An ICI Canceling Underwater OFDM Communication system with 2-step modified Delay and Doppler Profiler

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***Abstract*— In 2023, the first prototype of an Inter-Carrier-Interference (ICI) Canceling Underwater Orthogonal Frequency Division Multiplexing (OFDM) Communication system was proposed using modified Delay and Doppler Profiler (mDDP). However, the Bit Error Rate (BER) reduction was limited. As a result of continuous research, we found that the two-stage configuration of mDDP can dramatically improve BER reduction performance.**

This paper presents the results of pool experiments of OFDM communications in forward and reverse two-wave Doppler-shift environments. 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. After the 1st stage mDDP, the effect of ICI has been reduced from the Channel Transfer Function (CTF) and the more accurate CTF is processed by the second-stage mDDP, resulting in highly accurate channel parameter estimation and improved ICI cancellation in the final multi-tap equalizer.

To verify this effect, two transmit transducers and one receive transducer were used in the pool experiment to create a two-wave inverse Doppler-shifted multipath environment. By increasing the number of equalizer taps, the BER reduction performance of 64QAM modulation was improved by approximately one order of magnitude for 2step mDDP compared to 1step mDDP.

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

I. INTRODUCTION

Underwater wireless communications are used in many applications to reduce cable costs and time, such as harbor and shoreline monitoring, fish monitoring, and monitoring of oil wells, trenches, and other drilling sites. Orthogonal Frequency Division Multiplexing (OFDM) systems, which are universally used in radio wave communications, such as 5G systems [1] and WiFi, have attracted widespread attention for their high transmission rates and high spectrum efficiency in underwater applications. Since the speed of sound in water is much smaller than the speed of radio propagation, underwater wireless communications suffer significant performance degradation due to Doppler shift caused by the movement of equipment and vessels, and strong Doppler countermeasures are essential.

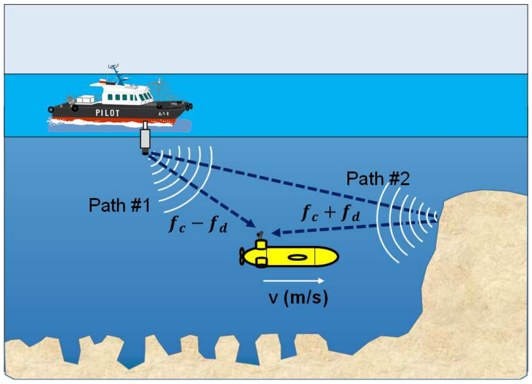

Fig. 1: Underwater acoustic communication with reflected multi-path

Previously, Doppler compensation signal processing algorithm for desired propagation path was proposed [2-4]. However, it could not handle multi-path situations consisting of different Doppler shift components as shown in Fig.1, which shows a two-wave multi-path environment subject to Doppler shift in the opposite direction. In this situation, underwater communication causes expand or shrink of the received signal as shown in Fig. 2. To address this situation with one receiving element, the first prototype of an Inter-Carrier-Interference (ICI) Canceling Underwater OFDM Communication system was

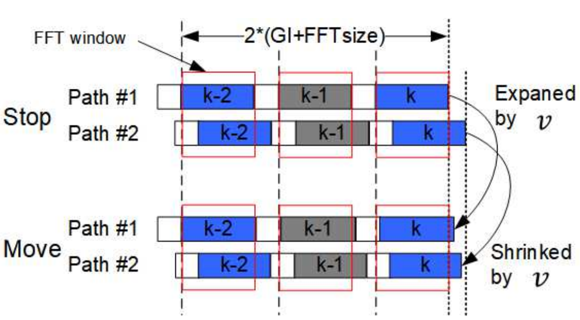

Fig. 2: Expanded and shrunk signals in multi-path

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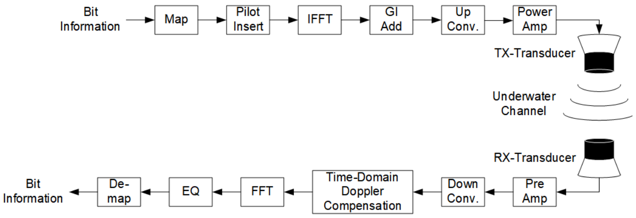


Fig. 3: Typical UWA OFDM Communication system

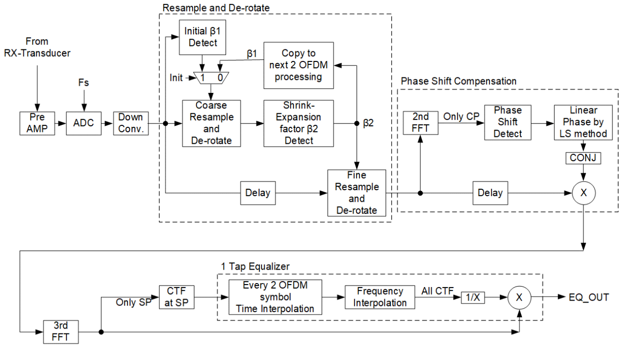


Fig. 4: Conventional Receiver Block Diagram

proposed using modified Delay and Doppler Profiler (mDDP) in 2023 [5-6]. However, the Bit Error Rate (BER) reduction was limited. As a result of continuous research, we found that the two-stage configuration of mDDP can dramatically improve BER reduction performance.

This paper proposes a unique trial to combat the BER degradation in multi-path Doppler Underwater acoustic (UWA) OFDM communication system by 2-step mDDP. In section II, the proposed UWA OFDM Communication System with 2-step mDDP is explained. Then pool experiment results are shown in section III. Finally, in section IV, conclusions will be given.

II. ARCHITECTURE OF UWA OFDM COMMUNICATION SYSTEM

Figure 3 shows a block diagram of a typical UWA OFDM communication system. The upper side is the transmitter (TX) and the lower side is the receiver (RX); the TX is a conventional OFDM transmitter, but the RX has additional time-domain Doppler compensation [2-4]. Details of the receiving side processing are shown in Fig. 4. Resample and De-rotations processing and Phase Shift compensation processing are introduced for Doppler compensation signal processing in the desired propagation path. The 3rd Fast Fourier Transform (FFT) is the principal Discrete Fourier Transform (DFT) of OFDM demodulation, followed by the equalization process.

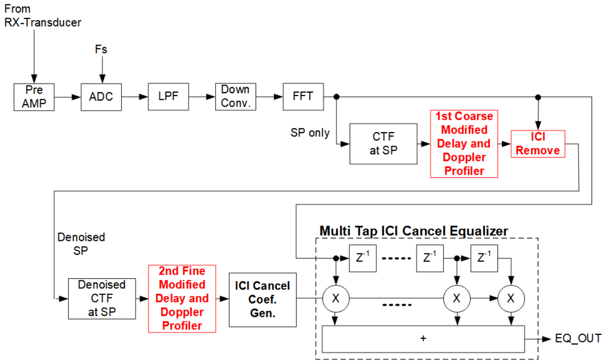


Fig. 5: Receiver Block Diagram with 2-step_mDDP

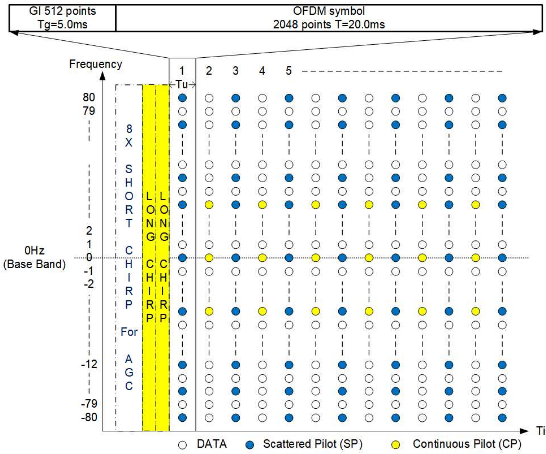


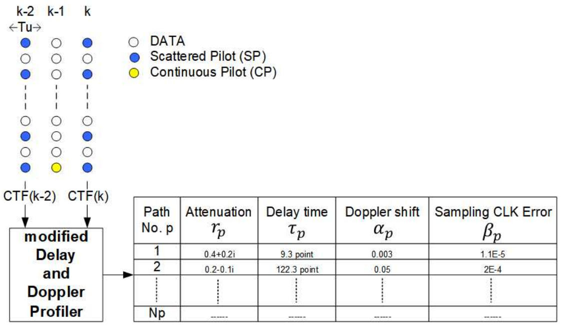
Fig. 6: Time-Frequency structure of OFDM

Figure 4 shows the proposed mDDP-based OFDM receiver without resample and de-rotation. After the first-stage mDDP, the ICI component is removed to improve the Channel Transfer Function (CTF) accuracy of the second-stage mDDP input. With the channel parameters estimated by the second-stage mDDP, the ICI cancellation process is performed by the multi-tap equalizer.

Figure 6 shows OFDM time-frequency structure. The scattered pilots are used to estimate 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

Table I: UWA OFDM System Features

Parameters	Value
Sampling Frequency Fs	102.4kHz
Band Width	8 kHz
Center Frequency	24 kHz
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
Scattered pilot	81 every 2 OFDM symbol
Continuous pilot	13
Carrier Modulation	64QAM



Path No. p	Attenuation r_p	Delay time τ_p	Doppler shift α_p	Sampling CLK Error β_p
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. 7: Modified Delay and Doppler Profiler

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 24 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. The mDDP estimates a combination of multiple Doppler-shifted propagation paths and their parameters such as attenuation, relative delay, Doppler-shift and sampling clock error as shown in Fig. 6. The details of mDDP computation are described in detail in an earlier paper [5-6] and the original DDP method are well documented in the papers [7-9].

III. POOL EXPERIMENT RESULTS

To verify the ICI cancellation effect in a real application, a pool experiment was conducted. Figure 8 shows the setup of the pool experiment. The walls and bottom of the pool are covered with non-reflective material, and reflections occur mainly at the water surface. To reduce the effect of water surface reflections, the transducers were placed at a depth of 1.8 m. Two sets of transducers (TX1 and TX2) were used for the transmit wave to create a two-wave multipath environment. The receiving transducer (RX) moves from near TX1 to near TX2 as shown in the figure. The speed of movement corresponding to the experimental results described below is 0.25 m/sec, which means that it moves a distance of 75 cm in about 3 seconds.

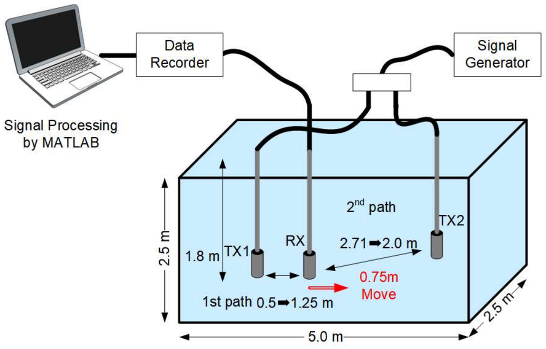


Fig. 8: Pool Experiment setup

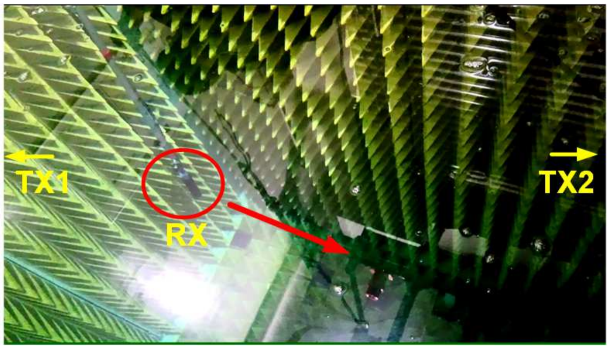


Fig. 9: Photo of Pool Experiment

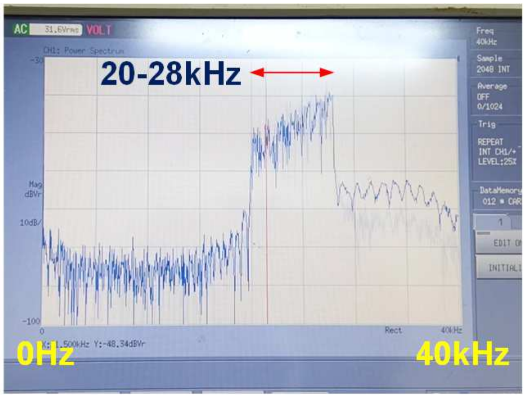


Fig. 10: Measured Spectrum at Pool Experiment

Figure 9 shows a photograph of the pool taken from above, and Fig. 10 shows the measurement results of the received signal spectrum: the center of the OFDM spectrum is 24 kHz and the bandwidth is 8 kHz. Due to the multipath channel, the upper end of the OFDM spectrum, from 20 to 28 kHz, is fluctuating with overall upward shifting. This rightward power increase in gain is determined by the transducer's transmitting characteristics.

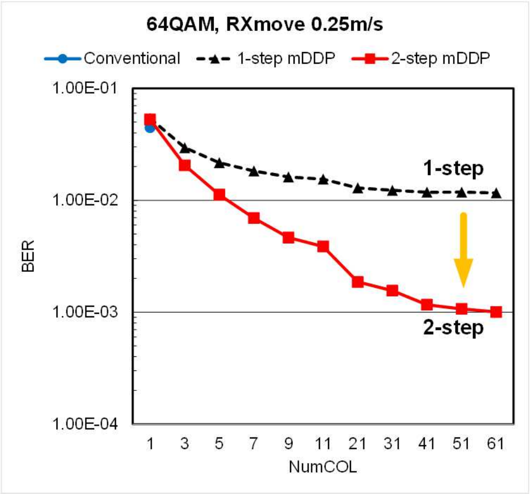
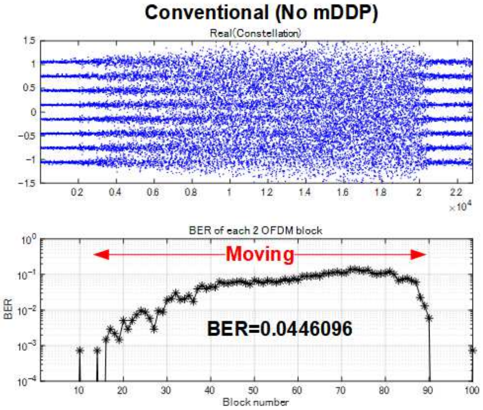
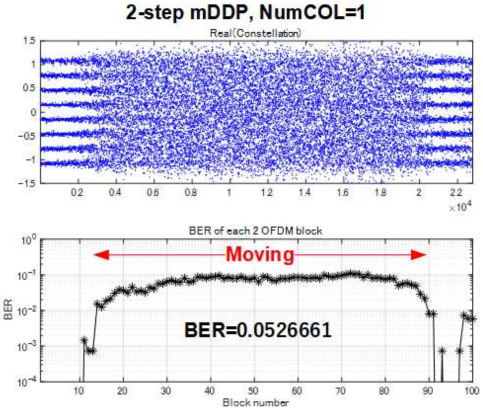


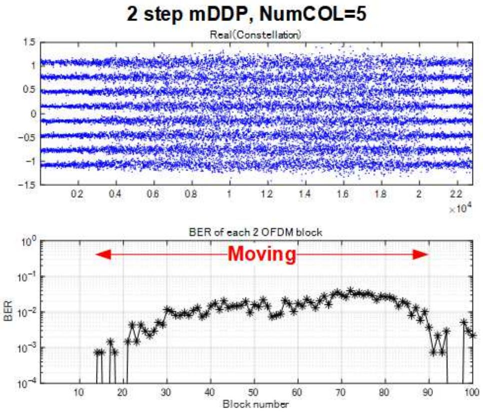
Fig. 11: Measured BER in Pool Experiment



(a) Conventional (No mDDP)

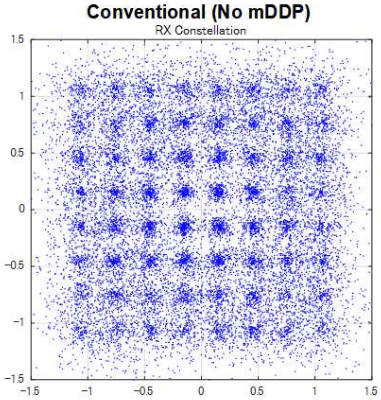


(b) 2-step mDDP, NumCOL=1



(c) 2-step mDDP, NumCOL=5

Fig. 12: Time dependences of Constellation (Real part of complex) and measured BER



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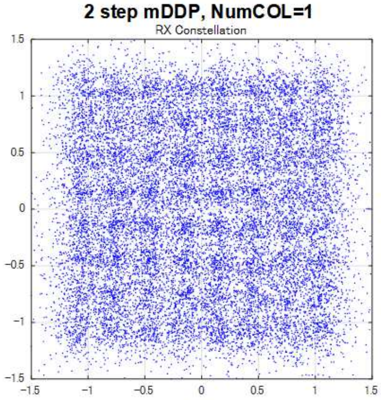

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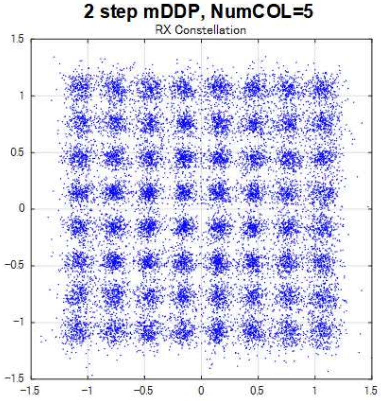
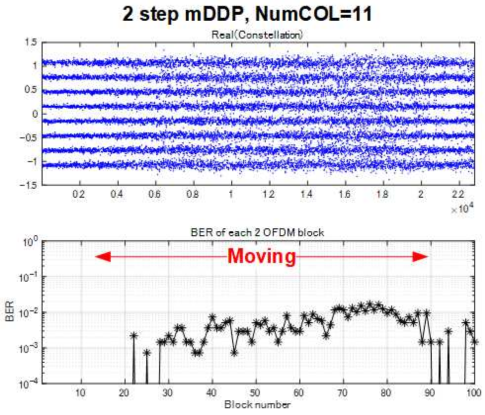
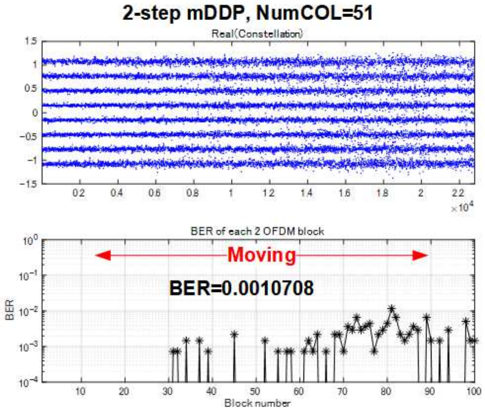


(c) 2-step mDDP, NumCOL=5

Fig. 13: Constellation of Moving Period



(d) 2-step mDDP, NumCOL=11

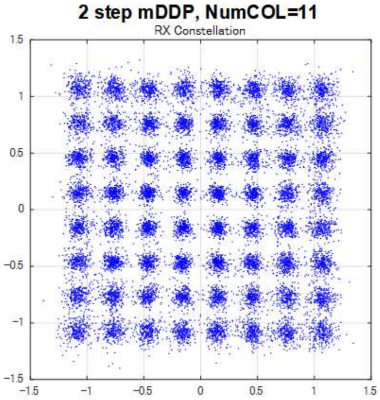


(e) 2-step mDDP, NumCOL=51

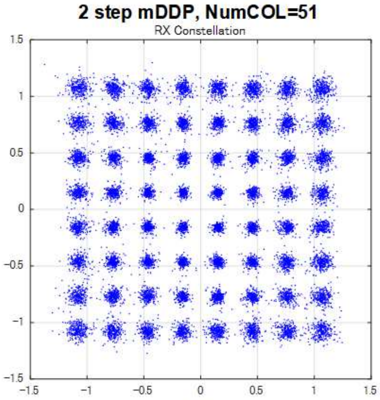
Fig. 12: Time dependences of Constellation (Real part of complex) and measured BER

Figure 11 shows the measured BER with 64QAM modulation for a conventional receiver [2-4], and 1-step and 2-step mDDP. Here, the BER measurement period is about 5 seconds, corresponding to 200 OFDM symbols. NumCOL is the number of taps for the ICI cancel equalizer. The BER for the Conventional Receiver is close to NumCOL=1 for 1-step and 2-step mDDP. While 1-step mDDP showed small improvement for increasing NumCOL, 2-step mDDP showed dramatic improvement for changing NumCOL, achieving about an order of magnitude improvement at larger NumCOL values compared to 1-step mDDP.

Figure 12 (a)-(e) show the time dependences of measured BER and the real component of 64QAM constellation in pool experiments for 5 cases such as conventional, 2-step NumCOL=1, 5, 11, 51. 2-step mDDP dramatically reduces constellation scatter and BER as NumCOL value is increased in the moving area. Figure 13 (a)-(e) show 5 corresponding constellations of its moving segments. 2-step mDDP NumCOL=51 case shows very clear 64QAM constellation comparing with 2-step NumCOL=1 or Conventional.



(d) 2-step mDDP, NumCOL=11



(e) 2-step mDDP, NumCOL=51

Fig. 13: Constellation of Moving Period

IV. CONCLUSION

This paper proposes a unique trial to combat the Bit Error Rate (BER) degradation in multi-path Doppler Underwater acoustic OFDM communication system by 2-step modified Delay and Doppler Profiler (mDDP). In 2023, the first prototype of an Inter-Carrier-Interference (ICI) Canceling Underwater OFDM Communication system was proposed using 1-step mDDP. However, the BER reduction was limited. As a result of continuous research, we found that the two-stage configuration of mDDP can dramatically improve BER reduction performance. To mitigate the ICI effect, a mDDP, which estimates not only attenuation, relative delay and Doppler shift but also sampling clock shift of each multi-path component, is utilized. After the 1st stage mDDP, the effect of ICI has been reduced from the Channel Transfer Function (CTF) and the more accurate CTF is processed by the second-stage mDDP, resulting in highly accurate channel parameter estimation and improved ICI cancellation in the final multi-tap equalizer. Two transmit transducers and one receive transducer were used in the pool experiment to create a two-wave inverse Doppler-shifted multipath environment. By increasing the number of equalizer taps, the BER reduction performance of 64QAM modulation was improved by approximately one order of magnitude for 2step mDDP compared to 1step mDDP. At the end of 2024, marine experiments will be carried out to see if the results of the pool experiment have a similar ameliorative effect in a real marine environment.

REFERENCES

[1] Erik Dahlman, Stefan Parkvallm Johan Skold, “5G NR: The Next Generation Wireless Access Technology,” Academic Press, London, UK, 2018.

[2] Mohammad Ariful Hoq, Shiho Oshiro, and Tomohisa Wada, “Two steps Doppler compensation Algorithm from moving AUV to AUV/Mother Ship for OFDM-based UWA communication system,” IJICSNS International Journal of Computer Science and Network Security, VOL.20, No.12, December 2020.

[3] Tomohisa Wada, Taisaku Suzuki, Hiromasa Yamada, Shigeo Nakagawa; An Underwater Acoustic 64QAM OFDM Communication System with Robust Doppler Compensation, MTS / IEEE OCEANS 2016, Monterey California USA, September 2016.

[4] Shiho Oshiro, Yukiko Muller, Hiromasa Yamada, and Tomohisa Wada, “An UWA OFDM Communication System with Improved Doppler compensation and Initial Synchronization,” MTS/IEEE OCEANS 2022 Hampton Roads Virginia Beach Convention Center In-Person & Virtual: October 17-20, 2022.

[5] Shiho Oshiro, Catherine Akioya, Hiromasa Yamada and Tomohisa Wada, “A prototype ICI Canceling Underwater OFDM Communication system for Multi-path Doppler Channel,” MTS/IEEE OCEANS 2023 Mississippi Coast Coliseum & Convention Center, September 25-28, 2023.

[6] Catherine Akioya, Shiho Oshiro, Hiromasa Yamada and Tomohisa Wada, “A Modified Delay and Doppler Profiler based ICI Canceling OFDM Receiver for Underwater Multi-path Doppler Channel,” IJICSNS International Journal of Computer Science and Network Security, VOL.23, No.7, pp1-8, July 2023.

[7] Mitsuru Nakamura, Makoto Itami, Kohji Itoh and Hamid Aghvami, “ICI Cancellation Technique based on Estimating Delay and Doppler Profile in OFDM Reception,” The Institute of Image Information and Television Engineers, Vol. 56, No. 12, pp.1951-1958 (2002).

[8] Mitsuru Nakamura, Masahiro Fujii, Makoto Itami and Kohji Itoh, “MMSE ICI Canceller for OFDM Mobile Reception,” The Institute of Image Information and Television Engineers, Vol. 58, No. 1, pp.83-90 (2004).

[9] Akito Yamazaki, Mitsuru Nakamura, Masahiro Fujii, Makoto Itami, Kohji Itoh and Hiroki Ohta, “A Study on Improving Performance of an OFDM ICI Canceller,” The Institute of Image Information and Television Engineers, Vol. 58, No. 1, pp.94-101 (2005).