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An at-sea experiment of Time-Reversal MIMO communication off the coast of Fukushima

福島沖におけるタイムリバーサル MIMO 通信海域試験

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1. Introduction

Underwater acoustic communication (UAC) techniques are almost the only solution for remote communication over several hundreds of meters in underwater environment, where the electric wave attenuates immediately. However, UACs are confined to bandwidths dependently on the communication distaces, simply because of the frequency dependent attenuation, power limitation and backgroud noise. Generally, the low and narrow frequency bands are required for long range communication, therefore the data rate of UAC are considered to be inverse proportional to the communication distance. A past study suggests that the range-rate product of the UAC obeys the 40 kmkbps boundary1), and the performances of the commercial UAC modems usually follows this limitation.

Recently, the spatial devision multiplexing (SDM) based multiple-input/multiple-output (MIMO) communication techniques have been widely studied for the improvement of the data rate of UACs. In this study, we conducted an at-sea MIMO communication experiment by SDM using the time reversal (TR) communication technique2). The results demonstrate (1) the improvement of the communication rate by SDM using TR, and (2) the improvement of the perfomance which far exceeded the range-rate product boundary of 40kbpskm.

2. Experimental Configuration

The at-sea experiment for long-range UAC MIMO off the coast of Fukushima, named YK20-11C, was carried out in Sept. 2020. **Fig. 1** shows the sea area of the experiment. The bathymetric line profile between source and receiver was nearly flat about 750m depth. The 6 m equi-spaced 4-elements vertical source array and the 24-elements vertical 25 m long receiver array were moored at the depth of about 400m. The distance between source and receiver was about 12.5km. The signaling parameter for the experiment is summarized in **Table. 1**.

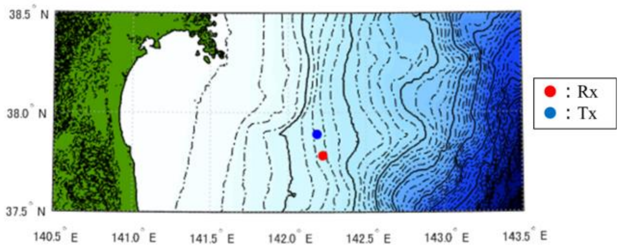

Fig. 1 Sea map of the experimental location

Table 1 Signaling parameters

parameter	*value*	*units*
Carrier Frequency	6.5	kHz
Symbol Rate	4	kHz
Max. Num. of Tx.	4	channels
Modulation	Single Carrier	-
M-ary	1,2,3	bits/symbol

3. Time-Reversal MIMO Receiver

Assume that the channel response from the ith transmitter to the jth receiver is $h_{ij}(t)$, the original transmitted signal is $s_i(t)$, and the received signal at the jth receiver is $r_j(t)$, TR process for single transmission is expressed as:

$$\sum_j \hat{h}_{ij}(t) \otimes r_i(t) = \left(\sum_j \hat{h}_{ij}(t) \otimes h_{ij}(t) \right) * s_i(t)\,, \qquad (1)$$

where ⊗ denotes the cross correlation, and * denotes the convolution. In this study, the estimated channel response $\hat{h}_{ij}$ was acquired by the measurement of the frequency modulated signals.

In SDM-MIMO communication, the information bearing signals in the same frequency band are sent simultaneously from each transmitter. In this study, to enhance the interference cancelation ability of the TR process, an adaptive weighting scheme2) based on the minimum variance distortionless response was utilized. The adaptive weight function in frequency domain $W_{ij}(f)$ is calculated as follows:

$$\mathbf{w}_i = \mathbf{R}^{-1}\mathbf{d}_i \big/ \mathbf{d}_i^{\dagger}\mathbf{R}^{-1}\mathbf{d}_i\,, \qquad (2)$$

where

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$$\mathbf{R} = \sum_k \mathbf{d}_k \mathbf{d}_k^\dagger + \sigma^2 \mathbf{I}, \mathbf{d}_k = \left[\hat{H}_{k1}(f)\cdots\hat{H}_{kM}(f)\right]^T$$

$$\mathbf{w}_i = \left[W_{i1}(f)\cdots W_{iM}(f)\right]^T$$

subject to constraint that $w_i^T d_i = 1$. Here, over script † denotes the complex conjugate transpose, M is the number of receivers, and $\sigma^2\mathbf{I}$ is a small diagonal loading for a matrix inversion with an identity matrix. In the TR MIMO receiver, the estimated channel response is replaced by the inverse Fourier transformation of the adaptive weight function calculated from **Eq.** (2). After the TR process, the signals are demodulated and equalized by a recursive least square based decision feedback equalizer.

4. Results

Fig. 2 shows the results of the single-input/ multiple-output (SIMO) with the signal modulated by 8-PSK (3 bits/symbol). Note that the results of the bit error ratio (BER) below 10^{-4} are error free and plotted on the line of BER = 10^{-4}. In this paper, the data packets within 15 seconds after the channel estimation opportunities are plotted on the figure. It should be noted that the OSNR and BER deteriorates with time advancement from the channel estimation. The most of data packets were error free, but there can be seen bit errors in the data packets with post-process (output) SNR (OSNR) below about 16dB. **Fig. 3** shows the results of 4-channels MIMO with QPSK modulation signal (2 bits/symbol). The punctured convolutional coding of rate 5/6 and Viterbi decoder are used for coded BER results. As is the case with SIMO results, the bit errors can be observed below typical values about 12 and 8 dB for uncoded and coded BER results, respectively. The differences of OSNR-BER relations among SIMO, uncoded MIMO, and coded MIMO are due to multi-level modulation and coding gain. The percentages of error free packets of SIMO, MIMO, and coded MIMO were 92%, 47%, and 98%, respectively.

The result in Fig. 3 demonstrates that the TR-MIMO receiver could equalize the information bearing signals successfully. Although the OSNR of the MIMO results are about 6 dB below from the SIMO results, the BER characteristics of coded MIMO results show slightly better performance than that of SIMO. From this, it is suggested that the communication speed can be improved from 3 bits/symbol to 6.7 bits/symbol by MIMO communication as compared with the case of SIMO communication, while maintaining the reliability of the BER. The range-rate product of the maximum throughput in this MIMO experiment were 333 (coded) and 400 (uncoded) kbps km.

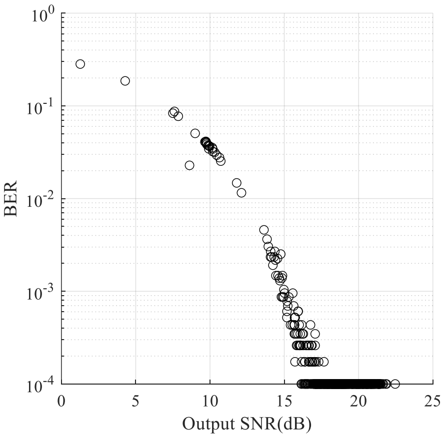

Fig. 2 Relationship of the output SNR and BER for single channel transmission of 8PSK modulated signal.

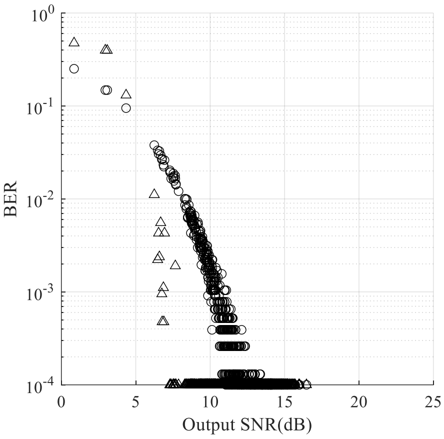

Fig. 3 Relationship of the output SNR and BER for multiple channels (4 channels) transmission of QPSK modulated signal. Opened circle/triangle show the result of the uncoded/coded (5/6) BER.

In this study, we demonstrate the performance of TR MIMO receiver for long range at-sea experiment data. It was confirmed that the data rate of the communication was certainly improved by spatial multiplexing, and it was shown that a large performance improvement could be expected compared to the conventional communication systems.

Acknowledgment

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References

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