

# An Underwater Acoustic 64QAM OFDM Communication System with Robust Doppler Compensation

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**Abstract**— This paper proposes an underwater acoustic OFDM communication system to transmit image or movie data from deep see AUV etc. to surface ship. In order to mitigate Doppler shift effect caused by transmitter and/or receiver movement, the OFDM receiver possesses additional time domain signal processing such as signal shrink-expansion processing and Doppler shift compensation capabilities. The outputs of the four OFDM receivers are further combined by frequency domain diversity combiner with Maximum-Ratio Combining (MRC) algorithm to improve Signal to Noise ratio. The proposed communication system is verified by Ocean measurement at Shizuoka prefecture in Japan. Our system utilized 20-28[KHz] ultrasonic OFDM channel and subcarrier spacing of 100[Hz]. Total number of sub-carriers is 81. QPSK / 16QAM / 64QAM modulations are used. By performing experiment in the ocean at depth of 1000m, BER of approximately less than  $1E-2$  has been successfully obtained using 64QAM without any error correction.

**Keywords**—Underwater, Acoustic Communication, OFDM, MRC, Doppler compensation

## I. INTRODUCTION

Underwater acoustic wireless communication is needed to transmit the digital data between equipment such as image or movie data from ROV (Remotely operated vehicle) to surface ship, control data of the opposite direction, exchange information data between diver, the biological information data necessary to manage the safety diving, etc. Most of equipment are moving during wireless communication, and therefore the Doppler shift effect is caused by transmitter and/or receiver movement. In order to mitigate Doppler shift effect, the receiver is necessary to have the signal processing for Doppler shift compensation capabilities.

In this paper, we propose an underwater acoustic OFDM (Orthogonal Frequency Division Multiplexing) communication system [1-4] with robust Doppler compensation. In order to mitigate Doppler shift effect, the OFDM receiver possesses additional time domain signal processing such as signal shrink-expansion processing and Doppler shift compensation capabilities. The section II describes the proposed OFDM diversity communication system and its detail signal processing.

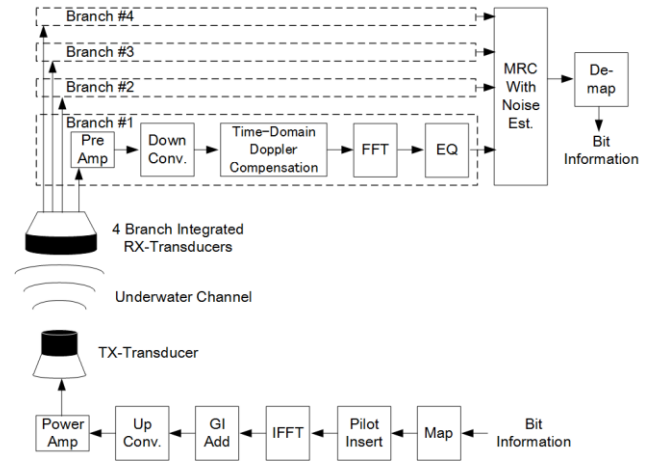


Fig. 1. Proposed communication system

Ocean field experiment results are shown in section III. Finally, the summary is concluded in section IV.

## II. PROPOSED SYSTEM

### A. System Block Diagram

Fig.1 shows the block diagram of proposed underwater acoustic OFDM communication system. The lower side of the figure corresponds to the transmitter TX and the upper side is receiver RX. The TX is typical OFDM transmitter while the RX has additional Time-Domain Doppler compensation capabilities. In TX side, bit data are modulated by using QPSK / 16QAM / 64QAM digital modulations, and BPSK modulated pilot symbol are inserted in order to measure time-varying channel condition. Guard Interval (GI) of 2.8125 ms is attached to the head of each OFDM symbol. The GI length is carefully determined by taking multi-path delay distribution. Then the baseband signal is up-converted to 24 KHz center frequency, and finally the output of TX is emitted into underwater channel via TX transducer with average power of 166dB.

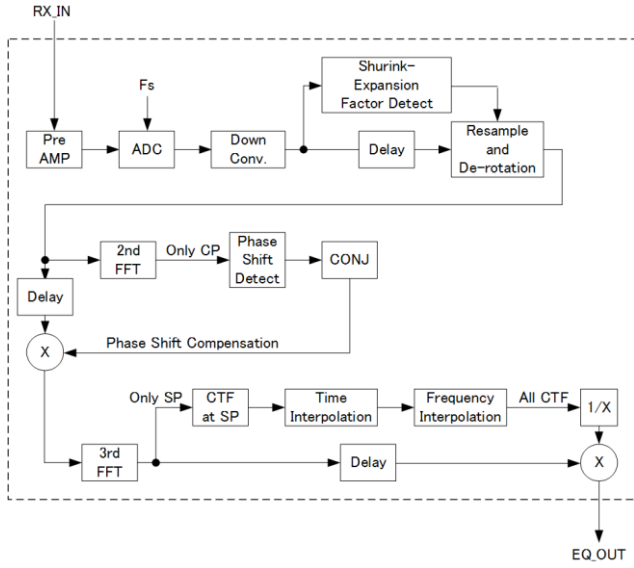


Fig. 2. Block diagram of 1 branch receiver

Fig. 2 shows the block diagram of one branch receiver in detail. The Time-Domain Doppler compensation block in Fig. 1 corresponds to Shrink-Expansion Factor detect, Resample/De-rotation, and fine Phase Shift Compensation. Those two stages signal processing have realized robust communication system which can use even 64QAM higher modulation. After the fine Phase-Shift compensation, 3rd FFT is performed. Then channel estimation processing is performed to generate a channel transfer function (CTF). By dividing the 3rd FFT output by CTF, equalization process is performed to recover correct constellations. Finally, Maximum-Ratio Combining (MRC) [2,4] is performed for diversity combining by using 4 RX outputs as shown in Fig.1.

### B. Time-Frequency Representation

Fig. 3 shows the time-frequency representation of the OFDM system. The number of total sub-carriers in one OFDM symbol is 81. The 41 symbols of Scattered Pilot (SP), which are

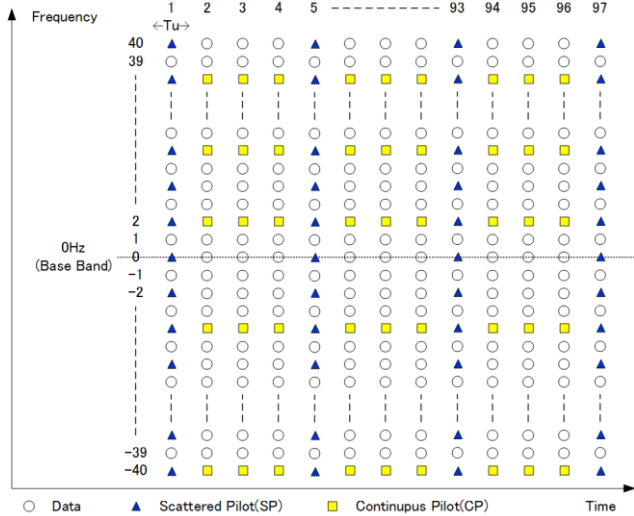
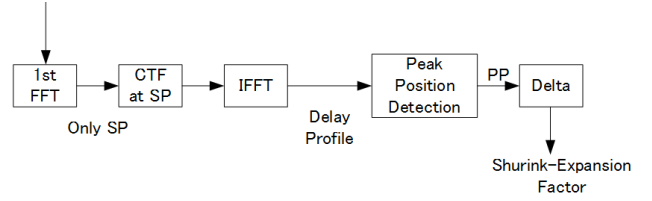
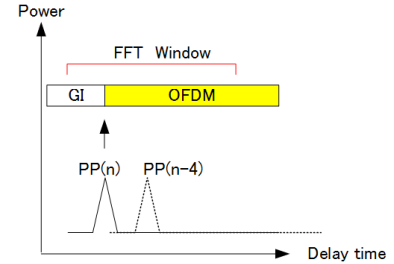


Fig. 3. Time-Frequency diagram for OFDM

placed at all even number sub-carriers, are allocated to one OFDM symbol in every 4 OFDM symbol intervals as shown by the triangle. The SP is used for channel estimation to generate channel transfer function (CTF). In order to obtain whole time-frequency grid points, CTF at SP position are interpolated in time and frequency axis. The 16 symbols of Continuous Pilot (CP) are allocated to each OFDM symbol randomly in even carrier numbers as shown by rectangles. The CP is used to calculate fine Phase Shift Estimation for fine phase compensation. The other white circles correspond to data sub-carriers, which are modulated by QPSK / 16QAM / 64QAM.



(a) Shrink-Expansion Factor Detector



(b) Delay Profiles for symbol number n and n-4

Fig. 4. Shrink-Expansion Function

### C. Shurink-Expasion processing

In order to mitigate Doppler shift effect caused by transmitter and/or receiver movement, time domain signal is either shrunk or expanded. As shown in Fig. 2, the received signal is amplified and sampled using sampling frequency  $F_s=102.4\text{KHz}$ . Fig. 4(a) shows a Shrink-Expansion Factor  $\beta$  detector. Since SP is placed every even sub-carrier index, the delay profile can be computed as shown in Fig. 4(b). The peak position (PP) of the profile indicates the starting time point of the effective OFDM symbol. Since the PPs are available every 4 OFDM symbol, by comparing current PP(n) with previous

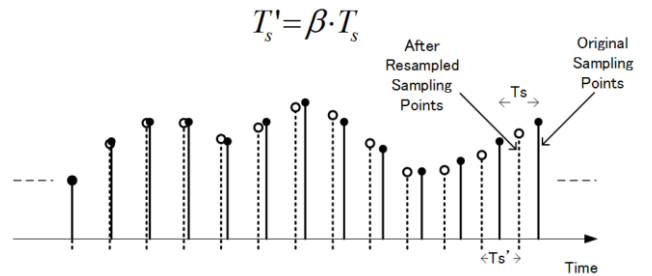


Fig. 5. Resample operation

PP(n-4), sampling interval  $T_s (=1/F_s)$  drift can be computed. Then Shrink-Expansion Factor  $\beta$  can be obtained such as

$$T_s' = \beta \cdot T_s \quad (1)$$

Here,  $T_s$  is system sampling Interval and  $T_s'$  is correct sampling interval. After the detection, resample operation is performed as shown in Fig. 5. Since the resample operation needs to computer interpolated point from original samples, 13 tap filter is used. De-rotation operation is also required in the case of  $\beta \neq 1$ , because Down-Conversion processing is to multiply received signal with  $\exp(-j2\pi F_c n T_s')$  in order to shift the center frequency to 0Hz. At the case of  $\beta \neq 1$ , the Down-Converted center frequency has the following Difference as shown in equation (2).

$$Diff = e^{-j2\pi f_c n (T_s - T_s')} = e^{-j2\pi f_c n T_s' (1-\beta)/\beta} \quad (2)$$

Then, additionla de-rotation multiply of conjugate of Diff is required.

The TABLE I indicates detail system features. The system utilizes 20 to 28 KHz (8 KHz bandwidth) ultrasonic sound for OFDM communication and subcarrier spacing of 100 Hz. The OFDM symbol length is 10.0 ms, which corresponds to 1024 points of samples. Total number of subcarriers are 81.

TABLE I. OFDM SYSTEM FEATURE

Parameters	Value
TX-RX Elements	1 TX and 4 RX Transducer
Sampling Frequency $F_s$	102.4 KHz
TX Center Frequency $F_c$	24000 Hz
Band Width	8000 Hz
FFT Size	1024
OFDM symbol length T	10.0 ms
GI length	2.8125 ms
Sub Carrier Spacing	100 Hz
Number of Sub Carrier	81
Average TX power	166dB
Max. Data Rate	27.5Kbps (64QAM)



Fig. 7. TX Transducer and camera system

### III. EXPERIMENTAL RESULTS

Fig. 6 shows the experiment scene of the proposed underwater acoustic OFDM communication system. The transmitter with 1 TX transducer is sank to the 1000m deep seabed using a crane from the ship. The moving speed of the TX is roughly maximum 1m/sec. The TX transducer regularly transmits the OFDM signal which carries photo JPEG data modulated by QPSK / 16QAM / 64QAM digital modulations. The camera is equipped in pressure-resistant glass case in order take photos at deep sea. The receiver with 4 RX transducers is fixed to the ship and receives the OFDM signal from the moving TX. Figures. 7 and 8 are Transmitter with camera system on the ship hung by crane and 4 integrated transduces photos.

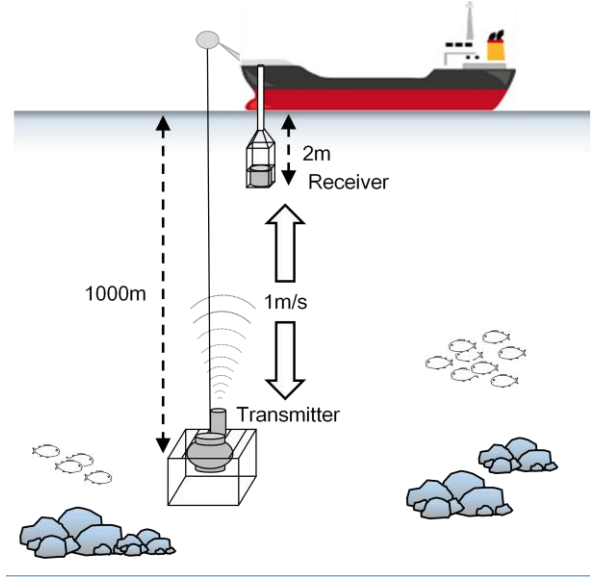


Fig. 6. Experimental Scene



Fig. 8. RX 4 branches integrated Transducer

Ocean experiment was performed at Suruga Bay in Shizuoka prefecture, Japan. Fig. 9 and 10 shows 64QAM measured constellation at 1000 depth and a taken image from 1000m deep TX (transferred by QPSK modulation because of error free).



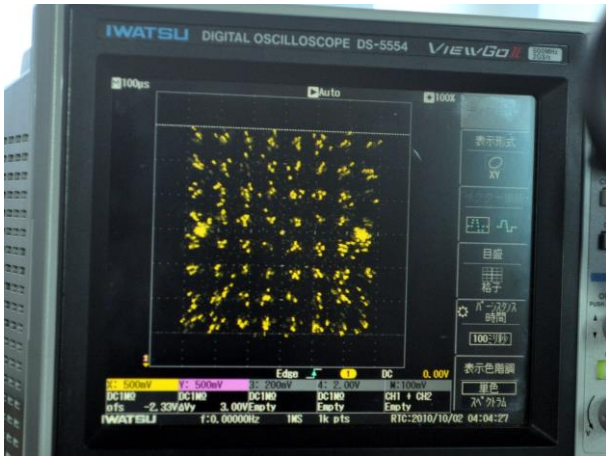


Fig. 9. 64QAM constellation at 1000m depth

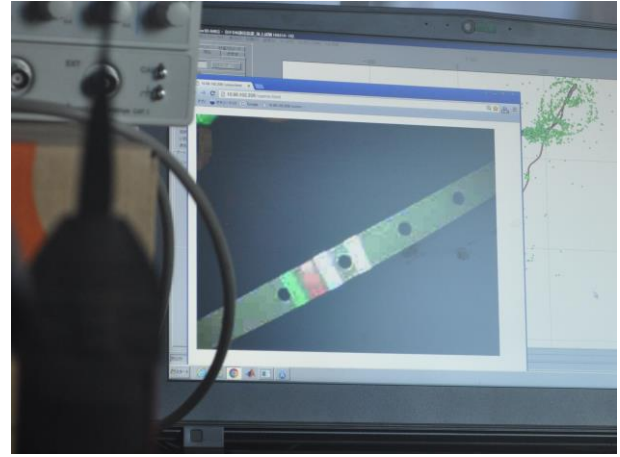


Fig. 10. Received image from 1000m deep camera

Finally, Fig. 11 shows a graph on Packet number vs BER (Bit Error Rates) in case of using 64QAM modulations. As packet number increases in the left half, the depth of TX increases and BER also increases. At the peak depth of 1000m, BER of approximately less than  $1E-2$  has been successfully obtained using 64QAM without any error correction. In addition, the TX moving speed is also indicated in the figure such as 0.54m/sec to 0.95m/sec. Robustness of two stages Doppler compensation in the proposed system with 64QAM modulation has been successfully confirmed.

#### IV. CONCLUSION

An underwater acoustic OFDM communication system with Robust Doppler Compensation is proposed. It can transmit image or movie data from deep see AUV etc. to surface ship. In order to mitigate Doppler shift effect caused by transmitter

and/or receiver movement, the OFDM receiver possesses additional time domain signal processing such as signal shrink-expansion processing and Doppler shift compensation capabilities. The outputs of the four OFDM receivers are further combined by frequency domain diversity combiner with Maximum-Ratio Combining (MRC) algorithm to improve Signal to Noise ratio.

The proposed communication system is verified by Ocean measurement at Shizuoka prefecture in Japan. The system utilized 20-28[KHz] ultrasonic OFDM channel and subcarrier spacing of 100[Hz]. Total number of sub-carriers is 81. QPSK / 16QAM / 64QAM modulations are used. By performing experiment in the ocean at depth of 1000m, BER of approximately less than  $1E-2$  has been successfully obtained using 64QAM without any error correction under the TX vertical movement speed of 0.54-0.95 m/sec.

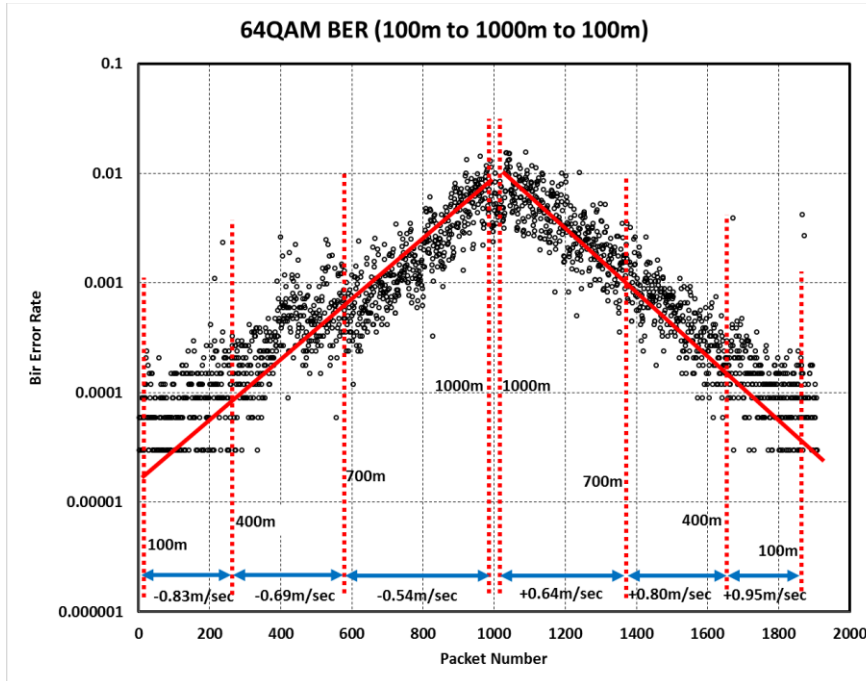


Fig. 11. 64QAM BER at 100m to 1000m and 1000m to 100m

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