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Improvement of Communication Quality Using Compressed Sensing in MIMO Underwater Acoustic Communication

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1. Introduce

Underwater acoustic (UWA) mobile communication is an important technology that is utilized for communication among underwater drones. And underwater drones are expected to be adopted for exploration of sea bottom resources and inspection of underwater infrastructure such as piers. However, the UWA channel is a severe communication environment because of the existence of time delays and Doppler spreads. In order to achieve reliable communication in such a severe environment, we have proposed Doppler-resilient orthogonal signal division multiplexing using compressed sensing (D-OSDM-CS) [1] and Multiple-input-multiple-output D-OSDM (MIMO-D-OSDM) [2]. D-OSDM-CS improves the communication quality of D-OSDM, and MIMO-D-OSDM has an advantage over D-OSDM. In D-OSDM-CS, compressed sensing [3] uses sparsity of UWA channel impulse response, therefore compressed sensing could be available MIMO-D-OSDM method as well.

Hence, in this paper, we propose MIMO-D-OSDM-CS method (combination of compressed sensing and MIMO-D-OSDM) and evaluate its utility through sea trial. We also compare MIMO-D-OSDM-CS with normal MIMO-D-OSDM-CS in BER and OSNR.

2. MIMO-D-OSDM-CS

Figure 1 shows a block diagram of MIMO-D-OSDM-CS in the transmitter (Tx) and receiver (Rx) employing J emitters and K hydrophones. Basically, the signal processing procedure performed in MIMO-D-OSDM-CS is the same as in normal D-OSDM-CS[1]. In normal D-OSDM-CS, Rx calculate $\boldsymbol{z}_q$ from received signal and despreading matrix, and estimate channel impulse response by solving

$$\boldsymbol{z_q} = \boldsymbol{h}_q \boldsymbol{P}, \qquad (1)$$

where $\boldsymbol{h}_q, \boldsymbol{P}$ are the channel impulse response and cyclic matrix of the pilot. In MIMO-D-OSDM-CS, the number of estimating channel impulse response increase by multipling input and output. For this reason, proposed system estimates channel impulse responses by solving

$$\boldsymbol{z}_{k,q} = \boldsymbol{h}_{j\to k,q} \boldsymbol{P}_j, \qquad (2)$$

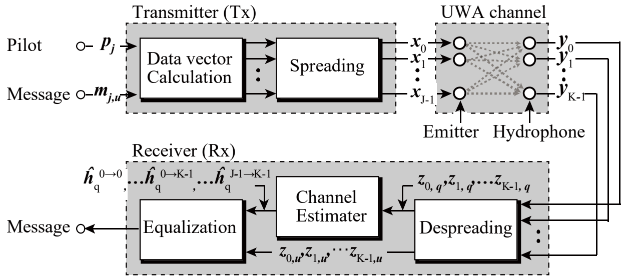

Fig. 1 Block diagram of MIMO-D-OSDM-CS

where $\boldsymbol{h}_{j\to k,q}$ (j=0,1,2...J-1, k=0,1,2...K-1), and $\boldsymbol{P}_j$ are impulse responses of the UWA channel from emitter #$\boldsymbol{j}$ to hydrophone #$\boldsymbol{k}$ at Doppler shift of $\boldsymbol{q}$ and cyclic matrix of the pilot $\boldsymbol{p_j}$, respectively. Finally, the receiver performs equalization by solving

$$\left(\boldsymbol{z}_{0,u}, \boldsymbol{z}_{1,u}, \dots, \boldsymbol{z}_{K-1,u}\right) = \left(\boldsymbol{m}_{0,u}, \boldsymbol{m}_{1,u}, \dots, \boldsymbol{m}_{J-1,u}\right)\boldsymbol{C_u}, \qquad (3)$$

where $\boldsymbol{C}_u$ is a channel matrix whose element consists of $\boldsymbol{h}_{j\to k,q}$. Normal D-OSDM-CS solves (1) by solving following optimization problem

$$\underset{\boldsymbol{h}_q}{\text{minimize}} \left\|\boldsymbol{z}_q - \boldsymbol{h}_q \boldsymbol{P}\right\|_2^2 + \boldsymbol{\tau}\left\|\boldsymbol{h}_q\right\|_1 \qquad (4)$$

where $\|\cdot\|_l$ and τ represents L-k norm and regularization parameters that determine the channel sparsity. When τ increase, estimated channel impulse responses become sparser (the estimated signal has numerous zero taps), while when $\tau_{j,k}$ decrease the ones become denser (the estimated signal has numerous active taps). On the other hands, MIMO-D-OSDM-CS solves (2) by solving

$$\underset{\boldsymbol{h}_{j\to k,q}}{\text{minimize}} \left\|\boldsymbol{z}_{k,q} - \boldsymbol{h}_{j\to k,q} \boldsymbol{P}_j\right\|_2^2 + \boldsymbol{\tau}_{j,k}\left\|\boldsymbol{h}_{j\to k,q}\right\|_1 \qquad (5)$$

In the case of normal D-OSDM-CS, the number of regularization parameter τ to be determined is only one because there is one channel from emitter to hydrophone. However, in MIMO-D-OSDM-CS, the number of $\tau_{j,k}$ to be determined is $J \cdot K$ because of the increase of emitters and hydrophones. To achieve the most reliable communication quality, $\tau_{j,k}$ would be determined as the optimal values that may be different from each other. However, in this paper, we use the identical value as $\tau_{j,k}$ over every channel estimation for simplicity.

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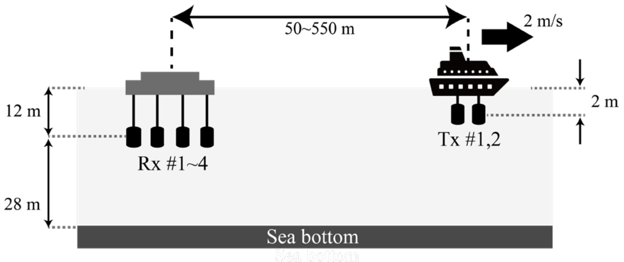

Fig. 2 Sea trial environment

3. Evaluation in sea trial

Figure 2 and **Table 1** show the experimental environment and parameters, respectively. 2 emitters and 4 hydrophones are employed in this trial. Tx1 and Tx2 emit signals (carrier frequency 8 kHz and 24 kHz) generated from different messages. Then, we perform channel estimation on the received data by LS sense and compressed sensing, varying the regularization parameter from 10^{-4} to 10^{-2}. As shown in **Fig. 3** (a), the estimated channel impulse responses by compressed sensing have few active taps, in comparison with that by LS sense (b). In the following analysis, the same processing is in place other than channel estimation. Hence, the difference in results stems from the degree of sparsity of the estimated channel impulse response.

Next, we evaluate Output-SNR (OSNR) and bit-error-rate (BER). **Fig. 4** and **5** show a relationship between Tx-Rx distance and OSNR and a relationship between Tx-Rx distance and BER, respectively. For each block, the value of τ is selected so that OSNR is maximized in fig. 4 and so that BER is minimized in fig. 5. As shown in Fig. 4 and 5, compressed sensing improves OSNR and BER in message1 and 2 commonly in comparison with LS sense method. In addition, the number of error-free blocks was 1102 and 873 in message1 and 2, respectively in MIMO-D-OSDM-CS, while that was 778 and 524 in message 1 and 2 in normal MIMO-D-OSDM (total number of the transmitted data block:1728). As a result, we figured out that compressed sensing is effective for MIMO-D-OSDM.

4. Conclusion

We combined compressed sensing and MIMO-D-OSDM and carried out a sea trial of mobile UWA communication. Consequently, MIMO-D-OSDM-CS achieved better OSNR and BER than normal MIMO-D-OSDM. Construction of a system that determines optimal regularization parameters $\tau_{j,k}$ for each channel is our future work.

Table 1 Parameters in sea trial

Carrier frequency	8 and 24 kHz
Bandwidth	4.8 kHz
Modulation	QPSK

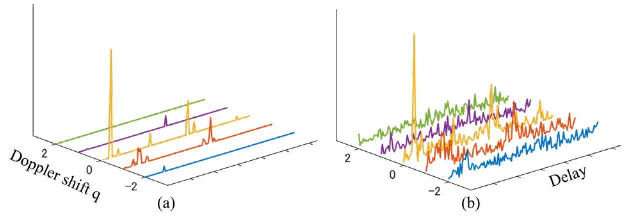

Fig. 3 Estimated channel impulse response; (a) Compressed Sensing (b) LS sense

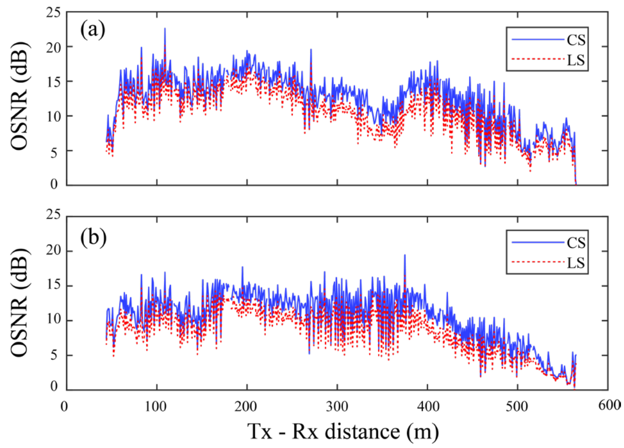

Fig. 4 Relationship between Tx-Rx distance and OSNR

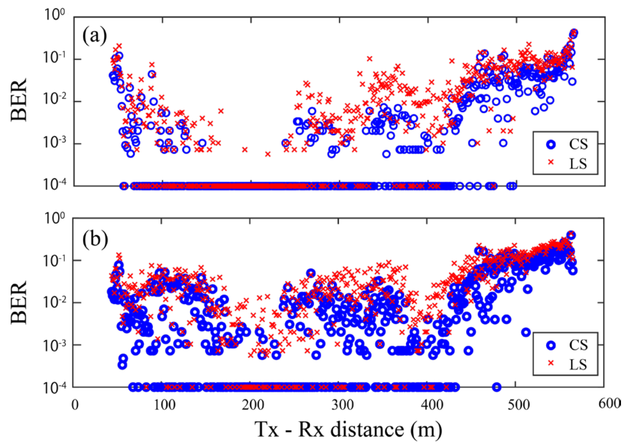

Fig. 5 Relationship between Tx-Rx distance and BER (CS means compressed sensing, LS means LS sense):(a) message 1 (b) message 2

References

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