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Underwater Acoustic Communication over Highly Doppler Spread Environment Exceeding Guard Band
ガードバンドを超えるドップラーシフトが存在する環境下における水中音響通信

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1. Introduction

Mobile underwater acoustic (UWA) communication is a key technology that supports ocean survey by managing various underwater drones. However, UWA channel is quite challenging for establishing mobile network; the UWA channel has long but sparse reverberation tails, and large frequency shift occurs due to the movement of the communication platform and sea surface. To provide reliable communication in such channel, we have proposed an OSDM (orthogonal signal division multiplexing) channel estimator using compressed sensing (CS) [1]. We have found that the use of CS, whose optimal parameter depends on the noise in UWA channel, can boost OSDM performance by exploiting the sparse nature of UWA channel.

However, we also have found that the dynamic movement of the communication platform makes for a large Doppler spread exceeding guard band and results in an increase of bit-error rate (BER). This is because the noise induced by an inter-carrier interference (ICI) increases as the Doppler spread increases. If we can measure the hidden noise induced by ICI, we can improve the performance of OSDM by optimizing the parameter of CS based on apparent and hidden noise.

In this paper, we propose an advanced OSDM channel estimator that can measure the ICI-induced noise and optimize the parameter of CS, by utilizing the channel impulse response regime without active taps. We also evaluate the performance of the advanced channel estimator in experiments.

2. OSDM with Advanced Channel Estimator

Figure 1 shows a block diagram of OSDM in the transmitter (Tx) and receiver (Rx). The Tx calculates a data matrix from a pilot signal $\boldsymbol{p}$ and message, reads the data matrix in a row direction, applies a spreading matrix, and transmits a signal $\boldsymbol{x}$ to the UWA channel. The transmitted signal is

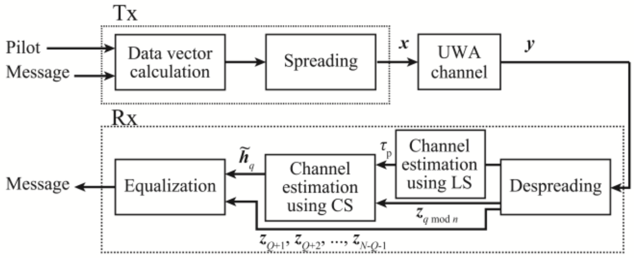

Fig. 1 Block diagram of OSDM in Tx and Rx.

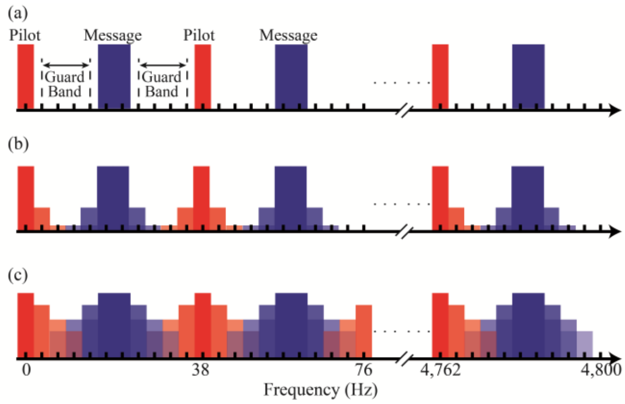

Fig. 2 Spectrum of OSDM signal; (a) transmission signal $\boldsymbol{x}$ and received signal $\boldsymbol{y}$ (b) with small and (c) large Doppler spreads.

affected by delay and Doppler spreads of the UWA channel and reaches the Rx as a received signal $\boldsymbol{y}$.

Figure 2 shows a spectrum of $\boldsymbol{x}$ [Fig. 2(a)] and $\boldsymbol{y}$ [Figs. 2(b) and 2(c)]. As shown in Fig. 2(c), ICI occurs when Doppler spread exceeds guard band, and ICI-induced noise affects both the pilot and message. The Rx applies a despreading matrix to $\boldsymbol{y}$ and obtains a vector $\boldsymbol{z}_n$ (n = 0, 1, …, N-1), where

$$\boldsymbol{z}_{q \bmod N} = \boldsymbol{h}_q \boldsymbol{P} + \boldsymbol{n}_n, \quad (1)$$

and $\boldsymbol{h}_q$, $\boldsymbol{P}$, and $\boldsymbol{n}_n$ are an impulse response of the channel at Doppler shift of q, cyclic matrix of the pilot, and additive noise, respectively. The Rx solves (1) using the least-squares (LS) sense as

$$\min_{\boldsymbol{h}_q^{\mathrm{LS}}} \| \boldsymbol{z}_{q \bmod N} - \boldsymbol{h}_q^{\mathrm{LS}} \boldsymbol{P} \|_2^2, \quad (2)$$

Then the Rx measures the standard deviation of $\boldsymbol{h}_q^{\mathrm{LS}}$ regime without active taps and determines the parameter τ_{p} of CS. Note that this technique is available when a guard interval between signal blocks is longer than the length of the channel impulse response. **Figure 3** shows an example of the channel impulse response $\boldsymbol{h}_q^{\mathrm{LS}}$ estimated by LS sense. As shown in the figure, the channel impulse response regime without active taps contains both additive and ICI-induced noise. Finally, the Rx solves (1) again using CS as

$$\min_{\boldsymbol{h}_q} \left(\frac{1}{2} \| \boldsymbol{z}_{q \bmod N} - \boldsymbol{h}_q \boldsymbol{P} \|_2^2 + \tau_p \|\boldsymbol{h}_q\|_1 \right), \quad (3)$$

and performs equalization by using the calculated channel impulse response.

In Section 3, we evaluate the performance of this advanced channel estimator in experiments.

3. Experiment

The experiment was performed in the coastal area of Suruga Bay, Japan. The Tx and Rx is set at depths of 2 m and 12 m, respectively. The Tx moves at 2 m/s, while transmitting the signal. The Tx-Rx distance is 50-500 m and the total number of transmitted bocks is 1,728. The OSDM signal parameters are the same to Ref. [1].

Figures 4(a) and **4(b)** show the measured Doppler spread and the parameter of CS at each block index, respectively. Note that τ_{o}, τ_{p}, and τ_{e} are the optimal parameter that maximizes the output signal-to-noise ratio (OSNR) (reference), the parameter determined based on the standard deviation of $\boldsymbol{h}_q^{\mathrm{LS}}$ (proposed method), and the parameter determined based on additive noise (existing method), respectively. As shown in Figs. 4(a) and 4(b), the optimal parameter τ_{o} increases as the Doppler spread increases. One of the reasons considered is due to the existing of the ICI-induced noise. Moreover, as shown Fig. 4(b), τ_{p} became almost the same value of τ_{o}. This means that the advanced channel estimator can successfully measure the ICI-induced noise by utilizing the channel impulse response regime without active taps.

Table I shows the number of error-free data blocks in OSDM communication with CS-based channel estimator using τ_{o}, τ_{p}, and τ_{e}. Specifically, there were 1,035, 978, 691 error-free data blocks, using τ_{o} (reference), τ_{p} (proposed), and τ_{e} (existing), respectively. This means that the advanced channel estimator achieves almost the optimal communication quality and provides reliable communication.

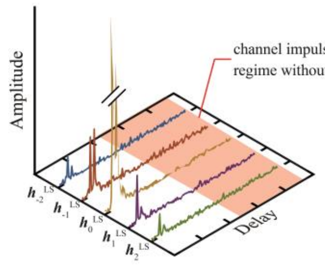

Fig. 3 Example of the channel impulse response $\boldsymbol{h}_q^{\mathrm{LS}}$.

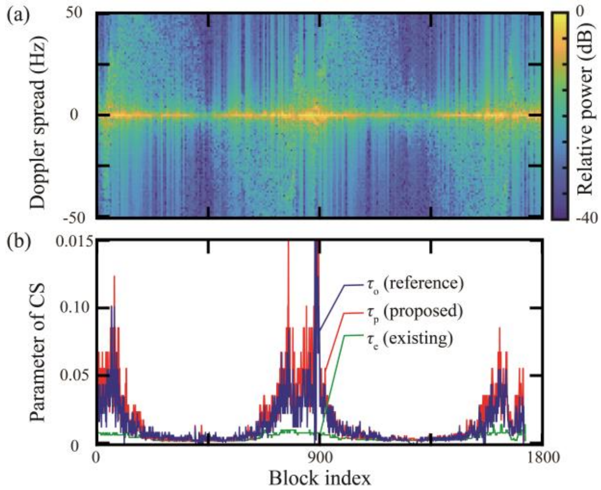

Fig. 4 (a) Doppler spread and (b) parameter of CS at each block index.

Table I Number of error-free data blocks in OSDM.

Channel estimator using		
τ_{o} (reference)	τ_{p} (proposed)	τ_{e} (Existing)
1,035	978	691

4. Conclusion

In this paper, we proposed an advanced OSDM channel estimator that can measure the ICI-induced noise and optimized the parameter of CS, by utilizing the channel impulse response regime without active taps. We also evaluated the performance of the advanced channel estimator in experiments. Consequently, we found that the advanced channel estimator can successfully measure the ICI-induced noise by utilizing the channel impulse response regime without active taps. We also found that the advanced channel estimator achieves almost the optimal communication quality and provides reliable communication.

References

1. Y. Tabata *et al.* Jpn. J. Appl. Phys. **59** (2020) SKKF04-1.