, a biomimetic long-range acoustic communication 2018 (BLAC18) was conducted in the East Sea, east of Pohang, Korea. The experiment site had a water depth in the range of 950–1,500 m. The communication signals were transmitted at ranges of 26 and 30 km and synthesized to generate a multiuser communication sequence. The sources at the ranges of 26 and 30 km were defined as user 1 and user 2, respectively. The VLA consisted of 16 elements spanning a 42-m aperture with an element spacing of 2.8 m. The source depth in the experiment was 200 m, and the VLA covered a depth range of 179–221 m at a water depth of approximately 950 m. Fig. 1 shows the experimental area. The square (yellow) and triangle (cyan) indicate the source locations of users 1 and 2, respectively. The red circle indicates the VLA location. The depth contours represent the depth in meters.

A schematic of MIMO communication is illustrated in Fig. 2. The sound-speed profile displayed in Fig. 2 is measured via the conductivity, temperature, and depth at the VLA location, which features an underwater sound channel with the channel axis at a depth of 250 m. In Fig. 2, the red and blue circles indicate the receivers and sources, respectively. The probe signal was a linear-frequency-modulation (LFM) chirp with a Hanning window having a duration and frequency of 3 s and 2.2–2.9 kHz, respectively. Communication signals modulated with quadrature phase shift keying were transmitted during the experiment. The aggregate data rate obtained with two users is 2048 bits/s.

Figs. 3 (a) and (b) show the source signals of the two users and the received signals obtained at the VLA, respectively. In Fig. 3 (b), the red box and the blue box represent the LFM chirps of user 1 and user 2, respectively, and the magenta box represents the synthesized communication sequence. From the blue box in Fig. 3 (b), impulsive signals were recorded during the experiment at a range of 30 km.

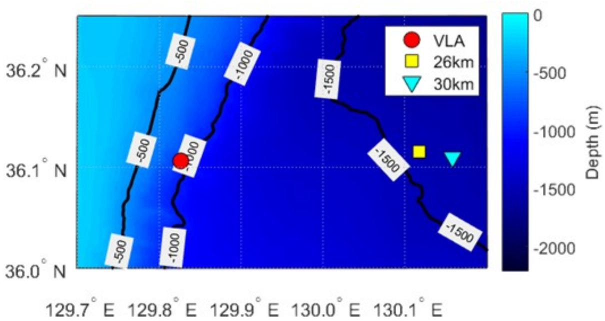

Fig. 1. Experiment area in the East Sea, east of Pohang, Korea.

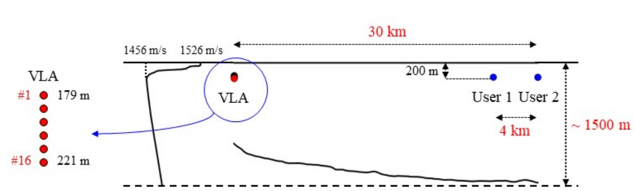

Fig. 2. Schematic of MIMO communication.

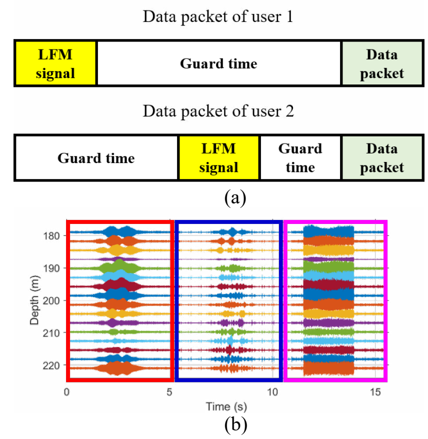

Fig. 3. (a) The transmitted signal packets and (b) the received signals obtained at the VLA.

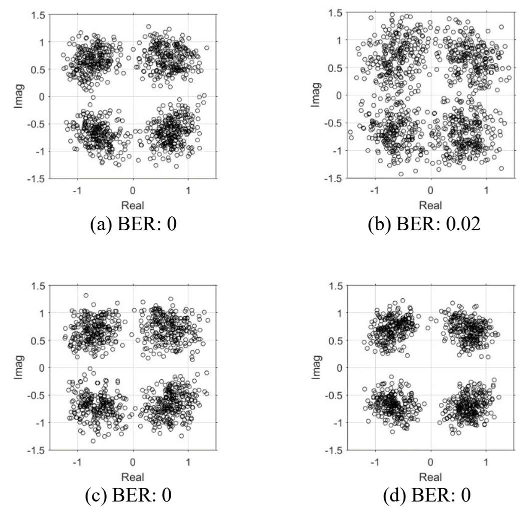

Fig. 4. Results of MIMO communication obtained using two PTR approaches: (a) user 1 with conventional PTR, (b) user 2 with conventional PTR, (c) user 1 with adaptive PTR, and (d) user 2 with adaptive PTR (BER: bit error rate).

IV. Results

Fig. 4 shows the results of the synthesized data for two-user communication. Figs. 4 (a) and (b) show the results obtained using conventional PTR, while Figs. 4 (c) and (d) show the results obtained using adaptive PTR. In addition, Figs. 4 (a) and (c) show the data transmitted from user 1, and Figs. 4 (b) and (d) show the data transmitted from user 2. Using the conventional PTR, the constellation was scattered due to impulsive sounds. The results indicate that the number of bit errors decreases when using adaptive PTR. In addition, Figs. 4 (b) and (d) show that, in the scatter plot pertaining to the use of adaptive PTR from user 2, the bit error rate is 0.02, while the values of the bit error rate for the other cases are 0. This improvement is obtained by minimizing the response of the interference signal through the MVDR technique.

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