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Demonstration of High Rate MIMO Communication with Adaptive Time Reversal in Tank Experiment

Adaptive Time Reversalによる高速MIMO音響通信の水槽試験による実証

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1. Introduction

In our previous studies, it was shown that the method of adaptive passive time reversal (PTR) combined with decision feedback equalizer (DFE) is very effective for spatial division multiplexing (SDM) [1,2].

In MIMO communication, it is important how many channels can be multiplexed to increase the total data rate. Especially, in underwater acoustic communication, the available bandwidth is very narrow, comparing with radio communication in air. Thus, performances should be also evaluated in terms of the spectral efficiency. In [3], space-time bit-interleaved coded demodulation is applied for MIMO communication in shallow water and its spectral efficiency is 0.55 bps/Hz/ch. In experiments of MIMO communication with OFDM [4], its spectral efficiency is 0.5 bps/Hz/ch. In [5], three kinds of MIMO DFE were proposed and performed in at-sea experiments, and the highest efficiency is 0.66 bps/Hz/ch. Thus, the spectral efficiency in these studies are less than 1.0 bps/Hz/ch.

In contrast, using adaptive PTR, it is possible to increase number of multiplexing in MIMO without degrading its high spectral efficiency. In simulation analysis [6], it is confirmed that demodulation performance of adaptive PTR do not deteriorate in spite of increasing the number of transmitter channels. Additionally, in analysis synthesizing experimental data, it was revealed that the performance of adaptive PTR for MIMO communication is much better than that of OFDM [2]. However, in this analysis, it was difficult to evaluate in precise quantitatively, because transmitter array was synthesized (virtual). Thus, in this study, tank experiments with real transmitter array were carried out, and the performances of adaptive PTR for MIMO communication are compared with that of OFDM as a conventional method.

2. Adaptive Passive Time-Reversal MIMO

Assuming that the channel response from the *i*th transmitter to the *j*th receiver is $h_{ij}(t)$ and the original transmitted signal is $s(t)$, the received signal at the *j*th element of receiver array is $r(t)$, adaptive PTR process is expressed as

$$\begin{aligned}\sum_j w_{ij}(t)\otimes r_j(t) &= \sum_j w_{ij}(t)\otimes\left(\sum_k h_{kj}(t)*s_k(t)\right)\\ &= q_i(t)*s_i(t)+\sum_{k\neq i} q_{ik}(t)*s_k(t)\end{aligned} \tag{1}$$

where * and ⊗ indicate convolution and correlation, respectively, and $w_{ij}(t)$ is adaptive time-reversal filter [7]. Here, $q_i(t)$ is the auto-q-function for the *i*th transmitter and $q_{ik}(t)$ is the cross-q-function between the *i*th and *k*th transmitters. If adaptive PTR works well, $q_i(t)$ is close to a delta function and $q_{ik}(t)$ is close to zero, that is, ISI and CCI are suppressed, respectively. Similarly as in the previous studies [1,2,6], after adaptive PTR combining, a single channel DFE is appended to remove residual ISI and CCI.

In the meantime, in case of OFDM, minimum mean square error (MMSE) combiner is used for MIMO array processing. Assuming that the channel response in the frequency domain is $H_{ij}(f)$, MMSE combiner is derived as,

$$W_{MMSE} = \left(\mathbf{H}^H\mathbf{H}+\sigma_z^2\mathbf{I}\right)^{-1}\mathbf{H}^H \tag{2}$$

where the element of $\boldsymbol{H}$ is $H_{ij}(f)$, which is estimated by the pilot symbol transmitted before an information-bearing symbol. If this technique works ideally, SDM should be realized.

3. Experiment Setup

The tank experiment was carried out in a rectangular tank as shown in **Fig. 1**. In this experiment, transducers whose beam pattern is toroidal, close to omni-directional, as shown in Fig. 1, were used for the transmitter array. Hence, reflections from not only surface and bottom but also side, fore and back walls were received. Thus, eight receivers were arranged in a cross shape, not vertical line array, as shown in Fig. 1. Therefore, the performance of 4×8 MIMO communication was evaluated in three dimensional and very strong reverberation environment.

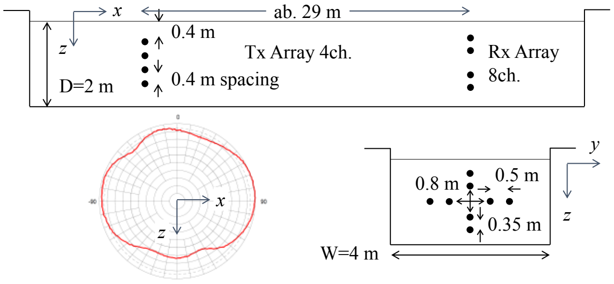


Fig. 1 Schematic of Tank Experiment.

In the experiment, the carrier frequency is 20 kHz and the bandwidth is 5 kHz. In case of adaptive PTR-DFE, the information-bearing signals contain 1,024 symbols at the rate of 5 ksps. In case of OFDM, number of subcarriers is 1,024 in the frequency band of 5 kHz, and the length of guard interval (GI) is 0.12 ms. For OFDM demodulation, pilot signals to estimate channel responses are transmitted prior to the information-bearing signals. For reference, this type of pilot arrangement is called block type, while comb type or lattice type arrangements are adopted in a time-varying channel. Thus, the same amount of information is transmitted in the approximate same duration in both cases of adaptive PTR and OFDM for fair comparison.

The purpose of this study is to compare the performance of adaptive PTR and OFDM under the assumption that channel responses are measured clearly without CCI. Thus, the probe signal for adaptive PTR-DFE and the pilot signal for OFDM are transmitted in advance to the information-bearing signals from each transmitter one by one, not simultaneously. After that, the information-bearing signals are transmitted simultaneously from all the transmitters. Because the channel in the tank experiment is not time-varying, any estimation error is not caused even if the information signals are transmitted long after the probe or pilot signals.

4. Results

In **Fig. 2**, the channel response from the top transmitter to the top receiver is shown. As mentioned above, reflections from side walls as well as surface and bottom are received. Thus, numerous multipaths are received. Additionally, waves which make twice round trips are observed. Thus, the acoustic channel is very highly reverberant. The length of reverberation is 0.12 ms approximately, which is equal to the length of GI in OFDM signals.

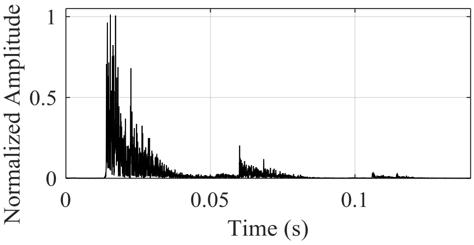
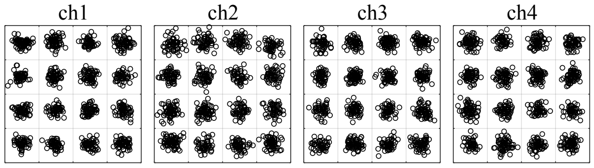


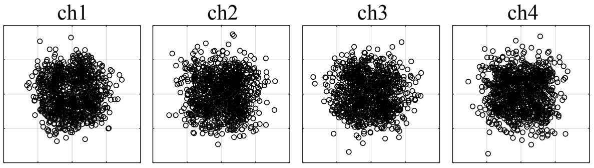
Fig. 2 Channel response in the experiment.

In **Fig. 3**, demodulated symbols in case of adaptive PTR-DFE with 16 quadrature amplitude modulation (QAM) are shown. This result shows that it is possible to achieve MIMO communication at the efficiency of 4.0 bps/Hz/ch by adaptive PTR-DFE. In the meantime, in **Fig. 4**, demodulated symbols in case of MMSE-OFDM with quadrature phase shift keying (QPSK) are shown. In this result, demodulation fails defectively even at the efficiency of 2.0 bps/Hz/ch.



ch1	ch2	ch3	ch4
oSNR : 19.6 dB	oSNR : 18.0 dB	oSNR : 19.1 dB	oSNR : 18.9 dB
SER : 0	SER : 0	SER : 0	SER : 0

Fig. 3 Results of adaptive PTR-DFE with 16QAM.



ch1	ch2	ch3	ch4
oSNR : 4.4 dB	oSNR : 3.3 dB	oSNR : 4.1 dB	oSNR : 3.8 dB
SER : 200	SER : 256	SER : 222	SER : 243

Fig. 4 Results of MMSE-OFDM with QPSK.

5. Summary

It was demonstrated that adaptive PTR-DFE can achieve much better performance than OFDM for MIMO communication in tank experiments.

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