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High-Speed Underwater Acoustic Communication Using Orthogonal Signal Division Multiplexing: A MIMO Approach

直交信号分割多重を用いる水中音響通信の MIMO による高速化

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1. Introduction

Underwater acoustic (UWA) communication in shallow water is still challenging due to large time and frequency spread of the channel, which act as barriers to achieve high-speed and reliable communication. Applying digital communications such as single-carrier system with decision feedback equalizer and orthogonal frequency division multiplexing (OFDM) has actively been researched[1)]. As an alternative, the application of orthogonal signal division multiplexing (OSDM) has been proposed by the author. It has been found that OSDM may lead to high-quality communication in the presence of channel reverberation and large Doppler shifts[2)]. However, effective data rate remains much below to other systems, such as radio communication.

Considering the bandwidth limitation of the underwater acoustic channel, improvement of frequency utilization efficiency becomes one of the key factor for high-speed UWA communication. Multiple-input multi-output (MIMO) techniques are attractive because they increase data rate by parallel data transmission over multiple transducers[3)]. In this paper, a MIMO approach for UWA communication using OSDM is considered, and its performance is evaluated in an experiment.

2. MIMO Approach for UWA Communication Using Orthogonal Signal Division Multiplexing

Figure 1 shows the signal processing flow for parallel data transmission using OSDM when both the transmitter and the receiver employ two transducers. Random complex messages of size 1×M, which are transmitted from transducers, Tx #0 and Tx #1, are defined as $\boldsymbol{x}^0_{t0}, \boldsymbol{x}^0_{t1}, \ldots, \boldsymbol{x}^0_{t(N-1)}$ and $\boldsymbol{x}^1_{t0}, \boldsymbol{x}^1_{t1}, \ldots, \boldsymbol{x}^1_{t(N-1)}$, respectively. We define each element of complex message as a symbol. These messages are multiplexed into sequences, $\boldsymbol{X}^0$ and $\boldsymbol{X}^1$, using inverse discrete Fourier transform (IDFT) matrix. After prepending a cyclic prefix, these sequences are frequency-up-converted and transmitted from transducers. The receiver obtained sequences, $\boldsymbol{Y}^0$ and $\boldsymbol{Y}^1$, by down-converting and sampling the received signal from transducers, Rx #0 and Rx #1, respectively, and removing cyclic prefix. The relationship between the outputs of the matched filter and the transmitted messages become;

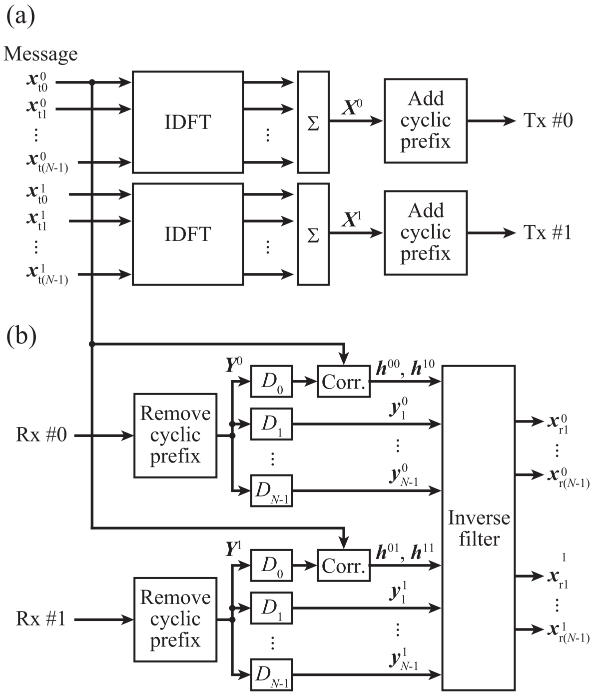

Fig. 1: Signal processing flow in (a) transmitter and (b) receiver for parallel data transmission using OSDM.

$$\begin{pmatrix} \boldsymbol{y}^0_n & \boldsymbol{y}^1_n \end{pmatrix} = \begin{pmatrix} \boldsymbol{x}^0_{tn} & \boldsymbol{x}^1_{tn} \end{pmatrix} \begin{pmatrix} H^{00} & H^{01} \\ H^{10} & H^{11} \end{pmatrix}, \tag{1}$$

where $\boldsymbol{y}_n^q = \boldsymbol{Y}^q D_n$ and n = 0, 1,…, N-1. Matched filter, D_n, is a Kronecker product of conjugate transpose of the n-th row of IDFT matrix and unit matrix of size M. H^{pq} is a channel matrix from Tx #p to Rx #q, where

$$H^{pq} = \begin{pmatrix} h_0^{pq} & h_1^{pq} & \cdots & h_{M-1}^{pq} \\ h_{M-1}^{pq} & h_0^{pq} & \cdots & h_{M-2}^{pq} \\ \vdots & \vdots & \ddots & \vdots \\ h_1^{pq} & h_2^{pq} & \cdots & h_0^{pq} \end{pmatrix}. \tag{2}$$

By solving eq. (1), the receiver can obtain the message, if the first row of H^{pq}, $\boldsymbol{h}^{pq}$, can be obtained from the received sequences. To obtain $\boldsymbol{h}^{pq}$, $\boldsymbol{x}^0_{t0}$ and $\boldsymbol{x}^1_{t0}$ are shared with both the transmitter and the receiver as pilot, where

$$\begin{aligned} x^0_{t0}[m] &= \exp\left[\left(2\pi\sqrt{-1}m^2\right)/M\right] \\ x^1_{t0}[m] &= \exp\left[\left(2\pi\sqrt{-1}(m-M/2)^2\right)/M\right] \end{aligned}. \tag{3}$$

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Assuming that the length of the channel impulse response does not exceed $M/2$, the receiver can successfully obtain $\boldsymbol{h}^{pq}$ from the received sequences. For example, the first half and the last half of $\boldsymbol{y}_0^0$ become the convolution of $\boldsymbol{x}^0_{t0}$ and $\boldsymbol{h}^{00}$, and $\boldsymbol{x}^1_{t0}$ and $\boldsymbol{h}^{10}$, respectively. Because periodical autocorrelation functions of $\boldsymbol{x}^0_{t0}$ and $\boldsymbol{x}^1_{t0}$ become an impulse, the receiver can successfully obtain $\boldsymbol{h}^{00}$ and $\boldsymbol{h}^{10}$ by calculating the periodical cross-correlation function between $\boldsymbol{x}^0_{t0}$ and $\boldsymbol{y}_0^0$, as shown in **Fig. 2**.

3. Experiment and Discussions

Parallel data transmission using OSDM was conducted in a test tank, as shown in **Fig. 3**. Two transducers (H1a, Aquarian) and four hydrophones (H2a, Aquarian), which work as Tx and Rx, are connected to a A-D/D-A converter (U2531A; Agilent). Signal processor was implemented on software (LabVIEW 2009, National Instruments). The impulse response of the channel was about 12 ms, which may result in inter-symbol interference of 120 symbols. The signal-to-noise ratio (SNR) was around 30 dB. The parameters for signal processing were shown in **Table 1**. As shown in the table, MIMO approach increases the effective data rate proportional to the number of the array element of the transmitter, Tx, without increasing the signal bandwidth.

Figure 4 shows the obtained constellation plot with and without MIMO approach. Focusing on the bit-error rate (BER), OSDM with MIMO approach achieved BER of under 10^{-3}, which was used for design of links according to ITU-T Recommendation G.821. However, in exchange for effective data rate, as shown in this figure, it was found that the output SNR with MIMO approach is less than that of without MIMO approach. Two reasons can be considered. In this experiment, the energy per one symbol with MIMO approach was half of that without MIMO approach to equalize the SNR. Moreover, the condition number in the channel matrix in eq. (1) also may lead the OSNR difference.

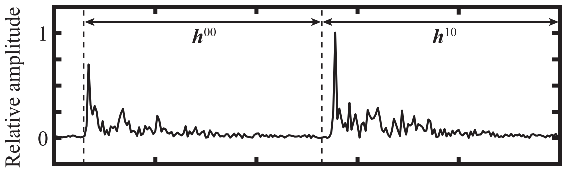

Fig. 2: Cross-correlation function between pilot, $\boldsymbol{x}^0_{t0}$, and matched filter output, $\boldsymbol{y}_0^0$.

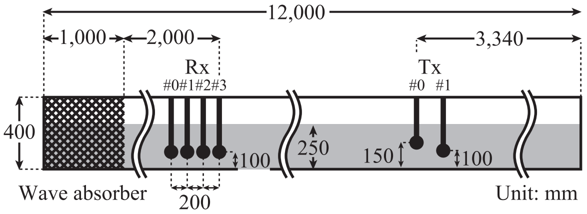

Fig. 3: Experimental setup for parallel data transmission.

Table 1 Parameters for experiment.

	with MIMO	without MIMO
Multiplicity, N	2	
Message length, M (symbols)	255	
Guard interval, L (symbols)	120	
Data modulation	16QAM	
Carrier frequency, f_c (kHz)	20	
Signal bandwidth (kHz)	10	
Frame length (ms)	63	
Effective data transfer rate (kbps)	**32.3**	**16.1**

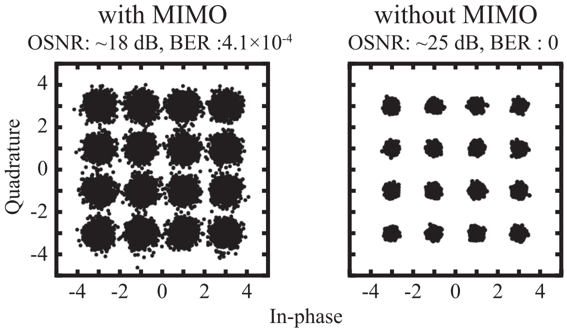

Fig. 4: Constellation plot obtained from the experiment.

4. Conclusions

A MIMO approach for UWA communication using OSDM is considered, and its performance is evaluated in experiment. To measure the channel response, whose number becomes a combination of the array elements in the transmitter and the receiver, the structure of the pilot signal was proposed. As a result, by employing two-array elements in the transmitter, the effective data rate become twice without increasing the signal bandwidth, and efficient BER was achieved. Considering the effect on Doppler spread is one of our future works.

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