2E3-4

An experiment of 400 kbps・km class underwater acoustic MIMO communication in shallow sea

Yukihiro Kida, Mitsuyasu Deguchi, Takuya Shimura (JAMSTEC)

1. Background

The underwater acoustic communication (UAC) technique is the key solution for the mid-to-long range wireless communication in the sea water because of the strong attenuation of the electric waves. However, the UAC channels have limited bandwidth, and often cause signal dispersions in time and frequency. As a prediction of the UAC performance, a past study suggests that the range-rate product of the UAC would be limited to the 40 km × kbps boundary1), and the performances of the commercial UAC modems follows this limitation in general. It is considered indispensable to improve the bandwidth efficiency in order to speed up UAC over long distance where the bandwidth limited strictly. Similar to in-air wireless communications, the spatial division multiplexing (SDM) based multiple-input/multiple-output (MIMO) communication techniques are expected to exploit the efficient usage of the bandwidth in the UAC environment.

Past studies have shown that the adaptive passive time-reversal (APTR) is a very effective method for SDM-MIMO UAC in multipath rich environment from the viewpoint of achieving both the convergence of the time spread and spatial focusing2-3). However, there have hardly been any researches demonstrating high spectral efficiency UAC at water depths shallower than several hundred meters where numerous practical applications can be considered: such as maritime affairs and natural resource development.

In this study, a result of an at-sea experiment of the SDM-MIMO UAC using APTR method over the communication distance of 13.5km in shallow sea of 200 m water depth. We investigated that the performances of the APTR method with changing the signaling parameters, and report a remarkable result of the quest for speed up of the UAC in long distance.

2. Time-Reversal MIMO Receiver

Assume that the channel response from the *i*th transmitter to the *j*th receiver is $h_{ij}(t)$, the original transmitted signal is $s_i(t)$, and the received signal at the *j*th 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 the experiment, 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. 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,

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

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

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.

3. Experimental Parameters

The at-sea experiment was carried out at Fukushima offshore in July 2021, where the water depth was about 200 m. Fig. 1 shows the sound speed profile estimated from the temperature measurement by the expendable bathythermograph and the bathymetric profile between the transmitter array and the receiver array. The transmitter array consists of 5 acoustic projectors vertically moored at the depth of about 145 to 170 m. The vertically aligned 24-element hydrophones are used for receiver array at nearly same depth. We summarized the signaling parameter for the experiment in Table 1. The communication signal is modulated by phase shift keying (PSK) using single carrier modulation scheme for 6.25 ± 2.25 kHz signal band. The overhead of the signaling frame

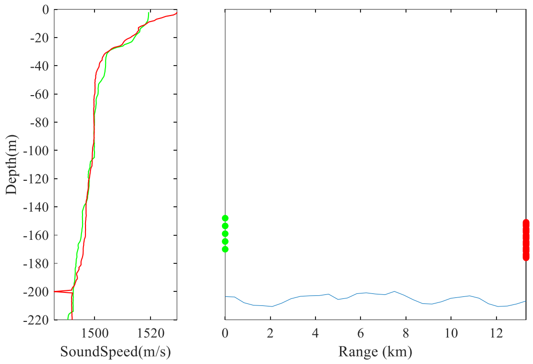

Fig. 1 left: sound speed profile, right: bathymetric profile, and transmitters (green) and receivers (red) location.

Table 1 Signaling parameters

Parameter	Value	Unit
Carrier Frequency	6.25	kHz
Signal Bandwidth	4.5	kHz
Num. of transmitters	1 - 5	channels
Modulation	Single Carrier	-
M-ary	1, 2, 3	bps/Hz
Signaling overhead	9.6 - 51.7	%

including synchronization codes, probe signal for channel response estimation utilized for APTR processing, and the training sequences for DFE, were varied from about 9.6 to 51.7 %. Namely, the data rate of the uncoded signaling for this UAC experiment was varied from about 2.2 to 61 kbps.

4. Results

Fig. 2 illustrates a temporal variation of the channel impulse response (CIR) of a transmitter-receiver pair acquired during the experiment. The time spread of the CIR was about up to 150 ms considering the thresholding value of -30 dB referred to the peak amplitude of CIR. The acoustic arrivals below the delay of about 40ms, which occupies most of the energy of the CIR, hardly fluctuates in amplitude within several tens of seconds, because these arrivals were considered to be surface refracted and bottom reflected waves. As a result, it is considered that a temporally stable propagation was realized throughout the experiment.

Fig. 3 shows the BER of the APTR-DFE results for the signaling frame of 14.6 % overhead. Here and after, we describe “*N*” simultaneous transmission as “*N*”IMO, excluding the result of single-input/single-output (SIMO). In SIMO result for this configuration, the bit-error was not observed. The most results of 2IMO, 3IMO, and

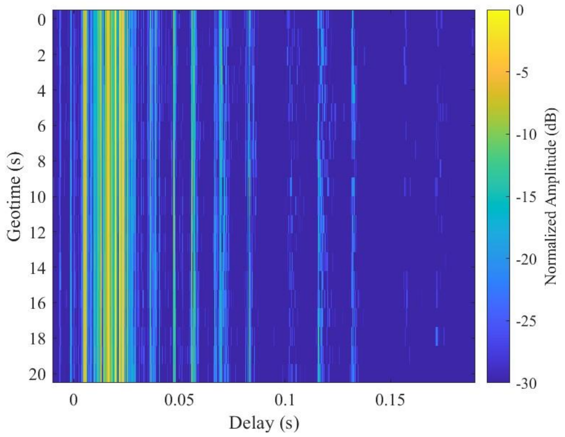

Fig. 2 Amplitude of CIR in delay–Geotime.

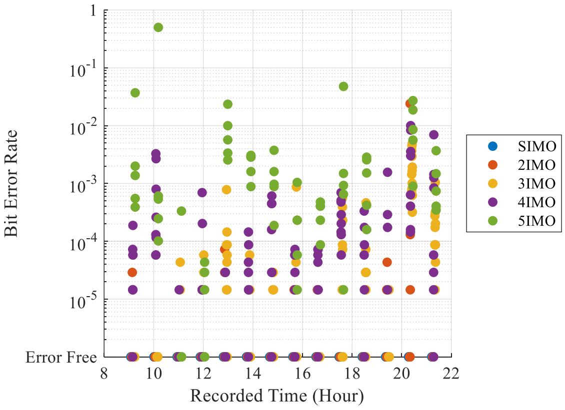

Fig. 3 relationship between recorded time of the signal packet and BER of processing result for 1-5 MIMO transmissions of QPSK signal.

4IMO show stable performance with practical BER. Although there were time slots of unstable performances, the 5IMO result also shows a practical BER, which may be useful depending on the environmental conditions. In the signaling configuration of the result of Fig. 3, the uncoded (without forward error correction coding) data rate of SIMO and 5IMO signal were 7.6 and 37.9 kbps, respectively. These results propose a possibility of breaking through the range-rate limitation of UAC by SDM-MIMO using the APTR method.

Acknowledgment

This work was supported by the Innovative Science and Technology Initiative for Security program offered by the Acquisition, Technology & Logistics Agency (grant number: JPJ004596).

References

1. D. B. Kilfoyle and A. B. Baggeroer, IEEE J. Ocean. Eng., **25** (2000) 4-27.
2. Y. Kida et al., Jpn. J. Appl. Phys., **57** (2018) 07LG01
3. Y. Kida et al., Jpn. J. Appl. Phys., **61** (2022) SG1057

kiday@jamstec.go.jp