Effect of Doppler Modeling Error on Communication Quality in Underwater Acoustic Communication

水中音響通信におけるドップラーモデル化誤差が通信品質へ及ぼす影響

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1. Introduction

Underwater acoustic (UWA) communication is a key technology that enables wireless communication among underwater drones for more efficient ocean surveys. However, UWA communication poses significant difficulties due to waveform distortion caused by delay and Doppler spreads. To address this problem, many communication schemes have been studied. Among them, we have proposed Doppler resilient orthogonal signal division multiplexing (D-OSDM) that accurately measures the delay and Doppler spreads of the UWA channel [1,2].

On the other hand, the effects of channel modeling errors on the performance of D-OSDM have not been fully considered yet. Specifically, in D-OSDM, the receiver (Rx) estimates a channel impulse response with discretized Doppler shift based on an assumption that the UWA channel can be expressed by the basis expansion model (BEM) [3]. However, actual UWA channel has continuous Doppler shifts, and error between BEM and actual UWA channel may affect the communication performance. Hence, in this paper, we clarify the effect of Doppler modeling error on communication quality in D-OSDM through a simulation.

2. Overview of D-OSDM and modeling errors

Figure 1 shows a block diagram of D-OSDM in the transmitter (Tx) and Rx. First, the Tx reads pilot signal $\boldsymbol{d}_0$, messages $\boldsymbol{d}_{2Q+1}$, $\boldsymbol{d}_{2Q+2}$, …, $\boldsymbol{d}_{N-2Q-1}$, and zero vectors $\boldsymbol{d}_1$, $\boldsymbol{d}_2$, …, $\boldsymbol{d}_{2Q}$, $\boldsymbol{d}_{N-2Q}$, $\boldsymbol{d}_{N-2Q+1}$, …, $\boldsymbol{d}_{N-1}$, and calculates a data vector

$$\boldsymbol{d} = (\boldsymbol{d}_0, \boldsymbol{d}_1, \ldots, \boldsymbol{d}_{N-1}), \tag{1}$$

where $\boldsymbol{d}_n$ ($n = 0, 1, \ldots, N-1$) is a vector of length M, N is the number of data vectors, and Q is a maximum allowable Doppler shift. Then, the Tx applies a spreading matrix to $\boldsymbol{d}$ as

$$\boldsymbol{x} = \boldsymbol{d}(\boldsymbol{F}_N \otimes \boldsymbol{I}_M), \tag{2}$$

where $\boldsymbol{x}$ is a baseband signal of length MN, $\boldsymbol{F}_N$ is an inverse discrete Fourier transform matrix of size $N \times N$, $\otimes$ is a Kronecker product, and $\boldsymbol{I}_M$ is a unit matrix of size $M \times M$. The Tx inserts a guard interval of the length L to $\boldsymbol{x}$ (L is maximum allowable delay spread), converts it to a passband signal, and emits it to a UWA channel.

The transmitted signal is affected by delay and Doppler spreads in the UWA channel and reaches the Rx as a received signal $\boldsymbol{y}$. In BEM, the received signal $\boldsymbol{y}$ is modeled as

$$\boldsymbol{y} = \boldsymbol{x} \sum_{q=-Q}^{Q} \boldsymbol{H}_q \boldsymbol{\Lambda}_q + \boldsymbol{n}, \tag{3}$$

where $\boldsymbol{H}_q$ and $\boldsymbol{\Lambda}_q$ are matrices of size $MN \times MN$ that represents the effects of delay and Doppler spreads, respectively, and $\boldsymbol{n}$ is additive noise in a UWA channel. $\boldsymbol{H}_q$ and $\boldsymbol{\Lambda}_q$ are represented as follows

$$\boldsymbol{H}_q = \begin{pmatrix} h_{0,q} & h_{1,q} & \cdots & h_{MN-1,q} \\ h_{MN-1,q} & h_{0,q} & \cdots & h_{MN-2,q} \\ \vdots & \vdots & \ddots & \vdots \\ h_{1,q} & h_{2,q} & \cdots & h_{0,q} \end{pmatrix}, \tag{4}$$

$$\boldsymbol{\Lambda}_q = \mathrm{diag}(W_{MN}^{0},\ W_{MN}^{q},\ \ldots,\ W_{MN}^{(MN-1)q}), \tag{5}$$

where $W_{MN}^{k} = \exp(2\pi\sqrt{-1}\,k / MN)$. Note that $h_{l,q}$ represents the channel impulse response at the delay of l ($= 0, 1, \ldots, MN-1$) and the Doppler shift of q, and $h_{l,q} = 0$ if $l \geq L+1$.

The Rx estimates a channel impulse response at each Doppler scale q ($= -Q, -Q+1, \ldots, Q$), and performs equalization by using the calculated channel impulse response.

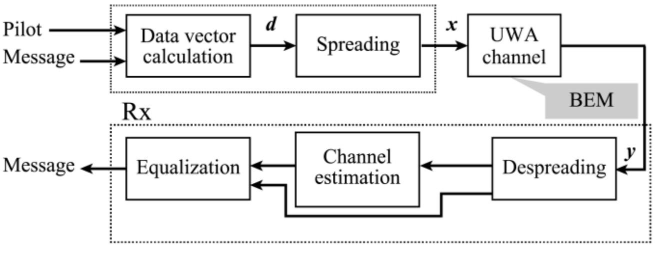

Fig. 1 Block diagram of D-OSDM.

In D-OSDM, the Rx can estimate the impulse responses without Doppler modeling errors only if the Doppler shifts caused in UWA channel belong to f_Q $(=\{\frac{-Q}{MNT}, \frac{-Q+1}{MNT}, \ldots, \frac{Q}{MNT}\})$ (Hz), where T represents symbol time. However, actual UWA channel has continuous Doppler shifts. Such difference between BEM and actual channel may affects communication quality. Hence, we clarify the effects of the Doppler modeling errors on communication quality though the simulations.

3. Simulations

3.1 Simulation environment

We performed the simulations using D-OSDM while changing Doppler shift of a signal and evaluated the communication quality on output SNR (OSNR) at each Doppler shift.

Figure 2 shows the simulation environment using D-OSDM. Signal-to-noise ratio (SNR) was about 35 dB. To observe only the effects of Doppler shift, only the direct signal was considered. Note that Doppler shift caused in a UWA channel was changed between 0 and 10 [Hz] to verify the Doppler modeling errors. Since the parameters of D-OSDM were $M=127$, $N=11$, $Q=2$, and $1/T=4.8$ (kHz), the Doppler modeling errors are expected to occur when the Doppler shift does not belong to f_Q (= {−6.8, −3.4, 0, 3.4, 6.8}) [Hz].

3.2 Simulation results

Figure 3 shows the channel impulse responses estimated by the Rx when the Doppler shift does not belong to f_Q [Fig. 3(a): Doppler shift = 1.7 Hz] and Doppler shift belongs to f_Q [Fig. 3(b): Doppler shift = 3.4 Hz]. As shown in Fig. 3(a), the channel impulse response has many active taps from $q=-2$ to 2. On the other hand, as shown in the Fig. 3(b), the channel impulse response had an active tap only at $q=1$. This means that the Doppler modeling errors occur and it is observed as the noise in the channel impulse response estimated by the Rx if Doppler shift does not belong to f_Q.

Figure 4 shows the relationship between Doppler shift and OSNR. Note that the blue-colored line is OSNR at each Doppler shift and the red-colored circles are OSNR at Doppler shift that belongs to f_Q. As shown in the figure, OSNR decreased when the Doppler shift does not belong to f_Q. This means that the effect of the Doppler modeling errors on communication quality exists. Hence, the communication quality of D-OSDM is expected to improve if the Doppler modeling errors can be addressed.

4. Conclusion

In this paper, we performed the simulations in UWA communication using D-OSDM to clarify the effects of Doppler modeling errors on communication quality. As a result, we found that OSNR of D-OSDM decreases and the effect of the Doppler modeling errors (error between BEM and actual UWA channel). This means that the communication quality of D-OSDM can be further improved if the Doppler modeling errors can be addressed.

References

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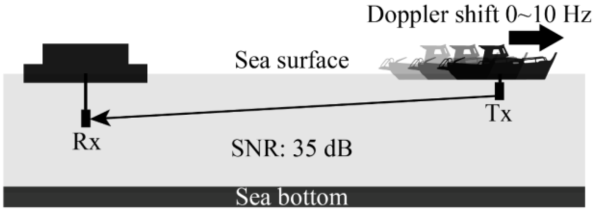
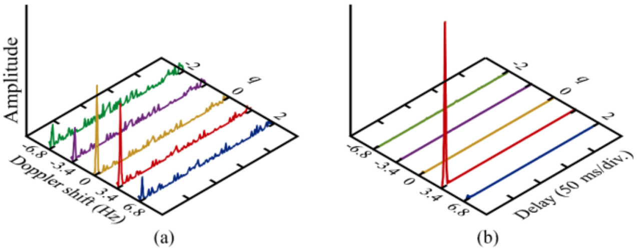


Fig. 2 Simulation environment.



(a) (b)

Fig. 3 Estimated channel impulse response when Doppler shift is (a) 1.7 Hz and (b) 3.4 Hz.

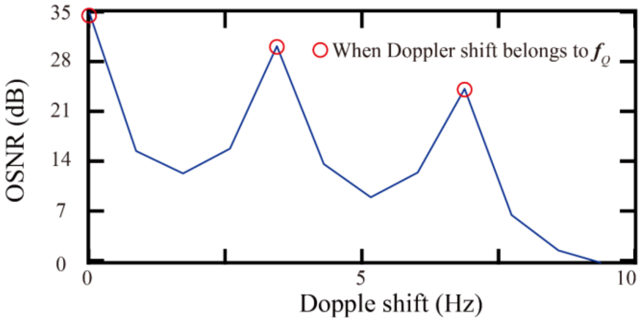


Fig. 4 Relationship between Doppler shift and OSNR.