A prototype ICI Canceling Underwater OFDM Communication system for Multi-path Doppler Channel

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***Abstract*— This paper proposes a unique trial to combat the Bit Error Rate (BER) degradation in UWA OFDM communication system caused by Ocean Surface reflection induced Multi-Path Doppler Channel. Since the Receiver sees different Doppler Shifts for the waves arriving from different directions, Time-domain resampling and de-rotation proposed by our previous papers cannot compensate those different Doppler Shifts simultaneously. Then Receiver Bit Error Rate (BER) is degraded by Inter-Carrier-Interference (ICI) caused in the case of Multi-path Doppler channel.**

To mitigate the ICI effect, a modified Delay and Doppler Profiler (mDDP), which estimates not only attenuation, relative delay and Doppler shift but also sampling clock shift of each multi-path component, is utilized. Based on the outputs of mDDP, an ICI canceling multi-tap equalizer is used. This is the first trial to perform pool experiment and ocean experiment of moving ship to ship underwater OFDM acoustic communication with a prototype ICI Canceling Underwater OFDM system based on the mDDP and ICI canceling multi-tap equalizer. In the pool experiment, receiving (RX) transducer depths are 0.6/1.2/1.8m and the horizontal distance between TX and RX is 2.8m. In case of 64QAM and RX depth=1.8m, BER is decreased roughly half from 0.00636 to 0.00291. In case of 16QAM and RX depth=1.8m, BER is decreased from 0.0001 to free. Then the effectiveness of proposed prototype ICI Canceling Underwater OFDM system is confirmed. In the Suruga Bay, moving ship to stational ship UWA multi-path Doppler channel communication experiment has been performed. Although the moving ship large background noise condition, some noticeable BER reduction has been observed.

Keywords—Underwater, Acoustic Communication, Networking, OFDM, Doppler effect, UWA, CTF, Delay and Doppler Profiler

I. INTRODUCTION

Underwater wireless communication is demanded for many applications such as surveillance of areas as harbors, ports and coastlines or monitoring of fishes and excavation sites such as oil well, trenches and so on to reduce cable cost or time consuming deploy. In order to increase data Bandwidth, Orthogonal Frequency Division Multiplexing (OFDM) based wireless communication system has drawn wide attention for its high transmission rate and high spectrum efficiency even in Underwater applications. The moving of equipment and/or surface ship causes Doppler shift effect during underwater wireless communication, so the receiver of each side is necessary to have the signal processing for Doppler shift compensation capabilities. Previously, Doppler compensation signal processing algorithm for Desired propagation path was proposed [1-3]. However, in the multi-path condition as shown in Fig.1, the AUV receives signals from different directions through desired path L1 and delayed undesired path L2. Consequently, different Doppler shifted arriving signals are multiplexed. Although the L1 path Doppler effect is compensated by the method shown in paper [1], the difference between L1 and L2 Doppler cannot be compensated. Then Receiver Bit Error Rate (BER) is degraded by Inter-Carrier-Interference (ICI). To solve the multipath Doppler problem described above, one famous method is to use multiple receivers to provide directionality and receive a single Doppler-shifted received signal in one direction [4]. In the previous paper [5], Delay and Doppler Profiler (DDP), which estimates attenuation, relative delay and Doppler shift of each multi-path component, is used to estimate more accurate Channel Transfer Function (CTF) [6-8].

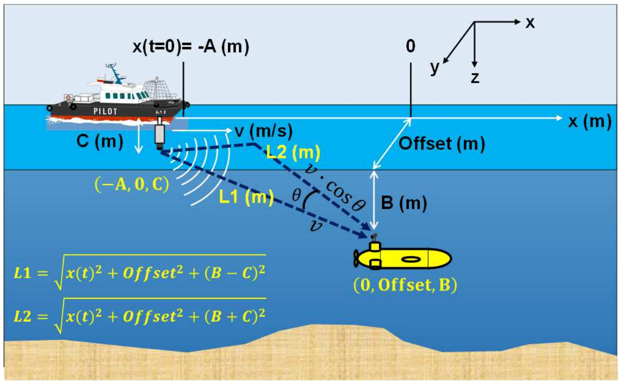


Fig. 1: UWA communication with surface reflection multi-path

This paper proposes a unique trial to combat the Bit Error Rate (BER) degradation in multi-path Doppler UWA OFDM communication system. To mitigate the ICI caused by multi-path Doppler, a modified Delay and Doppler Profiler (mDDP), which estimates not only attenuation, relative delay and Doppler shift but also sampling clock shift of each multi-path component, is utilized [9]. Based on the outputs of mDDP, an ICI canceling multi-tap equalizer is also used. This is the first trial to perform pool experiment and ocean experiment of moving ship to ship underwater OFDM acoustic communication with a prototype ICI Canceling Underwater OFDM system with mDDP and ICI canceling multi-tap equalizer. In section II, the prototype UWA OFDM Communication System is explained. Then pool and ocean experiment results are shown in section III. Finally, in section IV, conclusions will be given.

II. ARCHITECTURE OF UWA OFDM COMMUNICATION SYSTEM

Fig. 2 shows the Block diagram of typical UWA OFDM Communication system. The upper side is transmitter (TX) while lower side is the receiver (RX). The TX is Conventional OFDM transmitter, but RX has additional Time-Domain Doppler compensation capability. First, bit information will be mapped using digital modulation schemes like QPSK / 16 QAM / 64QAM. Then pre-determined pilots are inserted into the modulated symbols. Fig. 3 shows OFDM time-frequency structure. The scattered pilots are used to estimate channel transfer function (CTF) and the continuous pilots are used to detect change in time direction. Each OFDM symbol is converted to time domain using an inverse Fast Fourier Transform (IFFT) operation. A Guard Interval (GI) is attached at the beginning of each time domain OFDM symbol to overcome the distortion triggered by Inter Symbol Interference (ISI) in the channel. Then the baseband signal is up converted into the center frequency of 16 kHz. Finally, the OFDM passband signal amplified with the power amplifier is emitted from TX transducer into underwater acoustic channel. In the RX side, generally the reverse operations of TX are performed. UWA OFDM System Features are summarized in Table I.

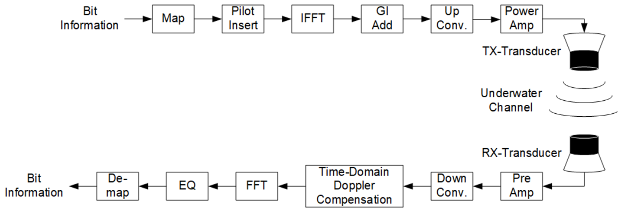


Fig. 2: Typical UWA OFDM Communication system

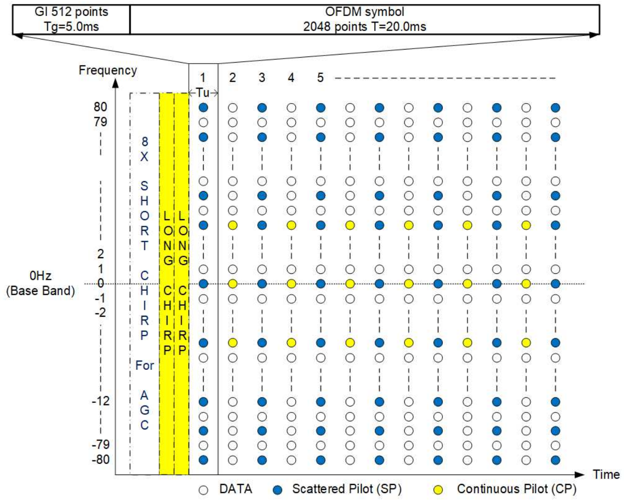


Fig. 3: Time-Frequency structure of OFDM

Table I: UWA OFDM System Features

Parameters	Value
Sampling Frequency Fs	102.4kHz
Band Width (Center frequency)	8 kHz (16kHz)
FFT size	2048
OFDM symbol length T	20.0 ms (2048 point)
Guard Interval length Tg	5.0 ms (512 point)
Sub-carrier spacing	50 Hz
Number of sub-carrier	161
Number of Scattered pilot	81 every 2 OFDM symbol
Number of Continuous pilot	13
Carrier Modulation	QPSK/16QAM/64QAM
Number of Taps in ICI Canceling Equalizer	11

Fig. 4 shows the detail receiver side diagram. Two steps Doppler compensation Algorithm [1] in the Resample and De-rotation portion is used. Then Fine phase error is compensated in the Phase Shift Compensation portion. The 3rd FFT is main

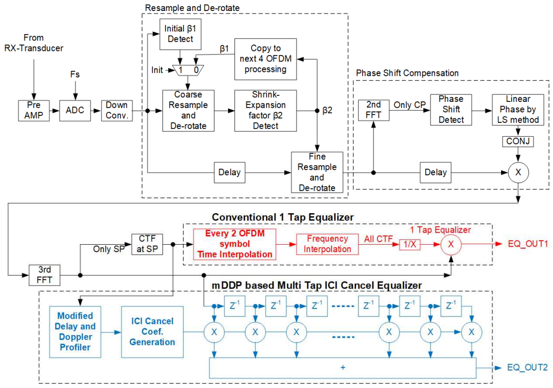
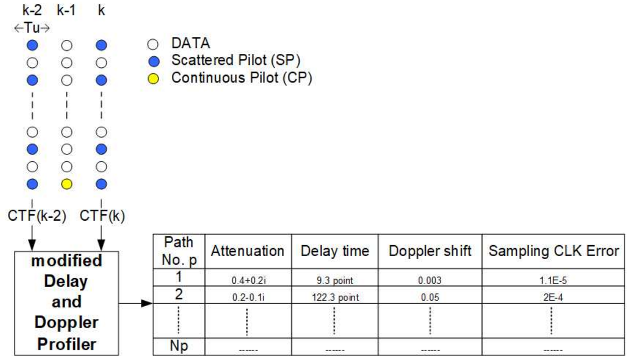


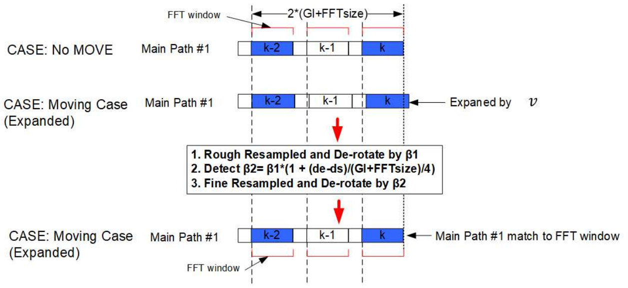
Fig. 4: Receiver Block Diagram with Two Equalizers: Conventional 1 Tap and ICI Cancel Multi Taps

OFDM demodulation. After that, conventional 1 tap equalizer and a new multi-tap ICI canceling Equalizer [9] are shown. As shown in the Fig. 5, modified Delay and Doppler Profiler estimates each Np multipath component waves to receiver. Each analyzed component can be characterized using four parameters such as Attenuation r_p, Propagation Delay time τ'_p, normalized Doppler shift α_p and Sampling CLK error β_p for wave component index p. Here the Attenuation r_p is complex value including amplitude attenuation and phase rotation and Doppler shift is normalized by sub-carrier spacing f_0 such as $\alpha_p = fd_p/f_0$. Using the symbol k measured CTF(k) and symbol k-2 measured CTF(k-2), mDDP detects N_P sets of those four parameters. Detail explanation of mDDP and ICI canceling method is available in the paper [9].

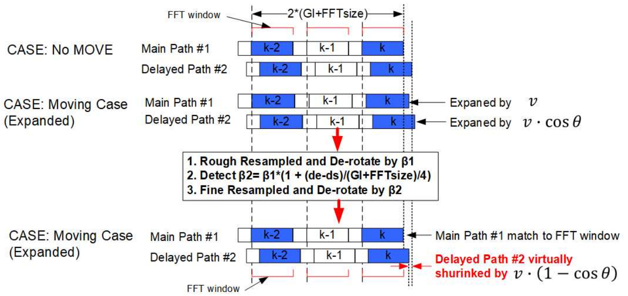


Path No. p	Attenuation	Delay time	Doppler shift	Sampling CLK Error
1	0.4+0.2i	9.3 point	0.003	1.1E-5
2	0.2-0.1i	122.3 point	0.05	2E-4
⋮	⋮	⋮	⋮	⋮
Np	------	------	------	------

Fig. 5: Modified Delay and Doppler Profiler



(a) Single-path case



(b) Case of Multi-path with different Doppler Shift

Fig. 6: OFDM signal after the Shrink and Expansion processing

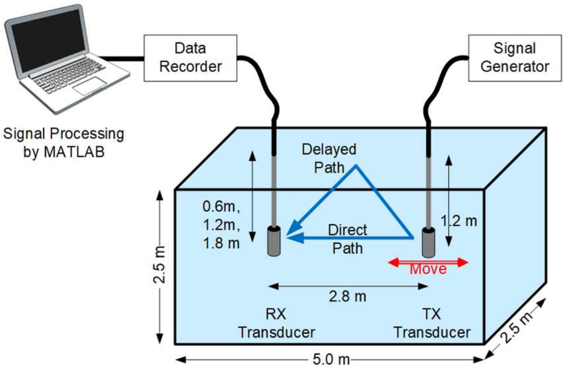


Fig. 7: Pool Experiment Setup

Fig. 6 shows two cases of OFDM signal after Resample and De-rotation portion in Fig.4. In Fig.6(a) of Single-path case, the 1st row shows 3 OFDM symbols with no movement and the 2nd row shows the case of received signal that appears to be stretched by moving reception. The 3 descriptions in the rectangle box corresponds to the function of Resample and De-rotation portion. After that, the received OFDM signal is shrunk to the same length of no move case. In Fig. 6(b) case of multi-path with different Doppler Shift, Delayed path #2 is added to Fig. 6(a). Since expansion factor of path #2 is different from that of path #1 by $\cos\theta$, Delayed path #2 OFDM symbols shown in the bottom row does not match with that of no move case. Then the Delayed path #2 disrupts orthogonality between OFDM sub-carriers and Inter-Carrier-Interference (ICI) between data sub-carriers are introduced.

III. POOL AND OCEAN EXPERIMENT RESULTS

A. POOL EXPERIMENT

The detail of pool experiment environmental is shown in Fig. 7. The non-reflection pool width is 5.0 m, hight is 2.5 m, depth is 2.5 m. Transceiver TX and receiver RX transducers are

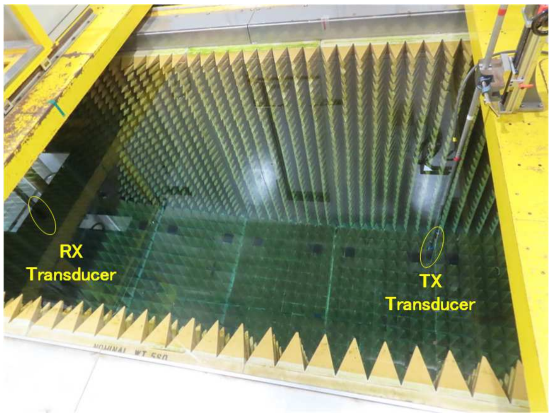


Fig. 8: Photo of Pool Experiment

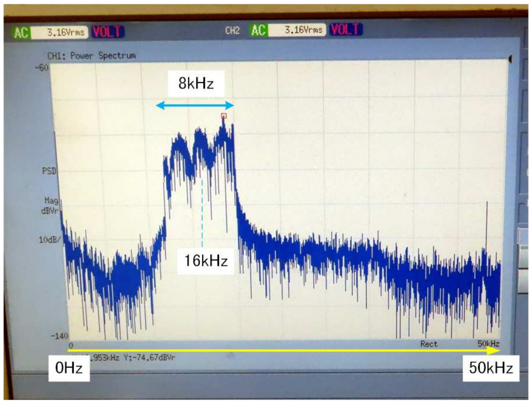
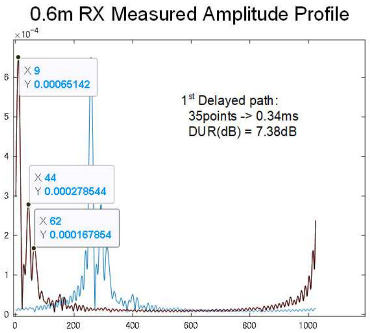
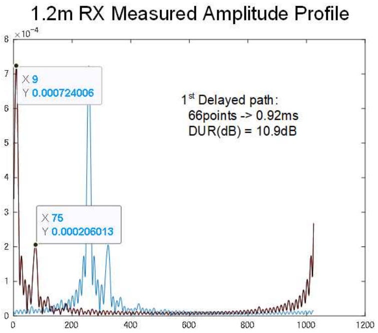


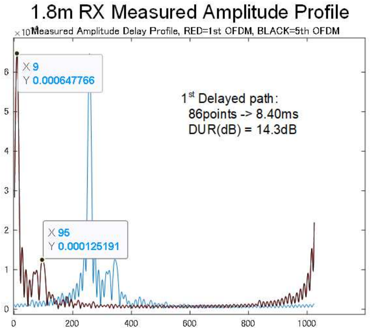
Fig. 9: Measured Spectrum at Pool Experiment



(a) RX depth=0.6m



(b) RX depth=1.2m



(b) RX depth=1.8m

Fig. 10: Measured Amplitude Delay Profiles

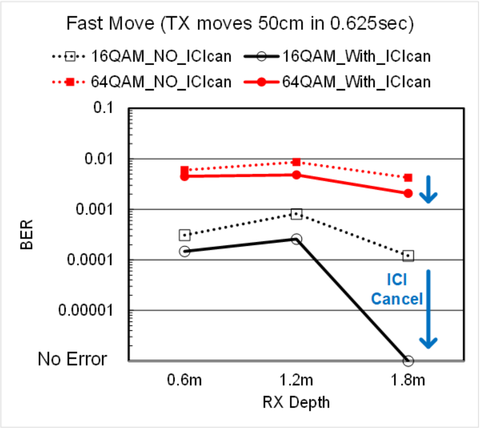


Fig. 11: Measured BER in Pool Experiment

installed at 1.2 m and 0.6/1.2/1.8 m depth respectively in the pool, and it spaced 2.8m apart. RX is fixed, and TX is rapidly moved 50cm interval in 0.625 sec. RX data is captured by Data recorder and is signal processed by Matlab S/W. Photo of the non-reflection pool is shown in Fig.8 and measured received signal spectrum is indicated in Fig. 9 with RX depth of 1.2 m. The center of OFDM spectrum is 16 kHz and the bandwidth is 8 kHz. Because of multi-path channel by water surface reflection, the top of the 8 kHz OFDM spectrum in the range of 12 to 20 kHz is fluctuating. Amplitude delay profiles are measured for 3 RX depths. In each figure, delay times and Desired to Undesired ratios (DUR) are also shown.

Fig. 11 summarized measured BER for 16 and 64QAM modulations for both conventional 1 tap and new multi-tap ICI canceling Equalizers. In case of 64QAM and RX depth=1.8m, BER is decreased roughly half from 0.00636 to 0.00291. In case of 16QAM and RX depth=1.8 m, BER is decreased from 0.0001 to free. Then the effectiveness of propose prototype ICI Canceling Underwater OFDM system is confirmed.

B. OCEAN EXPERIMENT

Ocean Experiment with similar situation shown in Fig. 1 has been performed in Suruga Bay, Shizuoka prefecture in Japan. The depth of the sea is around 100m. Fig. 12 shows the photo of the experiment using two vessels. TX transducer is equipped at the left moving vessel with 2m depth and RX transducer is suspended 20m downward of the right stationary vessel. Due to the magnitude of the power noise of the mobile vessel, measurement experiments were conducted using the noise-resistant QPSK modulation method.

The results of two comparative experiments are presented in Fig. 13. The case in Fig. 13(a) corresponds to a measurement in 10 seconds (400 OFDM symbols), when the transmitting vessel is moving at a speed of 2 knots, approaching from a

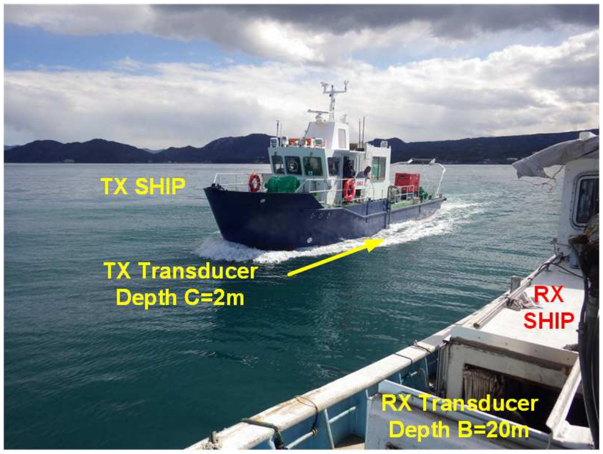
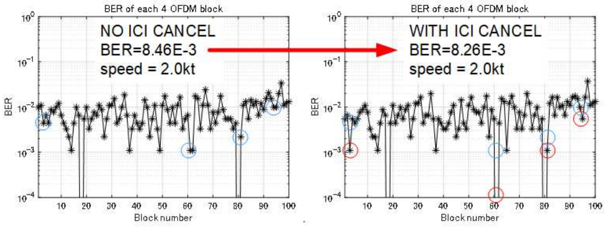


Fig. 12: Photo of Ocean Experiment at Suruga Bay

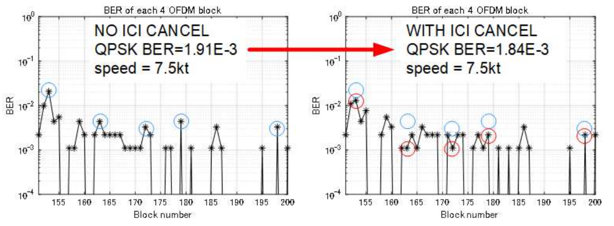
position 10 m away from the closest approach point and moving to there. The distance from the stopped vessel at the closest approach point is 9 meters. The case in Fig. 13(b) corresponds to a measurement of 5 seconds (200 OFDM symbols) from a point 13 m away from the stopped vessel at 7.5 knots, past the closest approach point, and 20 m away from the closest approach point, when the transmitting vessel is moving at a speed of 7.5 knots.

In both diagrams in Fig. 13, the left side corresponds to the conventional 1-tap equalizer and the right side corresponds to the new multi-tap ICI canceling equalizer. Block is 4 OFDM symbols and the BER for each block is measured. The blue circled point in the left figure is the several block number where the BER drop was identified in the right figure, and that left figure's blue circle is copied to the right figure, with the red circle indicating its dropped BER. The BER improvement effect of the prototype ICI Canceling Underwater OFDM system was confirmed despite the noisy environment of the moving ship. The total BER reduction in Figure 13(a) was from 8.46E-3 to 8.26E-3 and that in Figure 13(b) was from 1.91E-3 to 1.84E-3, confirming the effect in small amounts.



10sec, 400 OFDM symbols, TX Ship Speed v=1m/sec, x(t=0)=-10m, offset=9m, RX Depth B= 20m (Test17)

(a) QPSK, TX ship speed = 2.0kt, 400 OFDM symbols



5sec, 200 OFDM symbols, TX Ship Speed v=3.8m/sec, x(t=0)=+30m, offset=13m, RX Depth B= 20m (Test11)

(b) QPSK, TX ship speed = 7.5kt, 200 OFDM symbols

Fig. 13: Measured BER comparisons at Ocean Experiment

IV. CONCLUSION

This paper proposes a unique trial to combat the Bit Error Rate (BER) degradation in UWA OFDM communication system caused by Ocean Surface reflection induced multi-path Doppler Channel. To mitigate the ICI effect cause by multi-path Doppler, a modified Delay and Doppler Profiler (mDDP), which estimates not only attenuation, relative delay and Doppler shift but also sampling clock shift of each multi-path component, is utilized. Based on the outputs of mDDP, an ICI canceling multi-tap equalizer is used. This is the first trial to perform pool experiment and ocean experiment of moving ship to ship underwater OFDM acoustic communication with a prototype ICI Canceling Underwater OFDM system based on the mDDP and ICI canceling multi-tap equalizer.

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