3P6-1

Measurement of Delay and Doppler Spreads in Underwater Acoustic Channel with Line-of-Sight and Non-Line-of-Sight Environments

Takuya Waki[1†‡], Yuto Hara[1], Tadashi Ebihara[1*], Naoto Wakatsuki[1] and Koichi Mizutani[1] ([1]Univ. Tsukuba;)

1. Introduction

Underwater acoustic (UWA) communication is an essential technology to support maritime activities, such as marine construction, investigation of natural resources, and underwater security [1]. In UWA communication, a transmitter (Tx) emits a signal to UWA channel, and the signal propagates to a receiver (Rx) with numerous reflections from both the sea surface and seafloor, resulting in large delay spread. Furthermore, the movement of the communication platform and surface boundaries make a time-variant frequency shift of the signal, resulting in Doppler spread.

To address such large delay and Doppler spreads underwater, various studies including signal modulation techniques (e.g., single-carrier modulation [2], multi-carrier modulation [3,4], and combination of array processing and thereof[5]) have been conducted. Although numerous experiments have been conducted in above studies, most of them were performed in line-of-sight (LoS) condition. Therefore, investigations on how the communication performance changes with the environment are necessary. Hence, in this study, we focus on the characteristics of UWA channel in LoS and non-line-of-sight (NLoS) conditions, since the channel changes drastically between LoS and NLoS envirnments.

2. Experiment

2.1 Experimental environment

To explore the characteristics UWA channel, experiments were performed in the coastal area of Nabeta bay, Shizuoka, Japan. The weather was sunny during the experiment, and the temperature of the air and water were 24 and 18 (◦C), respectively.

Fig. 1 shows the experimental environment. As shown in Fig. 1, we fabricated a mobile Tx and a Rx. The Tx consists of a single board computer (SBC; UD-RP4B4, Raspberry Pi), a digital-to-analog converter (DAC; AMS-44, zoom), an amplifier (AMP; A07, Aiyima), and an acoustic emitter (BII-7523, Benthowave). The Rx consists of the SBC, an analog-todigital converter (ADC; AMS-44, zoom), an AMP (T-WBA01, Turtle industry), and a hydrophone (BII-7523, Benthowave). To explore the UWA channel in both LoS and NLoS conditions, the Tx is mounted on a boat and moved in a circle near the breakwater, while the Rx is fixed on the breakwater. During the experiment, the UWA channel becomes LoS and NLoS conditions when the boat moves between points Ⓐ to Ⓓ and Ⓔ to Ⓗ, respectively, as shown in Fig. 1.

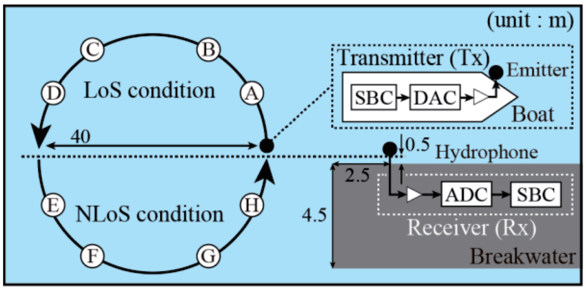

Fig. 1 Experimental environment.

Table 1 Experimental conditions to measure delay spread.

Parameters	Values
Sampling rate of DAC and ADC (kHz)	96
Frequency of LFM signal (kHz)	20-40
Length of LFM signal (s)	0.1
Frequency of sinusoid signal (kHz)	30

2.2 Measurement of delay and Doppler spreads

The delay spread is measured by measuring the impulse response of UWA channel. In this experiment, the Tx (mounted on a boat) modulates a linear frequency modulated (LFM) signal using parameters shown in **Table 1** and emits the signal from the emitter every 1 second. As shown in Fig. 1, the Tx moves in a circle near the breakwater, to switch LoS/NLoS conditions. The Rx on the breakwater obtains the impulse response by recording the signal and calculating a cross-correlation function between the transmitted and received signals.

The Doppler spread is measured by analyzing the recorded signal when a sinusoid signal of specific frequency is emitted to UWA channel. Specifically, the Tx modulates a sinusoid signal using parameters shown in **Table 2** and emits the signal from the emitter continuously. As well as the measurement of the delay spread, the Tx moves in a circle near the

E-mail: †waki.takuya.21@aclab.esys.tsukuba.ac.jp, *ebihara@iit.tsukuba.ac.jp

Table 2 Experimental conditions to measure delay spread.

Parameters	Values
Sampling rate of DAC and ADC (kHz)	96
Frequency of sinusoid signal (kHz)	30

breakwater, to switch LoS/NLoS conditions. The Rx on the breakwater calculates the Doppler spread by recording the signal and performing a short-time Fourier transform on the recorded signal (window size: 1.3 s and overlap: 1.0 s).

3. Result and discussion

The results of the measurement of the delay spread are shown in **Fig. 2**. Figs. 2(i) through 2(iv) show the envelope of the impulse response at points Ⓐ through Ⓗ, respectively. The figures are superimposed at each point where the linear distance between Tx and Rx is approximately the same. Fig. 2 shows that there is a clear difference between the impulse responses in the LoS and NLoS environments. Specifically, the impulse response in the LoS environment has a sharp peak and converges in about 10 ms or less. On the other hand, the impulse response in the NLoS environment has a peak that is approximately 10 dB or more smaller than that in the LoS environment and converges in 20 to 30 ms.

The results of the measurement of Doppler spread are shown in **Fig. 3**. Figs. 3(i) through 3(iv) show the results of spectrogram analysis at points Ⓐ through Ⓗ, respectively. As with Fig. 2, they are superimposed at each point where the linear distance between Tx and Rx is approximately the same. Fig. 3 shows that there is a significant difference in the Doppler spread between the LoS and NLoS environments. In the LoS environment, there was only one frequency peak that appeared to be a direct wave component, and the Doppler spread was around 20 Hz. In the NLoS environment, on the other hand, two frequency peaks were observed. These two peaks are considered to be caused by waves diffracted from the breakwater and reflected waves from the opposite shore direction. The Doppler spread was very large compared to the LoS environment, around 60 Hz.

4. Conclusion

In this study, we investigated the characteristics of UWA communication channels under LoS and NLoS environments. Experiments were conducted to measure the delay and Doppler spreads in UWA channel while switching between LoS and NLoS environments. As a result, it was confirmed that there were clear differences in the impulse responses and spectrograms in the LoS and NLoS environments.

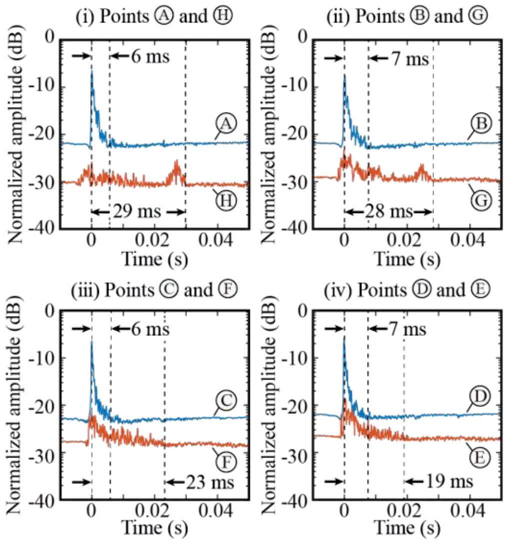

Fig. 2 Result of delay spread.

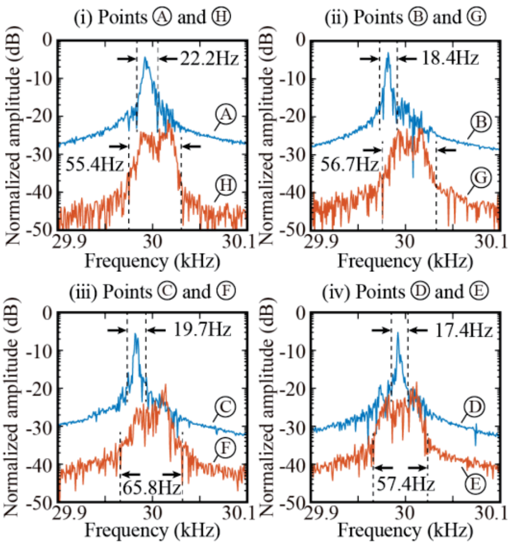

Fig. 3 Result of Doppler spread.

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