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

水中移動体通信における圧縮センシングを用いた通信品質の向上

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1. Introduction

Mobile underwater acoustic (UWA) communication is a critical technology that supports underwater exploration and sensing using various robots/vehicles. However, establishment of reliable mobile network is challenging, since there exist large delay and Doppler spreads in UWA channel. To provide reliable communication in the UWA channel, we have proposed Doppler-resilient orthogonal signal division multiplexing (D-OSDM) [1]. Furthermore, we also have clarified advantages of D-OSDM over existing communication schemes in simulations and experiments [2, 3].

However, D-OSDM does not fully exploit the characteristics of the UWA channel. The UWA channels are naturally sparse (in other words, the impulse response of the UWA channel consists of few active taps and numerous zero taps), and least square (LS) channel estimator can lead poor performance in such channels. Compressed sensing [4] that solves simultaneous equations by exploiting the sparse nature of sparse signals and optimizing solutions to be sparse has a potential to improve communication quality of D-OSDM in the UWA channel. Hence, in this paper, we combine compressed sensing and D-OSDM, clarify an optimal parameter of sparse channel estimator, and evaluate communication quality using simulations.

2. D-OSDM Using Compressed Sensing

Figure 1 shows a block diagram of D-OSDM in the transmitter (Tx) and receiver (Rx). The Tx calculates a data matrix from a pilot signal $\boldsymbol{p}$ and message $\boldsymbol{x}_{tu}$, reads the data matrix in a row direction, applies a spreading matrix, and emits a signal $\boldsymbol{x}$ to the UWA channel. The transmission signal is affected by both delay and Doppler spread of the channel. The Rx applies a despreading matrix and obtains two vectors, $\boldsymbol{z}_{pq}$ and $\boldsymbol{z}_u$. Then the receiver performs channel estimation by solving

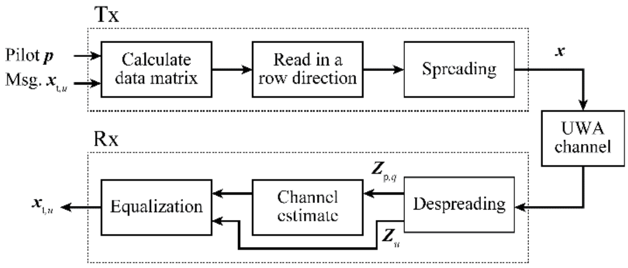

Fig. 1 Block diagram of D-OSDM in Tx and Rx.

$$\boldsymbol{Z}_{p,q} = \boldsymbol{h}_q \boldsymbol{P}, \quad (1)$$

where $\boldsymbol{h}_q$ and $\boldsymbol{P}$ are an impulse response of the channel at Doppler shift of q and cyclic matrix of the pilot, respectively. Finally, the receiver performs equalization by solving

$$\boldsymbol{Z}_u = \boldsymbol{x}_{tu} \boldsymbol{C}_u, \quad (2)$$

where $\boldsymbol{C}_u$ is a channel matrix whose element consists of $\boldsymbol{h}_q$. Existing D-OSDM solves (1) in a LS sense, i.e.,

$$\min \| \boldsymbol{Z}_{p,q} - \boldsymbol{h}_q \boldsymbol{P} \|_2^2, \quad (3)$$

where $\| \cdot \|_k$ represents L-k norm. In this case, the estimated impulse response $\boldsymbol{h}_q^e$ contains numerous active taps. This means that noise component of $\boldsymbol{h}_q^e$ is also regarded as the channel impulse response in equalization that can lead poor performance. To address this problem, we propose D-OSDM using compressed sensing that solves (1) considering the channel sparsity, i.e.,

$$\min \| \boldsymbol{Z}_{p,q} - \boldsymbol{h}_q \boldsymbol{P} \|_2^2 + \tau \|\boldsymbol{h}_q\|_1, \quad (4)$$

where τ is a parameter that determines the channel sparsity. In other words, large τ leads $\boldsymbol{h}_q$ of single tap, while small τ leads $\boldsymbol{h}_q$ of LS output. Hence, optimization of τ is necessary to improve communication quality of D-OSDM. In Section 3, we clarify optimal τ and performance of the proposed D-OSDM (using compressed sensing) in simulations.

3. Simulations

Figure 2 and **Table I** show the simulation environment and parameters used in the simulation, respectively. As shown in the figure, we consider

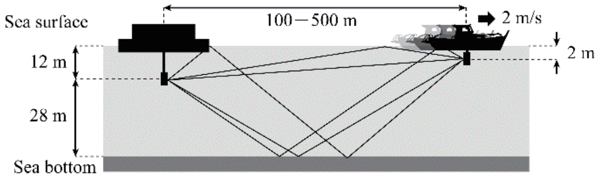

Fig. 2 Simulation environment.

mobile UWA communication in a shallow water whose depth is 40 m. In this simulation, we calculate the transmission signal $\boldsymbol{x}$, using parameters shown in Table I calculate the channel impulse response between Tx and Rx $\boldsymbol{h}_q$ using ray tracing (the Tx moves with speed of 2 m/s), calculate the received signal $\boldsymbol{y}$ using $\boldsymbol{x}$ and $\boldsymbol{h}_q$, and perform channel estimation and demodulation.

We firstly perform simulation by changing Tx-Rx distance (100 to 500 m), signal-noise ratio (SNR), and parameter of sparse channel estimator τ. **Figure 3** shows a relationship between SNR and optimal τ that achieves the best communication quality. From this simulation, we found that the optimal τ depends mainly on SNR (in other words, the optimal τ does not change when SNR is the same, if Tx-Rx distance changes). Hence, D-OSDM using compressed sensing would be available if the Rx has a function that determines τ by measuring SNR from the received signal.

We next perform simulation of UWA communication with D-OSDM using compressed sensing by changing Tx-Rx distance and SNR. **Figures 4 and 5** show the channel impulse response obtained by the Rx and a relationship between Tx-Rx distance and bit-error rate (BER), respectively. As shown in Fig. 4, estimated channel impulse response by compressed sensing has only few active taps, as well as the ideal one. On the other hand, estimated channel impulse response by LS estimator has numerous active taps. This means that the communication quality (BER) would be improved by using compressed sensing. Actually, BER performance of D-OSDM using compressed sensing outperforms that of the normal D-OSDM, as shown in Fig. 5. Specifically, the number of error-free data blocks was 1,548 in proposed D-OSDM using compressed sensing, while that was 466 in normal D-OSDM (total number of the transmitted data block: 4,500). Consequently, we found that D-OSDM using compressed sensing can provide reliable communication in mobile UWA channels.

4. Conclusion

We combined compressed sensing and D-OSDM, and performed simulation of mobile UWA communication. As a result, we found that D-OSDM using compressed sensing with the optimal τ for SNR can provide reliable communication in mobile UWA channels.

Table I Parameters used in simulation.

Parameters	Value
Carrier frequency (kHz)	32
Bandwidth (kHz)	2.4
Modulation	16QAM
Effective data rate (kbps)	1.6

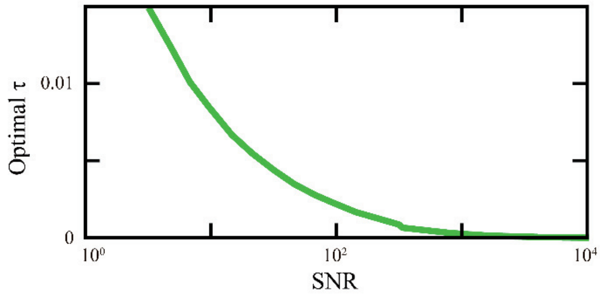

Fig. 3 Relationship between SNR and optimal τ.

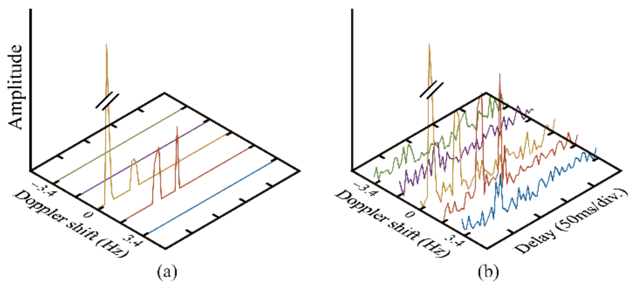

Fig. 4 Estimated channel impulse response;
(a) proposed method and (b) existing method.

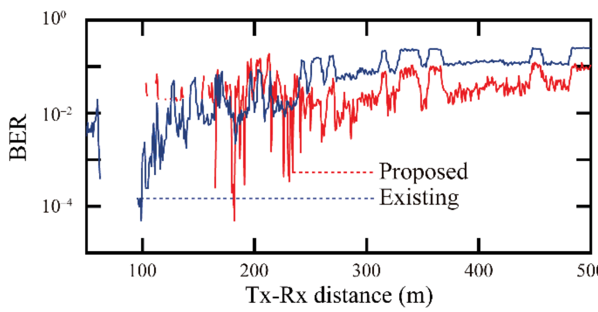

Fig. 5 Relationship between Tx-Rx distance and BER.

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