A Prototype Wireless Underwater Robot Control system using a 32 kHz Bandwidth Underwater Small Area Acoustic Network (USAAN)

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Summary
This paper proposes an underwater small area acoustic network (USAAN) system with a 32kHz bandwidth OFDM signal and robust TDD synchronization. An ocean experiment was conducted at a barge in Uchiura Bay, Shizuoka Prefecture. Although the transducer on the BS side is moving, a stable signal delay time from DL to UL was measured, and the demodulated 16QAM constellation was confirmed normally on the UE side. Using this TDD-USAAN and the results of ocean experiments, we developed a prototype of a wireless underwater robot control system. The prototype was actually tested offshore off the coast of Yomitan Village, Okinawa Prefecture. In QPSK / 16QAM modulation, basic robot movement control such as upward, downward, right turn, left turn, etc. has been demonstrated by a bidirectional link. In addition, 240x213 pixel underwater photos can be uploaded in real time.

Key words:
Underwater, Acoustic Communication, Networking, OFDM, MAC, TDD

1. Introduction

Underwater wireless network is being demanded for underwater engineering and researches, to reduce a cable cost and a time to deploy. Not only long range wireless communication such as vertical deep sea to surface, horizontal submarine to coast station is demanded [1-4], but short range Underwater Small Area Acoustic Network (USAAN) is also wanted for some applications such as 1) marine civil engineering, 2) marine aquaculture monitoring, 3) person-to-person communication in ocean leisure, as shown in Fig. 1. Because of long propagation delays in underwater acoustic channel, Media Access Control (MAC) design is challenging. Although many radio access MAC protocols are based on handshake type between a sender and a receiver, it is not efficient in underwater. Our research team have been working on a Time Division Duplex (TDD) USAAN system with Orthogonal Frequency Division Multiplexing (OFDM) modulation, to make a bidirectional link for exchanging control data and image or movie data packets inside small underwater area [4][8]. The system realizes four times bandwidth of 32 kHz to 8 kHz our previous prototype design [4]. Fig. 1

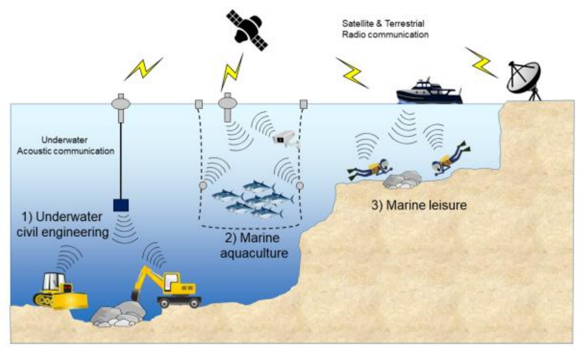

Fig. 1 Target applications of TDD-USAAN system.

In this paper, we first propose a USAAN system with TDD, non-handshake protocol, and OFDM modulation. Using this proposal and experimental results, we developed a prototype of a wireless underwater robot control system.

In this paper, we propose an Time Division Duplex (TDD), non-handshake protocol, Underwater Small Area Acoustic Network (USAAN) system with Orthogonal Frequency Division Multiplexing (OFDM) modulation. And we developed a prototype wireless underwater robot control system by making use of the TDD-USAAN and the ocean experimentation results.

2. Proposal of USAAN system with 32kHz bandwidth

This section describes the proposal and experimental results of USAAN system with 32kHz bandwidth.

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2.1 Overview of The System

Figure 2 shows an overview of our TDD-USAAN system. It makes the wireless service area with one base station and plural of user equipment (UE). The base station sends a downlink (DL) signal every 1.0 second. During a given empty slot, one of the user equipment (UE) can synchronize with DL signal and transmit uplink (UL) signal.

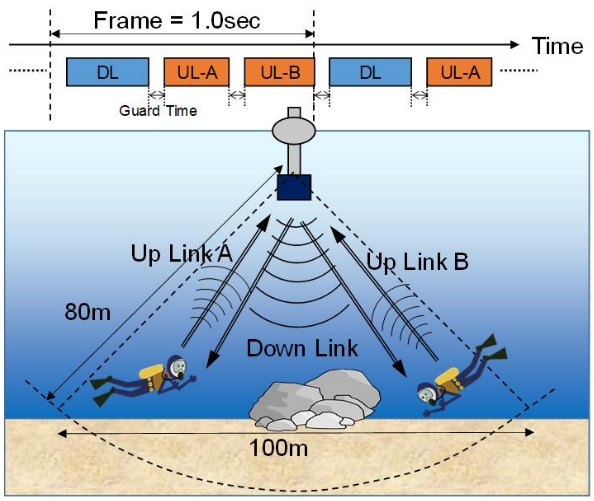


Fig. 2 Overview of TDD-USAAN system.

This figure shows the case of two users. A guard time is assigned between all DL / UL signals to prevent interference.

2.2 System Block Diagram

The TABLE I shows the detail system features. This system has 1 TX transducer and 1 RX transducer. The size of FFT is 2048 points. The OFDM symbol length is 20.0 ms and number of subcarriers are 641. Then bandwidth of the signal is 32 kHz, and the range of transmit frequency is 16kHz – 48kHz. Guard Interval (GI) length is 5.0 ms with assuming major multi-path delay of less than 7.5 meter. The DL/UL total actual data transfer rate is 62.4 kbps in the case of using 16QAM modulation. Figure 3 shows a block diagram of the system. The top is the transmitter and the bottom is the receiver. In the TX side, the bit information is modulated using QPSK / 16QAM / 64QAM digital modulation and BPSK modulated pilot symbols are inserted to measure the time varying channel conditions. GI is added to the beginning of each OFDM symbol. To achieve robust and fine time synchronization, the chirp signal is added before all DL / UL signals. The baseband signal is upconverted to the center frequency of 32kHz. Finally, the OFDM passband signal amplified by the power amplifier is emitted from the TX transducer to the underwater acoustic channel. On the RX side, the signal

Table 1: System Parameters

Parameters	Value
TX-RX Elements	1 TX and 1 RX Transducer
Sampling Frequency	102400 Hz
TX Frequency	16k – 32k Hz
Band Width	32k Hz
FFT Size	2048
OFDM symbol length T	20.0 ms (2048 points)
GI length Tg	5.0ms (512 points)
Effective Symbol length Tu=T+Tg	25.0ms
Chirp Signal Length for Frame Sync	20.0ms
Guard Time between DL/UL packet	55.0ms
Sub Carrier Spacing	50.0 Hz
Number of Sub Carrier	641
Number of Pilot in OFDM symbol	Zadoff –Chu, N_{ZC}= 352 and 41
Data Rate	62.4kbps (16QAM)

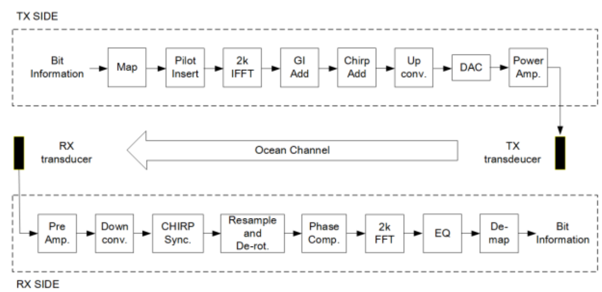


Fig. 3 Block diagram of USAAN system.

amplified by the preamplifier is downconverted to the baseband signal. Time synchronization is performed and time domain Doppler correction is performed. This consists of sample reverse rotation and phase correction[4], which consists of Resample, Derotation, Phase compensation, is performed.

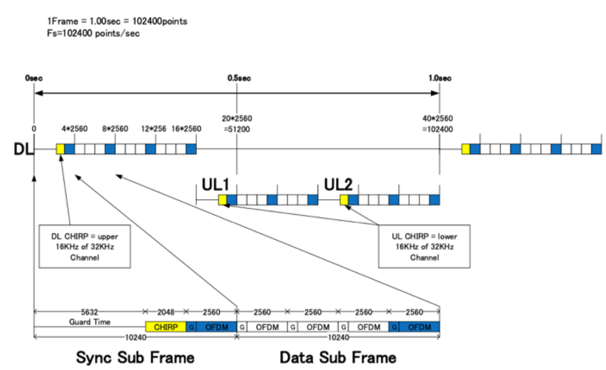


Fig. 4 Frame Design of USAAN system.

Figure 4 shows the frame design of the USAAN system. Since this system is designed assuming two UEs, the TDD frame consists of one DL signal and two UL signals (UL1 and UL2). UL1 and UL2 are composed of a DL signal composed of a synchronous subframe and three data subframes, and a synchronous subframe and two data subframes, respectively. A synchronous subframe is composed of three parts: guard time, chirp signal, and OFDM symbol, and the timing between base station terminals is synchronized by the chirp signal. Since each data subframe is composed of 4 OFDM symbols, there are 13 OFDM symbols in the DL signal and 9 OFDM symbols in the UL1 / UL2 signal.

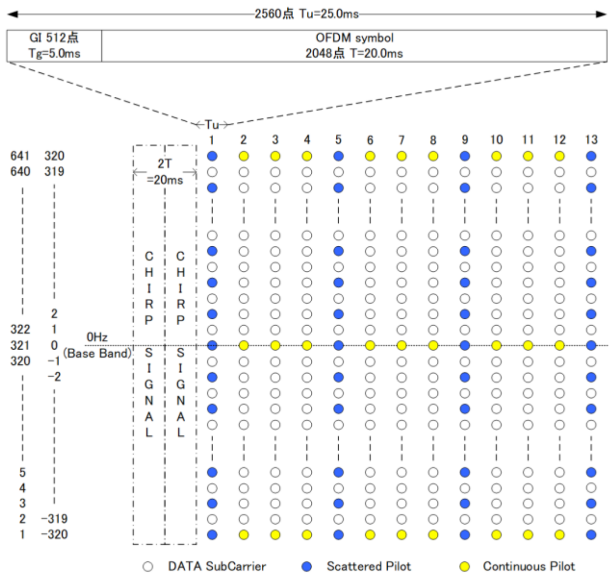


Fig. 5 Time-Frequency Diagram of USAAN system.

Figure 5 shows the time-frequency diagram of the USAAN system. In this figure, the blue symbols correspond to the scattered pilot (SP) symbols and the yellow symbols correspond to the continuous pilot (CP). The SP assigned to each even subcarrier is used to measure the channel transfer function (CTF). The CTF value of the blue subcarrier is interpolated in two dimensions to obtain the entire CTF value on the time-frequency diagram. The 13 CP placed on only even number of sub-carriers of both edges. The chirp signal is a linear frequency sweeping signal. The DL chirp signal sweep range is 0 Hz to 16 kHz using the upper 16 kHz of the 32 kHz channel, and similarly, the UL chirp signal range is 16 kHz to 0 Hz using the lower 16 kHz. To realize easy synchronization, there are twice 2048 points sweeps. At the RX side, the DL signal starting point can be detected by chirp signal.

2.3 System Implementation

Figure 6 shows a block diagram of the implemented target system. BS consists of UE components. The signal processing board with Xilinx Zynq-7000 (ARM core + FPGA) is used for digital signal processing, and OST 7010 power amplifier drives TX transducer through transmit transformer.

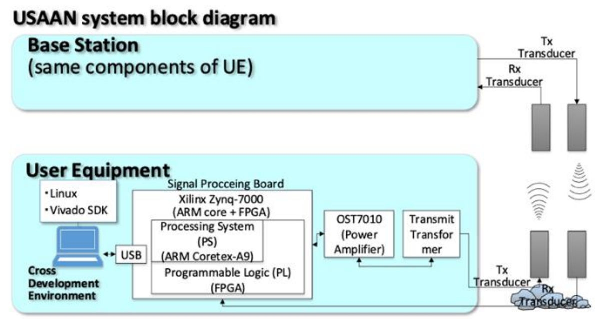


Fig. 6 USAAN implemented target system block diagram.

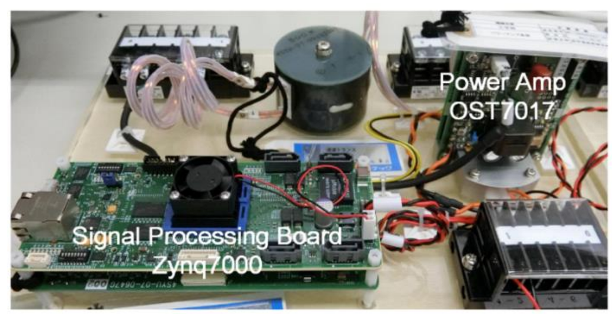


Fig. 7 Developed small hardware system.

Fig. 7 shows the developed small hardware system of BS and UE. The DL/UL total data bandwidth is 62.4 kbps in the case of using 16QAM modulation. This system has the capability to enable communication at a distance of about 1000 m or more in the vertical direction from bottom to surface of sea.

2.4 Simulation results

In order to show an accuracy improvement of signal propagation with time-domain Doppler compensation which consists of Resample, De-rotation and Phase compensation, a computer simulation results are shown. Figure 8 shows a simulation of a DL signal with varying transducer speed. In this simulation, four frames output at

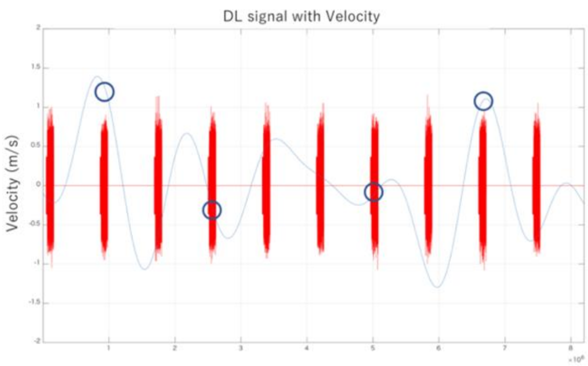


Fig. 8 DL signal with velocity of moving.

high speed or very low speed were sampled. The sample points in each frame are marked with blue circles.

Figure 9 shows the constellation of the selected frame output without time domain Doppler compensation. In the 7th frame, which was output very slowly, the constellation is relatively clear. On the other hand, in the frames that are output at high speed, such as 2 and 9 frames, chaotic output was displayed. Figure 10 shows the constellation of the selected frame output by all the functions of Doppler compensation. Each frame gives a fine output, no matter what the speed. Signal propagation is greatly improved by Doppler correction in the time domain.

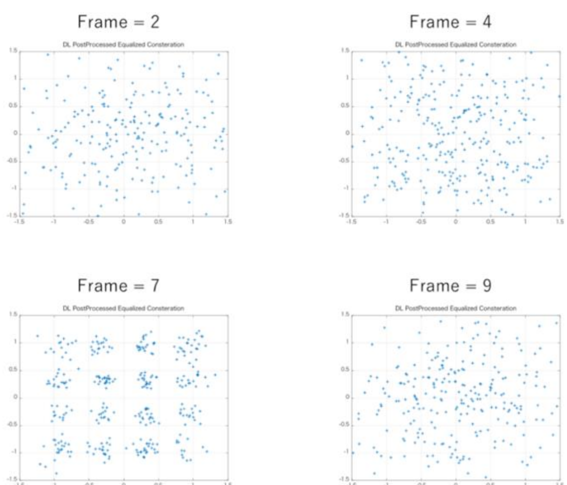


Fig. 9 Simulation results of Resample, De-rotate, Phase compensation are OFF.

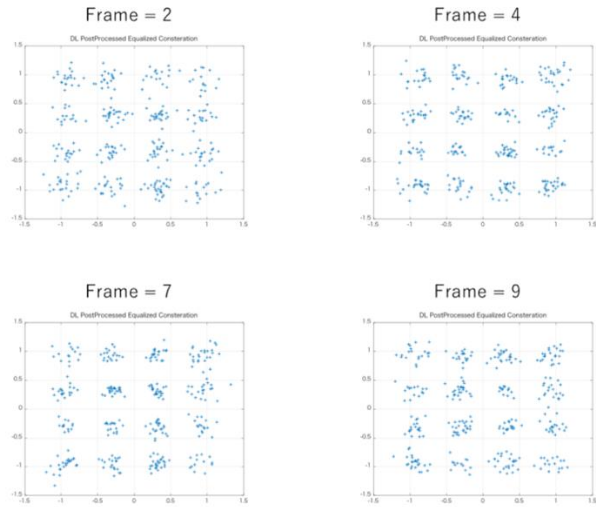


Fig. 10 Simulation results of Resample, De-rotate, Phase compensation are ON.

2.5 Ocean Experiment results

To verify a robustness of the Chirp synchronization of the system, ocean experiment is performed at the barge in Uchiura bay, Shizuoka prefecture, Japan with the configuration shown in Fig. 12.

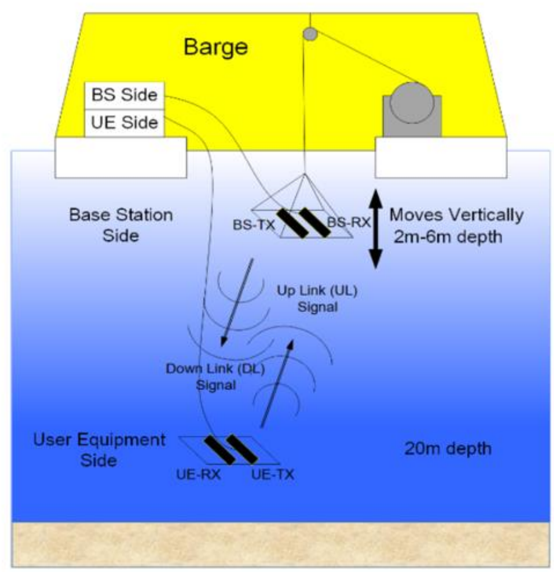


Fig. 11 Ocean Experiment to check Robust TDD synchronization.

The BS side transducer moves vertically up and down using a motor drive at a depth of 2 to 6 m from the sea surface.

Fig. 12 Ocean Experiment scene at the barge.

Maximum moving speed is 1.1ms. The transducer on the UE side is fixed at a depth of 20 m from surface of sea.Fig. 12 shows the scene of ocean experiment at the barge. Transducer spacing is 30 cm and Figure 13 shows the time domain DL and UL signals measured by triggering the DL signal. Although BS-TX is moving, stable signal delay time from DL to UL has been measured, and fine synchronization performance has been confirmed. As shown in Fig. 14, the 16QAM constellation demodulated on the UE-RX side was confirmed normally.

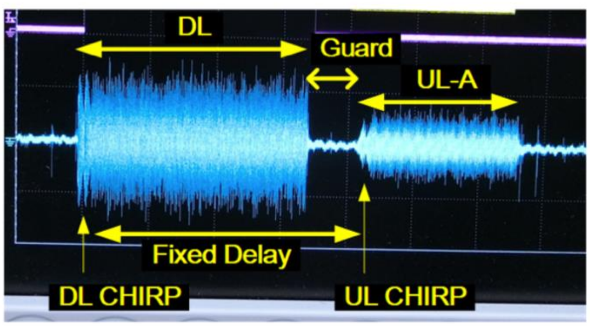


Fig. 13 Measured TDD waveform.

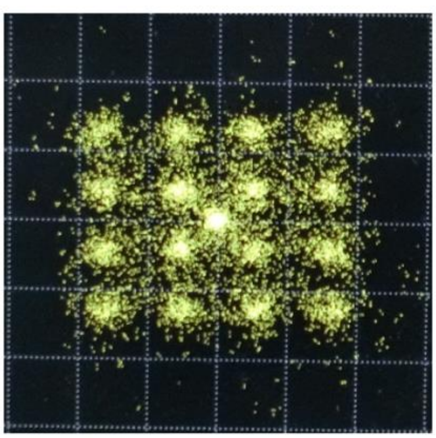


Fig. 14 Demodulated 16QAM constellation at UE-RX side

3. Prototype wireless underwater robot control system

In this chapter, a prototype of a wireless underwater robot control system is explained using the results of the proposal and the ocean experiment in Chapter 2.

3.1 Simulation Experiment

Figure 14 shows the system block diagram on the BS side. The host PC is connected to the controller. Type-Length-Value (TLV) data packets are used for communication between the controller and robot.

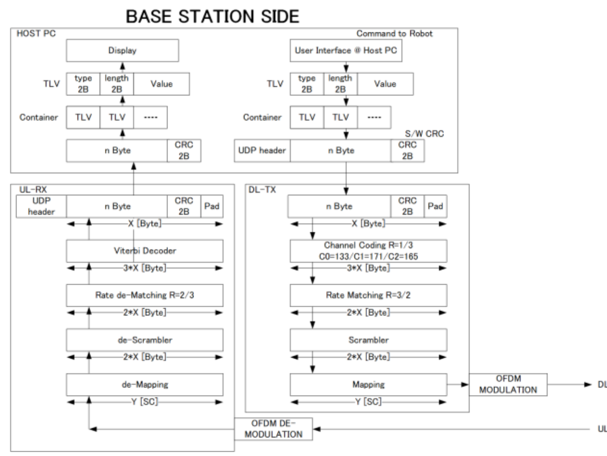


Fig. 15 Block diagram of Base Station side system.

Host PC interfaces with a controller. Type-length-value (TLV) data packet is used to communicate between the controller and the robot. For the DL transmission, Cyclic Redundancy Check (CRC) appended packet is transferred from the host PC to the communication system by UDP protocol. Then convolutional coding [7] is used to correct the packet data error. The encoded data is digitally modulated by QPSK / 16QAM and OFDM modulation is applied. For the UL reception, the reverse process using Viterbi forward error correction is executed to recover the TLV packet. Then the packet is then sent by UDP to the host PC and the CRC is checked to detect packet errors.

Figure 16 is a block diagram of the robot system. The same signal processing as on the BS side is used for both DL reception and UL transmission, and a small Raspberry Pi single board computer is used for underwater robot control. Details of OFDM modulation and demodulation and time-frequency diagrams are the same as in Figs. 3 and 5 described in Section 2.2 of Chapter 2. The details of the system functions are shown in Table 1 in Chapter 2,

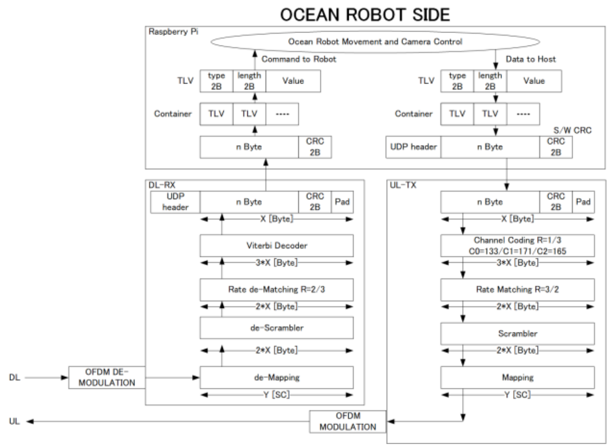


Fig. 16 Block diagram of Robot side system

Section 2.2, only the TX frequency is changed to a fixed value of 32 kHz. Figure 17 shows a photograph of the modem H / W system. The Zynq7000 ARM embedded FPGA is used for digital signal processing, and the OST7010 power amplifier drives the TX transducer via a transformer.

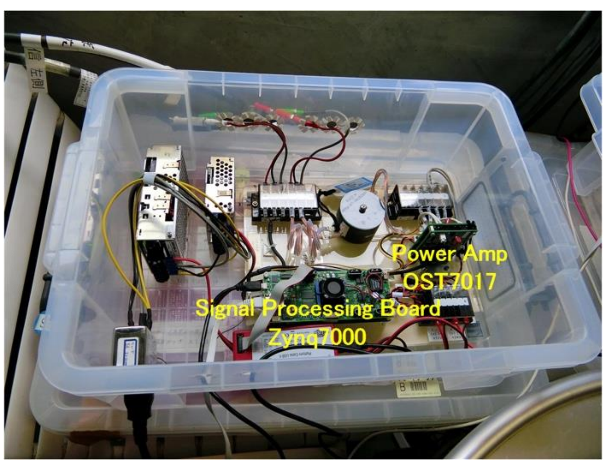


Fig. 17 Zynq7000 ARM-embedded FPGA is used for digital signal processing and OST7010 Power Amplifier drives TX transducer through transformer.

3.2 Underwater Robot

The underwater robot has two pairs of motor thrusters for vertical and horizontal movement. At the front of the robot, a camera is mounted to take underwater photo images. Raspberry Pi small single board computer is used as the controller of the robot for those motor thrusters and the camera. In addition, a 9 axes gyro system to measure the Robot tilts is embedded. Because of the size limitation of the prototype robot body, the modem H / W system and battery could not be housed in the robot and those are placed at outside and connected through wires.

Figure 8 illustrates the underwater robot system and the connection to the modem H / W and power supply.

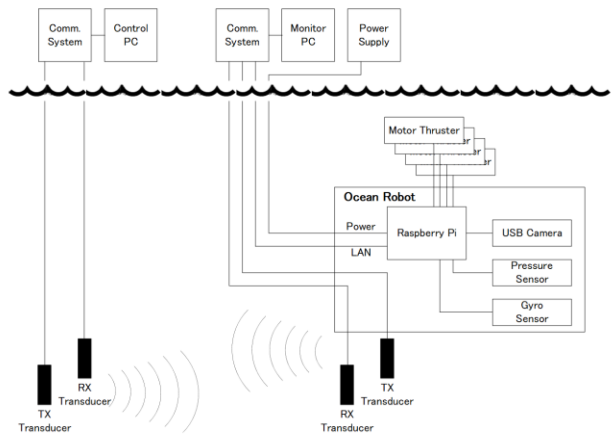


Fig. 18 Block diagram of the prototype ocean robot system.

Figure 19 is a photograph of an underwater robot with and without a pressure cover. In order to perform an underwater robot control experiment, the modem H / W system and battery cannot be housed in the robot due to the size limitation of the prototype robot body, and it is placed on the ship as shown in Fig. 17.

(a) (b)

Fig. 19 Underwater Robot with cover (a) and without cover (b).

3.3 Ocean Experiment results

Ocean experiment has been performed at 500 m offshore from Yomitan coast, Okinawa prefecture Japan. Table 2 shows the details of the ocean experiment parameters.

Table 2: System Parameters

Parameters	**Value**
Experiment site	500 m offshore from Yomitan coast in Okinawa, Japan
Ocean Depth	5 – 10 m
Depth of Transducers	1 – 3 m below BS, 1.5 - 3 m below UE
Modulation	QPSK/16QAM
BS to Robot Distance	1 - 10 m

Transmission Direction	Horizontal
MS moving speed	Max 1.0 m/sec

BS is set up on ocean surface by a float and Transmission TX and Receiver RX transducers are set below the float by 1 to 3 m depth. TX and RX transducers for the robot were set 1.5 – 3 m below it in order to avoid ocean surface noise and water flow by the motor thrusters as shown in fig. 20.

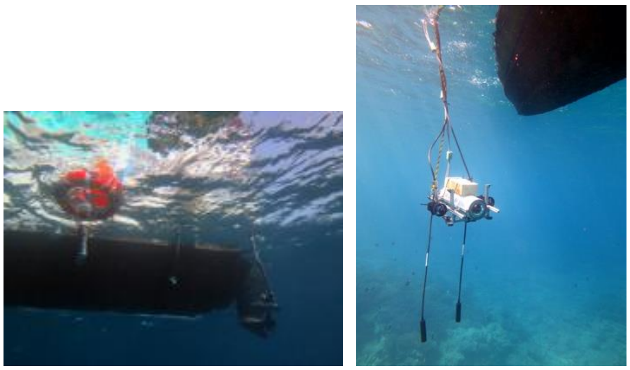
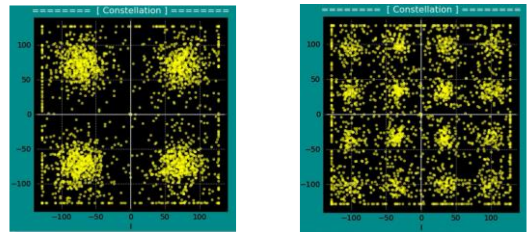
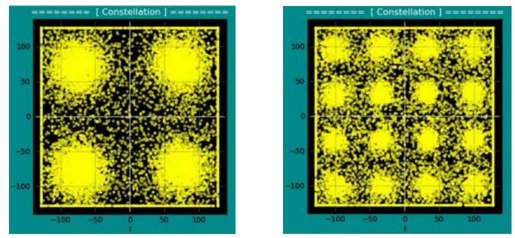


Fig. 20 Photos of the underwater robot with TX/RX transducers.

The robot's TX and RX transducers were set 1.5 to 3 m below the robot to avoid sea surface noise and water flow due to motor thrusters. Using QPSK / 16QAM modulation, basic motion control of robot such as upward, downward, clockwise, counterclockwise was confirmed. In addition, 240x213 pixel underwater photographs can be taken and uploaded from the robot to the BS. Figures 21 (a) and (b) correspond to DL and UL QPSK / 16QAM constellations of 1 frame, respectively. Although these outputs are not so clear, many error-free packets are received due to the forward error correction in the system. The horizontal distance between the BS and the robot is about 5 to 10 m, and the depth of the robot is about 0 to 5 m. Horizontal acoustic communication is mainly evaluated due to the limited directivity of the TX / RX transducers. The measured delay profile is also evaluated using the scattered pilot of the OFDM signal. The channel transfer function (CTF) can be obtained by inserting a scat pilot in the frequency domain. The delay profile in the time domain can be obtained by executing IFFT with CTF. Figure 21 shows a 240x213 pixel photo taken by an underwater robot and uploaded via USAAN. These pictures could be observed normally on the control PC on the BS side.



(a) DL QPSK/16QAM Constellations



(b) UL QPSK/16QAM Constellations

Fig. 21 DL and UL measured constellation.

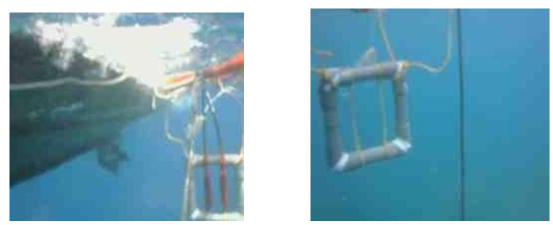


Fig. 22 Photos taken and uploaded by Robot.

4. Conclusion

We first proposed a USAAN system with a 32kHz bandwidth OFDM signal and robust TDD synchronization. 16QAM constellation demodulated by BS-TX in a barge in Uchiura Bay, Shizuoka Prefecture, where BS-TX is moving, stable signal delay time from DL to UL was measured, fine synchronization performance was confirmed Was confirmed normally. Next, a tatami coder, Viterbi decoder, and Cyclic Redundancy Codec were added to this proposed system, and a prototype wireless underwater robot control system was developed [5-6]. The prototype underwater robot can be controlled by a two-way link and can upload photographic image data packets in a small underwater area. The underwater robot is controlled by a small single board computer of Raspberry Pi. BS can send control command to robot by TLV data packet via USAAN. Ocean experiment was conducted 500 m off the coast of Yomitan Coast, Okinawa Prefecture, and demonstrated using basic robot movement control with QPSK / 16QAM modulation and real-time upload of 240x213 pixel underwater photographs.

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