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Experiment of Underwater Acoustic Communication Using Orthogonal Signal Division Multiplexing and Diversity Technique in a Harbor

直交信号分割多重とダイバーシチ技術を用いる水中音響通信の港湾における実証実験

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1. Introduction

Underwater sensor networks is an attractive tool for many application areas, such as monitoring, control, and surveillance. Recently, the use of mobile nodes, such as autonomous underwater vehicles, for underwater wireless sensor networks has actively been researched. The mobile node can be utilized to increase the measurement area. Moreover, scalable sensor networks can be established by using such nodes as mobile sensors [1].

Underwater acoustic (UWA) communication is a critical technology for underwater sensor networks, and the communication quality of UWA communication determine the performance of the sensor network. As a result, design of UWA communication system has actively been researched in multiple layers. For physical layer, we have to overcome two problems; heavy inter-symbol interference (ISI) and Doppler spread. To cope with them, the use of single-carrier and multicarrier techniques, and combination of array processing has been found to provide high-quality communication.

As an alternative, the authors have proposed the use of orthogonal signal division multiplexing (OSDM) for UWA communicatinon. OSDM with multichannel receiver has been found to achieve better communication quality in a test tank with heavy ISI [2]. The authors have also proposed a Doppler-resilient OSDM that enables reliable communication even in doubly (time and frequency) spread channels [3]. However, these techniques require multichannel receiver, and employment of hydrophone array is necessary to utilize space diversity, hence, it is not suitable for UWA communication among mobile nodes, whose physical size is severely limited.

The scope of this study is to achieve reliable UWA communication for mobile nodes; UWA communication without using an array in both the transmitter and the receiver. In this paper, we propose UWA communication based on OSDM and time-diversity technique (OSDM-TD), and evaluate its performance by experiment in a harbor.

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2. OSDM with Time-diversity Technique

In conventional OSDM [2], N complex sequences of length M, $\boldsymbol{x}_{tn}$ (n = 0, 1, …, N−1), are multiplexed into a single data stream of length MN, according to

$$\boldsymbol{x} = \sum_{n=0}^{N-1} \boldsymbol{f}_{N,n} \otimes \boldsymbol{x}_{tn}, \tag{1}$$

where $\boldsymbol{f}_{N,n}$ corresponds to the n-th row of the IDFT matrix. After inserting cyclic prefix (CP) of length L ($L \le M$), the signal is transmitted to the UWA channel. The received and CP-removed sequence, $\boldsymbol{y}$, becomes,

$$\boldsymbol{y} = \boldsymbol{x}\boldsymbol{H} = \boldsymbol{x}\begin{pmatrix} h_0 & h_1 & \cdots & h_{MN-1} \\ h_{MN-1} & h_0 & \cdots & h_{MN-2} \\ \vdots & \vdots & \ddots & \vdots \\ h_1 & h_2 & \cdots & h_0 \end{pmatrix}, \tag{2}$$

where h_0, h_1, …, h_{M-1} is a channel impulse response and $h_l = 0\ (l \ge L)$. The relationship between $\boldsymbol{x}_{tn}$ and $\boldsymbol{y}$ is expressed by

$$\begin{aligned} \boldsymbol{y}\left(\boldsymbol{f}^*_{N,n} \otimes \boldsymbol{I}_M\right) &= \boldsymbol{x}_{tn}\boldsymbol{H}_n \\ &= \boldsymbol{x}_{tn}\begin{pmatrix} h_0 & h_1 & \cdots & h_{M-1} \\ W_N^{-n}h_{M-1} & h_0 & \cdots & h_{M-2} \\ \vdots & \vdots & \ddots & \vdots \\ W_N^{-n}h_1 & W_N^{-n}h_2 & \cdots & h_0 \end{pmatrix}, \end{aligned} \tag{3}$$

where $\boldsymbol{I}_M$ and W_N^{-n} are an identity matrix and $W_N^{-n} = \exp(-2\pi jn/N)$, respectively. In OSDM, the first data sequence, $\boldsymbol{x}_{t0}$, is shared in both the transmitter and the receiver. The receiver obtains the channel impulse response by solving (3) using $\boldsymbol{x}_{t0}$, and obtains the transmitted message by solving (3) using obtained channel impulse response, h_0, h_1, …, h_{M-1}. However, the condition number of (3) sometimes become large which results in severe noise enhancement, hence, the use of multichannel receiver is necessary.

To achieve reliable communication without using an array in both the transmitter and the receiver, the idea of time-diversity is utilized. **Figure 1** shows a block diagram of OSDM-TD when N = 2 and K = 3. In OSDM-TD, the data sequence, $\boldsymbol{x}_{tn}$ ($n \ge 1$), is a

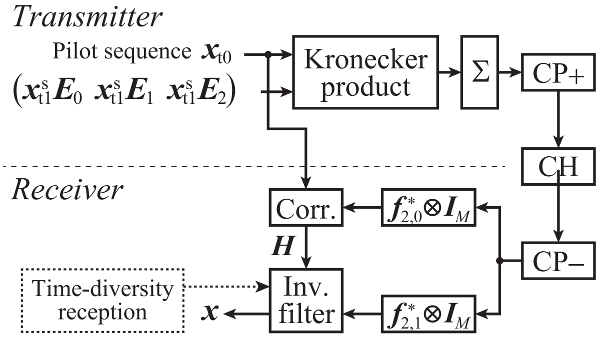

Fig. 1. Block diagram of OSDM-TD (N = 2, K = 3).

repetition of the data sequence of length M/K, $\boldsymbol{x}^{s}_{tn}$, as,

$$\boldsymbol{x}_{tn} = \left(\boldsymbol{x}^{s}_{tn}\boldsymbol{E}_0\ \ \boldsymbol{x}^{s}_{tn}\boldsymbol{E}_1\ \cdots\ \boldsymbol{x}^{s}_{tn}\boldsymbol{E}_{K-1}\right), \qquad (4)$$

where $\boldsymbol{E}_k$ (k = 0, 1, …, K-1) is a diagonal matrix whose element is random complex sequence and $\boldsymbol{E}_k\boldsymbol{E}_{k'}^{*} = 0$ ($k \neq k'$). The multiplexed and transmitted sequence is received by the receiver, and CP is removed. The relationship between $\boldsymbol{x}_{tn}$ and $\boldsymbol{y}$ is expressed by

$$\begin{aligned}\boldsymbol{y}\left(\boldsymbol{f}^{*}_{N,n}\otimes\boldsymbol{I}_M\right) &= \boldsymbol{x}_{tn}\boldsymbol{H}_n \\ &= \boldsymbol{x}^{s}_{tn}\left(\boldsymbol{E}_0\boldsymbol{H}_n\ \ \boldsymbol{E}_1\boldsymbol{H}_n\ \cdots\ \boldsymbol{E}_{K-1}\boldsymbol{H}_n\right).\end{aligned} \qquad (5)$$

As shown in (5), by introducing the repetition of data vector and random diagonal matrix $\boldsymbol{E}_k$, the received can utilize K independent channel matrices, without using an array in both the transmitter and the receiver, in exchange for effective data rate (1/K compared to normal OSDM).

3. Experiment

We evaluated the performance of OSDM-TD in experiment. The experiment was conducted in a Hashirimizu port (Kanagawa, Japan) for about 85 hours. The weather was mild throughout the experiment. We set two transducers (BII-7512, Benthowave) and four transducers (BII-7520) for projector and hydrophone, respectively, as shown in **Fig. 2**. Note that the same signal is input each projector at the same time. For normal OSDM, the received signal obtained by three hydrophones were used for demodulation, while one hydrophone was used for demodulation for OSDM-TD. The transmitter (Tx) generates OSDM-TD and OSDM signal by using the following parameters; M = 63, N = 2, L = 48, and K = 3. The carrier frequency and the signal bandwidth were selected as 30 and 1.2 (kHz), respectively. In this case, the efficient data rate of OSDM-TD and OSDM become 0.15 and 0.45 (kbps), respectively.

Figure 3 shows the relationships between input SNR (ISNR) and bit-error rate (BER) obtained in experiment. As shown in the figure, the OSDM-TD and OSDM achieves almost the same curve. The obtained result suggests that the OSDM-TD can achieve almost the same communication quality of

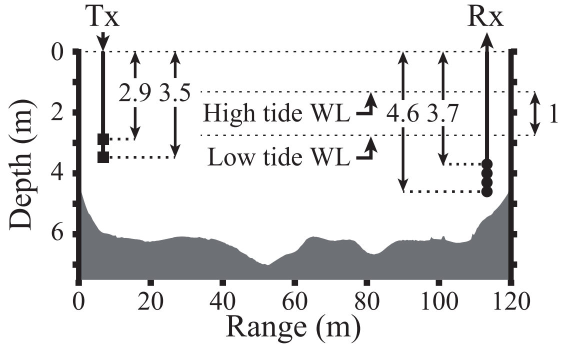

Fig. 2. Vertical sectional view of the transducer arrangement in water (gray colored region means sea floor).

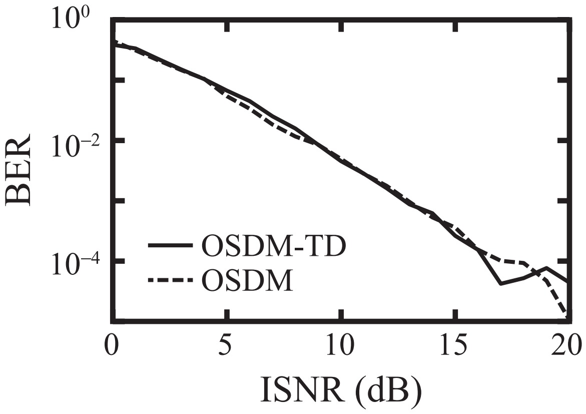

Fig. 3. Relationships between ISNR and BER in experiment.

OSDM without using an array, in exchange for effective data rate.

4. Conclusions

In this report, UWA communication without using an array in both the transmitter and the receiver was proposed to promote UWA communication among mobile nodes. We showed the design of OSDM-TD and evaluated its performance in experiment. We found that OSDM-TD achieves almost the same communication quality compared to normal OSDM without using an array, in exchange for data rate.

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