

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

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Abstract— This paper describes a prototype wireless underwater robot control system using a Time Division Duplex (TDD) Underwater Small Area Acoustic Network (USAAN) system with Orthogonal Frequency Division Multiplexing (OFDM) modulation. The prototype underwater robot can be controlled by the bidirectional link and can upload photo image data packets inside small underwater area. The TDD communication system consists of OFDM modem, Convolutional coder, Viterbi decoder and Cyclic Redundancy Codec. The underwater robot is controlled by Raspberry Pi small single board computer. The Base Station (BS) can send control commands to the robot by Type-length-value (TLV) data packets through the USAAN. Ocean field experiment has been performed at 500 m offshore from Yomitan coast, Okinawa prefecture Japan. Using a QPSK/16QAM modulation, basic robot movement control such as upward, downward, forward, backward, right-turn, and left-turn has been demonstrated. In addition, 240x213 pixels underwater photo could be captured and uploaded from the robot to BS.

Keywords—Underwater, Acoustic Communication, Networking, OFDM, MAC, TDD

I. 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 machine control and monitoring in ocean civil engineering, marine aquaculture monitoring, and human to human communication in marine leisure. 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 [5-6]. Fig.1 shows an overview of the TDD-USAAN. It makes the wireless service area with one base station and plural of users. The base station transmit a Down Link (DL) signal in every frame of 1.0 sec. During the pre-determined empty slot, one of the UE can send a Up Link (UL) signal with synchronizing to the DL signal. The figure shows the two users case. Between all DL/UL signals, guard time is allocated to prevent interferences.

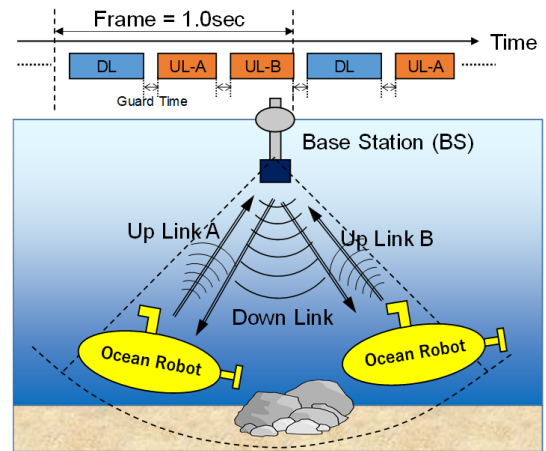


Fig. 1: Overview of TDD-USAAN system with Ocean Robot.

This paper describes a prototype wireless underwater robot control system by making use of the TDD-USAAN and the ocean experimentation results. The section II describes the detail of the network system architecture including BS side and Robot side packet data processing, error correction and detection, OFDM signal design and so on. Then, the robot design is disclosed in section III. Ocean field experiment results are shown in section IV. Finally, the summary is concluded in section V.

II. NETWORK SYSTEM

Fig. 2 shows the block diagram of the BS 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] are used to correct packet data error. The coded data are digitally modulated by QPSK/16QAM and OFDM modulation is applied. For the UL reception, the reverse process with Viterbi forward error correction is performed to recover the TLV packet. Then the packet is sent to the host PC by UDP and

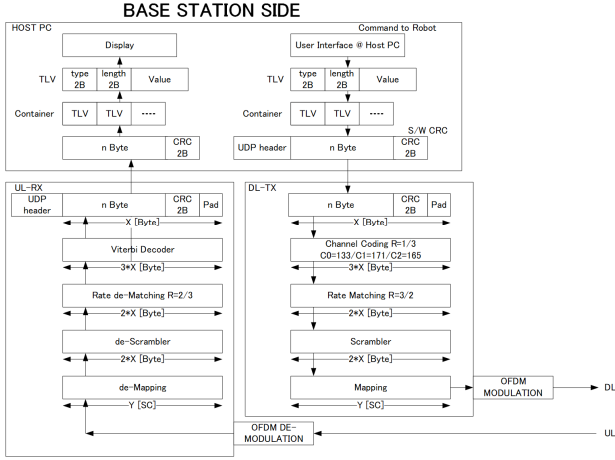


Fig. 2: Block diagram of Base Station side system.

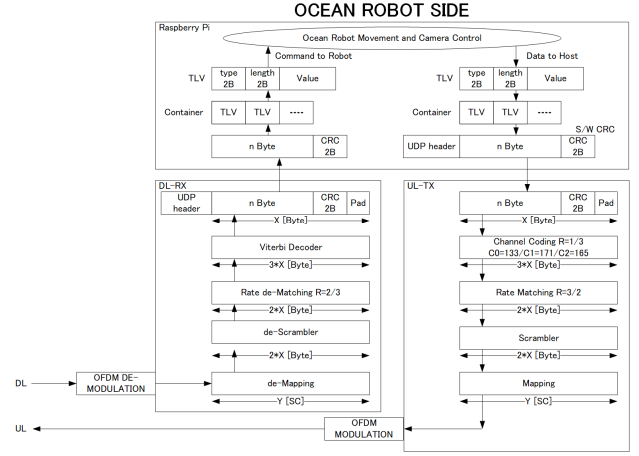


Fig. 3: Block diagram of Robot side system.

CRC will be checked to detect packet error. Fig. 3 is the block diagram of the Robot side system. For both DL reception and UL transmission, same signal processing as the BS side is used, while the Raspberry Pi small single board computer is used for underwater robot control.

The detail of the OFDM modulation and de-modulation is shown in fig. 4. The upper side corresponds to OFDM

modulation and the lower side is de-modulation. After the QPSK/16QAM digital modulation mapping process, 641 complex constellation signals including Scattered or Continuous Pilot signals are converted to time-domain signal by 2048 point IFFT. Then, 512 points cyclic prefix is attached to the head of the signal as Guard Interval (GI) addition. The time-domain OFDM symbol and the detail of sub-carrier placement are shown in fig. 5. Every 4 OFDM symbols, Scattered Pilots are inserted to estimate Channel Transfer Function. At the front of the OFDM time-domain signal packet, 20 ms Chirp signal is prepended for the time-domain synchronization. Finally, the time-domain signal packet is up-converted by +32 kHz to generate real passband signal of 16 – 48 kHz band. In the de-modulation side, basically the reverse operations of modulation are performed. But, the time-domain Doppler compensation [4], which is composed of three functions such as 1) signal shrink-expansion factor detection, 2) resample for signal shrink-expansion and de-rotation for radio frequency shift compensation, and 3) fine phase shift compensation, is applied. The TABLE I shows the detail system features. The OFDM symbol length is 20.0 ms and number of subcarriers are 641. Guard Interval (GI) length is 5.0 ms with assuming there are no long multi-path delayed signals. The Scattered and Continuous Pilot signals are Zadoff–Chu Sequences [8].

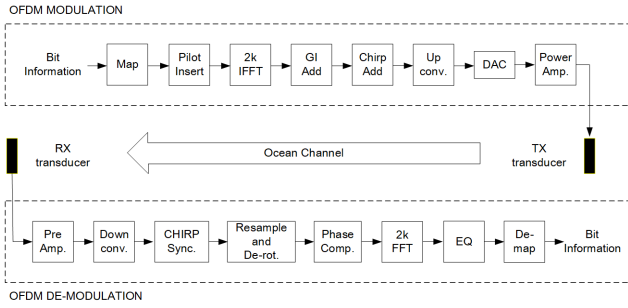


Fig. 4: Block diagram of OFDM modem. Upper side is modulator while lower side is de-modulator.

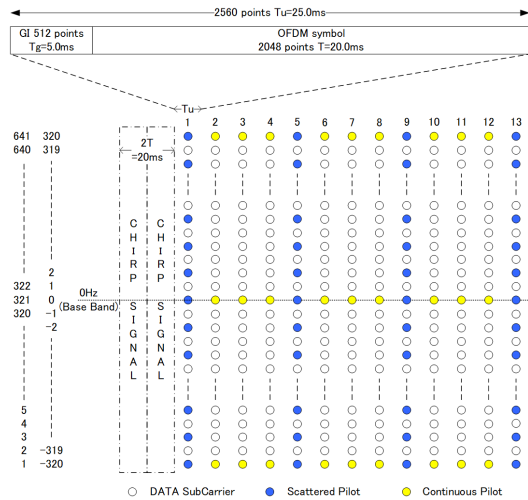


Fig. 5: Time-domain OFDM symbol and the sub-carrier placements including Data, Scattered and Continuous Pilots.

TABLE I: OFDM SYSTEM PARAMETERS

Parameters	Value
TX-RX Elements	1 TX and 1 RX Transducer
Sampling Frequency	102400 Hz
TX Center Frequency	32k Hz
Band Width	32k Hz
FFT Size	2048
OFDM symbol length T	20.0 ms (2048 points)
GI length T _g	5.0ms (512 points)
Effective Symbol length T _u =T+T _g	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} = 321 and 41
Data Rate	62.4kbps (16QAM)

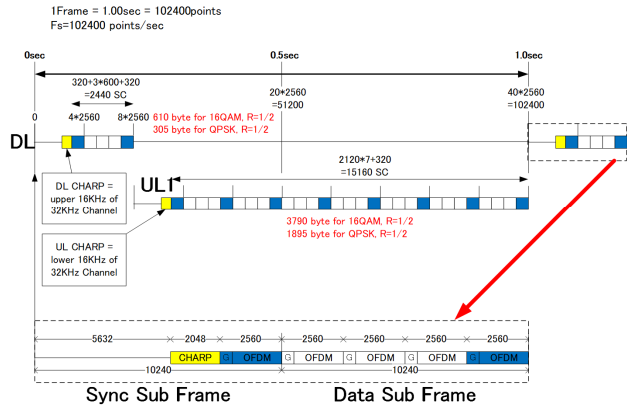


Fig. 6: TDD 1.0 s frame structure with 5 OFDM symbols DL and 29 OFDM symbols UL.

Fig. 6 shows TDD frame structure for the robot control system. DL frame length is 5 OFDM symbols while UL frame length is 29 OFDM symbols to upload large photo image data. The blue box corresponds to the OFDM symbol with Scattered Pilots. The one UL frame can transfer 3790 byte for 16QAM modulation with code rate $R=1/2$, 1895 byte for QPSK with $R=1/2$. The photo of the modem H/W system is shown in fig. 7. Zynq7000 ARM-embedded FPGA is used for digital signal processing and OST7010 Power Amplifier drives TX transducer through a transformer.

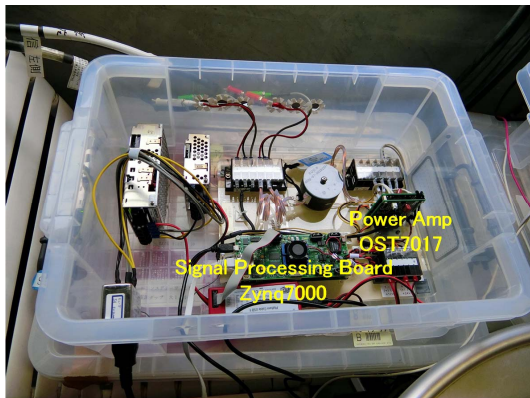


Fig. 7: Zynq7000 ARM-embedded FPGA is used for digital signal processing and OST7010 Power Amplifier drives TX transducer through transformer.

III. UNDERWATER ROBOT

The underwater robot has two pairs of motor thrusters for vertical and horizontal directional movements. 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.

Fig. 8 explains the underwater robot system and the connection with the modem H/W and Power Supply. Fig. 9 shows the photos of underwater robot with and without a

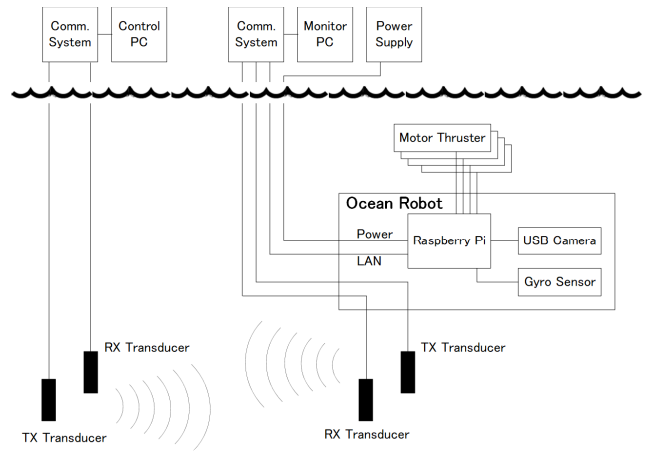
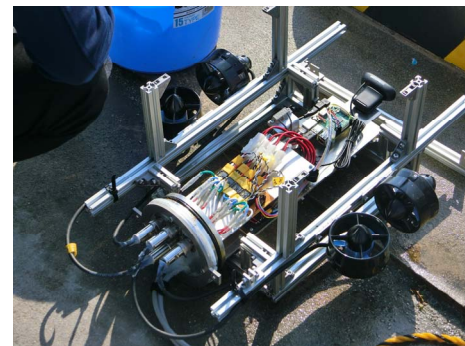


Fig. 8: Block diagram of the prototype ocean robot system.



(a)



(b)

Fig. 9: Underwater Robot with cover (a) and without cover (b).



Fig. 10: Ocean experiment staffs and equipment's on the boat.

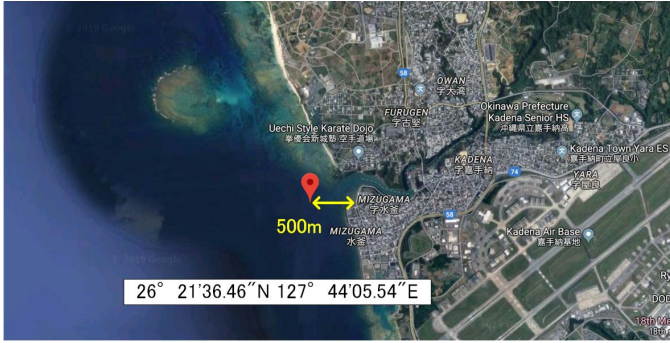


Fig. 11: Map of ocean experiment site, 500 m offshore from Yomitan coast

pressure cover. In order to perform underwater robot control experiment, the communication system and power supply for the robot have to be placed in the boat as shown in fig. 10.

IV. OCEAN EXPERIMENT

Ocean experiment has been performed at 500 m offshore from Yomitan coast, Okinawa prefecture Japan as shown in fig. 11. The point is one of the famous fun diving sites in Okinawa. The detail of ocean experiment parameters are shown in Table II. 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 as shown in fig. 12. 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. 13.

Using a QPSK/16QAM modulation, basic robot movement controls such as upward, downward, forward, backward, right-turn, and left-turn have been confirmed. In addition, 240x213 pixels underwater photo could be taken and uploaded from the robot to the BS.

TABLE II: OCEAN EXPERIMENT 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

Fig. 14 is measured constellations in the case of BS transducers' depth of 3 m and moving robot's transducer depth of 1.5 m below it. Fig. 14 (a) and (b) correspond to DL and UL QPSK/16QAM constellations in 1 frame, respectively. Although those constellations are not so clear, many error free packets has been received by the forward error correction in the system. The horizontal distance between BS and the robot is roughly 5 – 10 m and the depth of the robot is roughly 0 – 5 m. Because of the TX/RX transducers' directivity limitation, horizontal acoustic communication is mainly evaluated.

Measured Delay Profiles are also evaluated using the Scattered Pilots of OFDM signals. By interpolating the Scatted Pilots in frequency-domain, Channel Transfer Function (CTF)

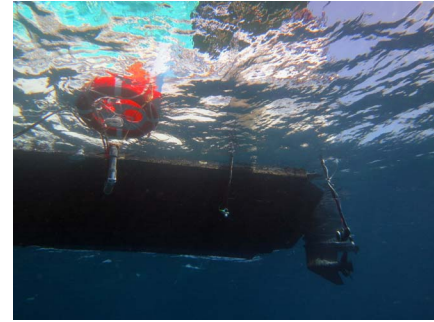


Fig. 12: Photos of the Base Station and TX/RX transducers 1 m below it.

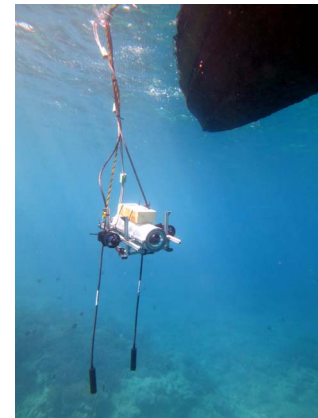
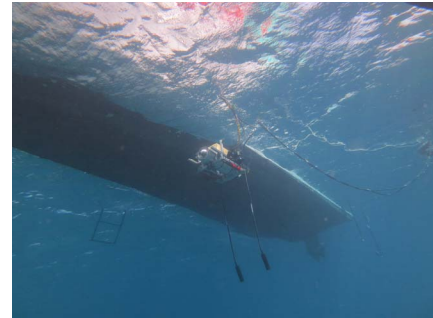


Fig. 13: Photos of the underwater robot with TX/RX transducers 1.5 m below it.

can be obtained. By performing IFFT on CTF, time-domain Delay Profile can be obtained. Fig. 15 (a) and (b) plot the Delay profiles of DL and UL, respectively. For both DL and UL, no significant multi-path delayed signal was observed. Fig. 16

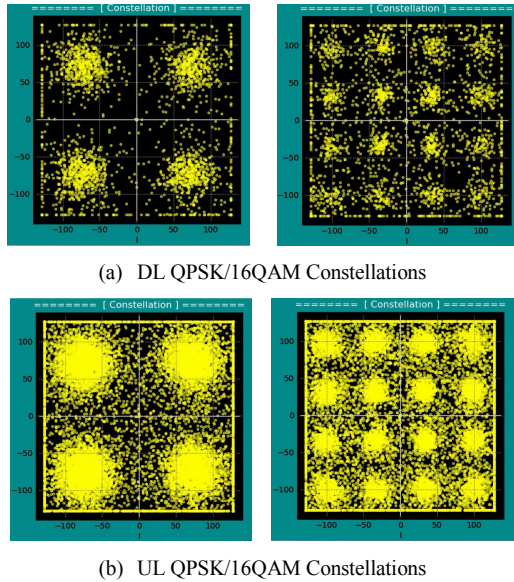


Fig. 14: DL and UL measured constellations

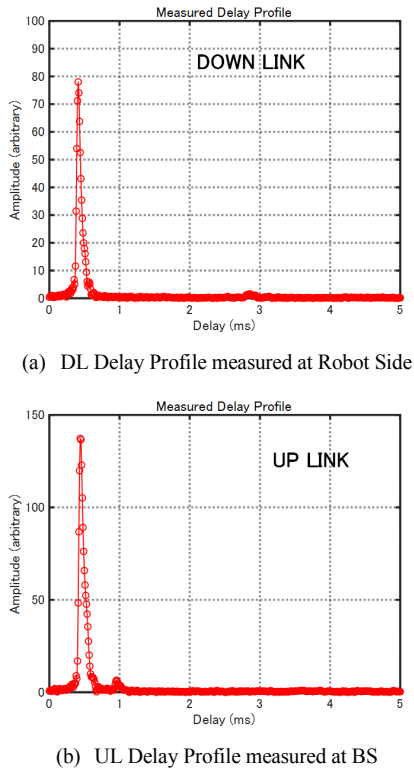


Fig. 15: Measured Delay Profiles

shows 240x213 pixels photos taken by underwater robot and uploaded through the USAAN. Those photos could be successfully observed by the BS side control PC.

V. CONCLUSION

A prototype wireless underwater robot control system was developed with adding Convolutional coder, Viterbi decoder and Cyclic Redundancy Codec onto the previously developed Time Division Duplex (TDD) Underwater Small Area Acoustic

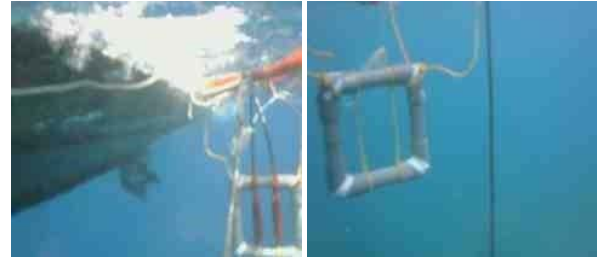


Fig. 16: Photos taken and uploaded by Robot

Network (USAAN) system with Orthogonal Frequency Division Multiplexing (OFDM) modulation [5-6]. The prototype underwater robot can be controlled by the bidirectional link and can upload photo image data packets inside small underwater area. The underwater robot is controlled by Raspberry Pi small single board computer. BS can send control commands to the robot by TLV data packets through the USAAN. Ocean field experiment has been performed at 500 m offshore from Yomitan coast, Okinawa prefecture Japan. Using a QPSK/16QAM modulation, basic robot movement control and 240x213 pixels underwater photo real-time uploading has been demonstrated.

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REFERENCES

- [1] J. Heidemann, M. Stojanovic, and M. Zorzi, "Underwater sensor networks: Application, advances and challenges," *Philosophical Transactions of the Royal Society A*, vol. 370, pp. 158-175, Aug 2012.
- [2] T. Melodia, H. Kulhandjian, L. C. Kuo, and E. Demiros, "Advances in underwater acoustic networking," in *Mobile Ad Hoc Networking: Cutting Edge Directions*, S. Basagani, M. Conti, S. Giordano, and I. Stojmenovic, Eds. Hoboken, NJ: John Wiley & Sons, Inc., Mar. 2013, ch. 23, pp.804-852.
- [3] Yashar M. Aval, Yu Han, Andrew Tu, Stefano Basagni, Milica Stojanovic and Yunsi Fei, "Testbed-based Performance Evaluation of Handshake-free MAC Protocol 102 IJCSNS International Journal of Computer Science and Network Security, VOL.17 No.10, October 2017 for Underwater Acoustic Sensor Networks," *MTS/IEEE OCEANS 2016, Monterey, CA, USA, September 19-23rd 2016*.
- [4] Yusuke Onna, Taisaku Suzuki, Hiromasa Yamada, Shigeo Nakagawa and Tomohisa Wada, "A 32 kHz Bandwidth, 8-branch Diversity Underwater Acoustic OFDM Communication System," *MTS/IEEE OCEANS 2018, Kobe Japan, May 28-31, 2018*.
- [5] Taisaku Suzuki, Atsushi Kinjo, Suguru Kuniyoshi, Rie Saotome, Tomohisa Wada, "A Prototype Design and Experiment of Time Division Duplex (TDD) Underwater Small Area Acoustic Network (USAAN) system," *IJCSNS International Journal of Computer Science and Network Security, VOL.17, No.10, October 2017*.
- [6] Atsushi Kinjo, Yusuke Onna, Suguru Kuniyoshi, Rie Saotome, Taisaku Suzuki, and Tomohisa Wada, "A 32kHz Bandwidth, Robust TDD Synchronization, Underwater Small Area Acoustic Network (USAAN) System," *MTS/IEEE OCEANS 2018, Charleston USA, October 22-25nd 2018*.
- [7] Todd K. Moon, *ERROR CORRECTION CODING Mathematics Methods and Algorithms*, WILEY, 2005, pp.452-486.

Sassan Ahmadi, *LTE-Advanced A Practical Systems Approach to Understanding 3GPP LTE Releases 10 and 11 Radio Access Technologies*, ACADEMIC PRESS, 2014, pp.724-734.