A 32 kHz Bandwidth, 8 branch Diversity Underwater Acoustic OFDM Communication System

Yusuke Onna[1)], Taisaku Suzuki[1,2)], Hiromasa Yamada[3)], Shigeo Nakagawa[3)] and Tomohisa Wada[4)]

1) Graduate School of Engineering and Science University of the Ryukyus, Senbaru 1, Nishihara, Okinawa, Japan

2) National Institute of Technology, Okinawa College 905 Henoko, Nago-shi, Okinawa, Japan

3) Oki Seatec Co., Ltd. Uchiuramito 537-5, Numazu-shi, Shizuoka, Japan

4) Dept. of Information Engineering, University of the Ryukyus, Senbaru 1, Nishihara, Okinawa, Japan

Abstract— **This paper describes a 32kHz bandwidth underwater acoustic Orthogonal Frequency Division Multiple Access (OFDM) communication system to transmit higher definition image or movie data packet from deep see AUV etc. to water surface ship. The transmission data rate is 150 kbps without error correction using 64QAM modulation and 641 sub-carriers. To increase the transmitting wave bandwidth to 32 kHz from 8kHz of the previous generation device, a new transmitting transducer was developed while 8 branches integrated receiver transducer was also developed. To realize a stable data communication with moving environment, two stage Doppler compensation is also applied. The system is verified by Ocean experiment at Uchiura Bay with 100m depth of transmitter in Shizuoka, Japan. By enabling the Doppler compensation signal processing, a stable data communication was confirmed. The approximately 4.7dB of diversity gain using the 8 branches diversity was measured.**

Keywords—Underwater Acoustic Communication, OFDM, Diversity, Doppler compensation

I. INTRODUCTION

Because of a progress in marine development for seabed natural resources such as hydrothermal deposits, methane hydrates, deep sea exploring more than 1000m depth becomes essential. Especially, AUV (autonomous underwater vehicle) without any wires is demanded since its searching area is not restricted by wire length. Then, wireless underwater communication has been become important to acquire AUV collected data at mother ship without docking. Fig.1 shows a target application of the communication system. By enabling high bandwidth wireless communication between AUV and water surface mother ship, AUV can continue a deep seabed exploring without rendezvousing with the mother ship.

In this paper, we propose an underwater acoustic OFDM communication system which is utilized in many radio wireless communication system such as LTE [1], WiFi and digital TV. The difference between underwater and radio is much severe Doppler effect for underwater acoustic because the propagation speed in underwater of roughly 1500m/s is very smaller than the speed of radio wave. Then additional time domain signal processing such as signal shrink-expansion processing and phase shift compensation are introduced. In addition, the system includes 8 branches receivers and Maximum Ratio Combining (MRC) diversity to improve Carrier to Noise power Ratio (CNR) in order to extend communication range.

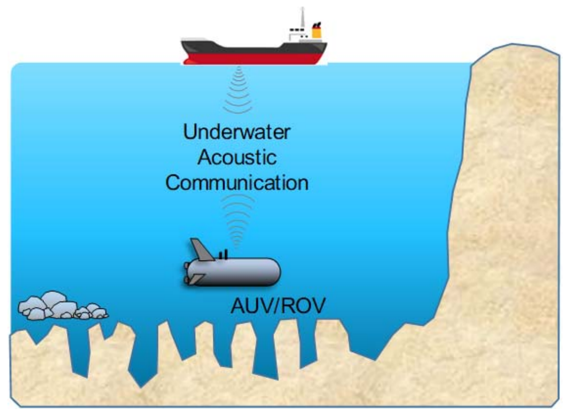

Fig. 1: Target application of OFDM communication system.

The section II describes the system architecture including the system block diagram, OFDM modulation and demodulation. The detail of the time domain Doppler compensation design is also described. The section III shows how the Doppler compensation mitigates the effect of moving environment by simulation. Ocean field experiment results including Doppler compensation and diversity effects are shown in section IV. Finally, the summary is concluded in section V.

II. SYSTEM AECHITECTURE

A. System Block Diagram

Fig. 2 shows a block diagram of the communication system. The lower side corresponds to transmitter TX and the upper side is receiver RX. First, a data packet is given to TX side through the interface. After forward error correction coding, the coded signal is mapper to QPSK / 16QAM / 64QAM. Then the 641 mapped complex signals are converted to time-domain signal by 2048 point IFFT. After that, 288 points cyclic prefix is attached to the head of the signal as Guard Interval (GI) addition. Finally, the output is up-converted by + 54 kHz to generate real passband signal of 38 – 70 kHz band. In the receiver RX side, basically the reverse operations of TX are performed. However, there are 8 parallel branch receivers are used and the time-domain Doppler compensation similar to our previous papers [2-4]. It is composed of three functions such as 1) signal shrink-expansion factor detection, 2) resample and de-rotation for signal shrink-expansion and 3) phase shift compensation in each receiver

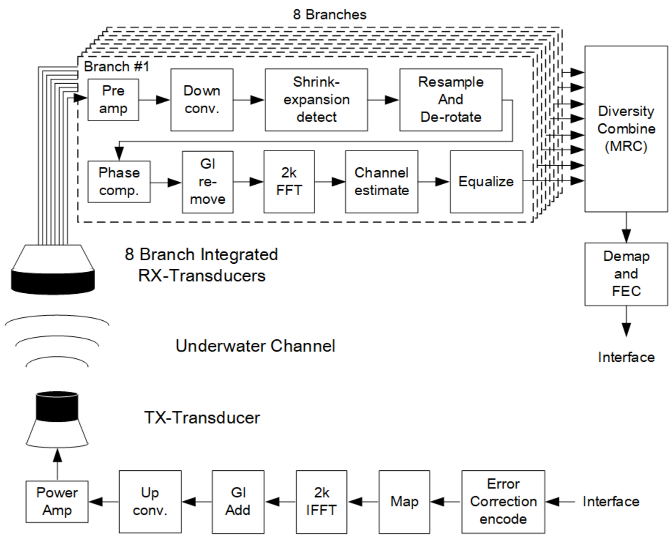

Fig. 2: Block Diagram of OFDM Communication System. Lower side is transmitter while upper side is 8 branch diversity receiver. The 8 outputs are combined by MRC algorithm.

TABLE I : COMMUNICATION SYSTEM FEATURE

Parameters	Value
Receiver	8 Integrated Transduces
Transmitter	1 Transduce
Baseband Sampling	102.4 kHz
Band Width	54 kHz ± 16 kHz
FFT size	2048
OFDM symbol length T	20.0 ms (2048 point)
Guard Interval length Tg	2.8125 ms (288 point)
Sub-carrier spacing	50 Hz
Number of sub-carrier	641
Scattered pilot	161 every 4 OFDM symbol
Continuous pilot	41
Carrier Modulation	QPSK/16QAM/64QAM BPSK(only control)
Max. Dara Rate w/o FEC	150 kbps (64QAM)

branch. The 8 branch outputs are combined by MRC diversity combiner. 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 2.8125 ms with assuming there are no long multi-path echo signals.

B. Time-Frequency Representation

Fig. 3 shows the time-frequency representation of OFDM modulation. The number of total sub-carriers in one OFDM symbol is 641. The 161 Scattered Pilot (SP), which are placed at all every four sub-carriers, are allocated to one OFDM symbol in every 4 symbol intervals as shown by the blue circle. The SP is used for channel estimation to generate channel transfer function (CTF). In order to obtain whole time-frequency grid CTF values, CTF at SP position are interpolated in time and

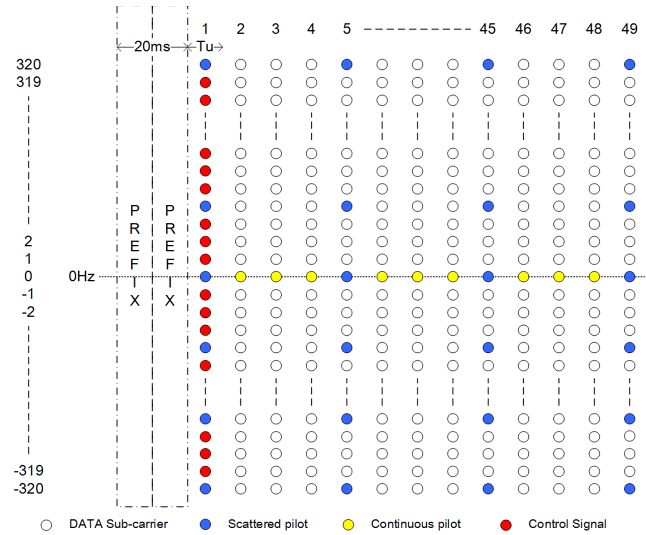

Fig. 3: Time-Frequency representation of OFDM. Every four symbol, Scattered Pilots (SPs) are placed and they are used to calculate Channel Transfer Function and Delay profiles.

frequency axis. The 41 symbols of Continuous Pilot (CP), which are placed at every 12 sub-carriers, are allocated to each OFDM symbol as shown as yellow circle. The CP is used to calculate fine Phase Shift Estimation along time axis for phase compensation. Zadoff-Chu sequence [5] is used for SP and CP values. The other white circles correspond to data sub-carriers, which are modulated by QPSK / 16QAM / 64QAM. At the first OFDM symbol, the red circles are used to send BPSK modulated control data such as modulation type, code rate and so on.

C. One branch receiver signal processng

Fig. 4 shows the block diagram of one branch receiver in detail. Received signal (RX_IN) is converted to digital representation with 8x102.4KHz sampling frequency. Then it is down-converted to baseband signal. After the down-conversion, sampling frequency is decimated to 102.4kHz. At first, Shrink-

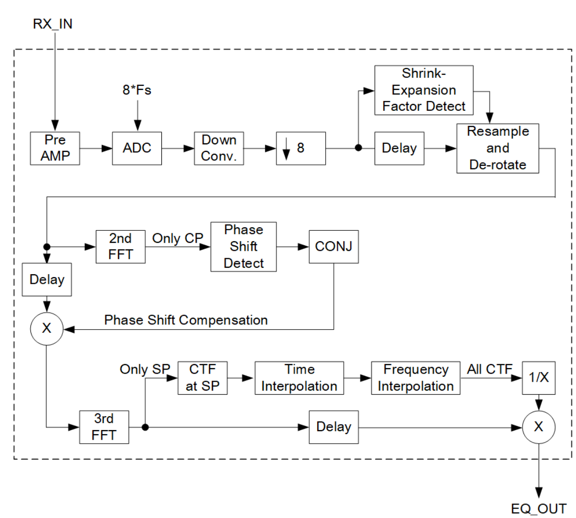

Fig. 4: Block diagram of 1 branch receiver.

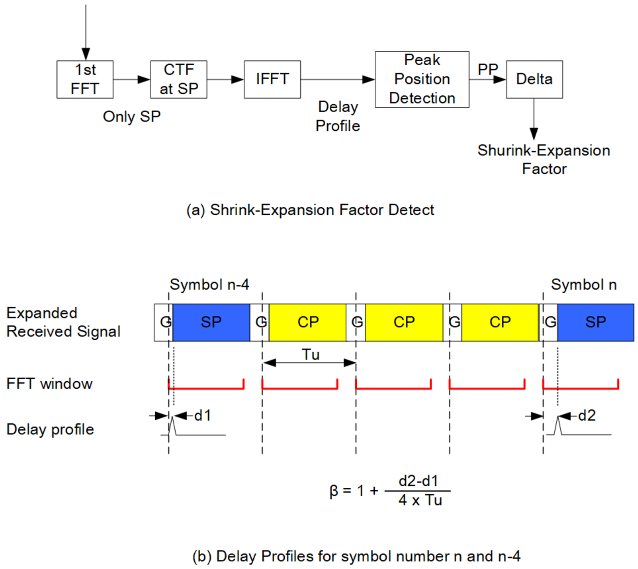

Fig. 5: (a) Block diagram of Shrink-Expansion Factor Detection and (b) two delay profiles of every four OFDM symbols contains SP pilots.

Expansion Factor β is detected. According to β, Resample and De-rotate block performs shrink or expand operation on time domain baseband signal. Fig. 5(a) and (b) show the detail of Shrink-Expansion Factor detection processing and its operations. As shown in Fig. 2, the SP is placed every four OFDM symbols such as n-4th and nth OFDM symbols. SP values are extracted by the 1st FFT output of the n-4th and nth SP OFDM. Then the Delay profiles can be obtained by IFFT operation on those CTF at SP positions. The peak position of delay profile indicates the starting point of OFDM symbol, then factor β can be obtained by the difference of the peak position as equation (1). Here, Tu corresponds to OFDM symbol length T + GI length Tg.

$$\beta = 1 + \frac{d2 - d1}{4 \cdot Tu} \cdots (1)$$

After the Resample and De-rotate processing, additional phase shift compensation is performed. Since CP is placed in all OFDM symbols in time direction including SP, symbol by symbol phase shift can be detected. By conjugating the detected phase shift value and converting the value at symbol by symbol to sampling period by interpolation, time domain OFDM symbol is compensated. Finally 3rd FFT is performed as OFDM de-modulation. By dividing the outputs by interpolated CTFs, equalized constellations can be obtained.

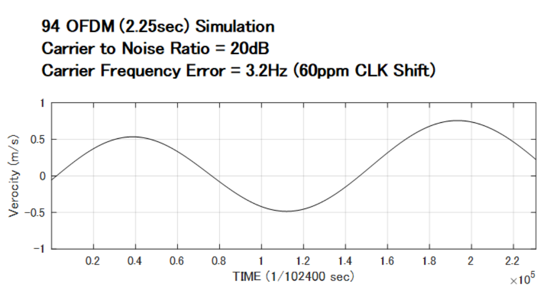

Fig. 6. Receiver moving computer simulation conditions.

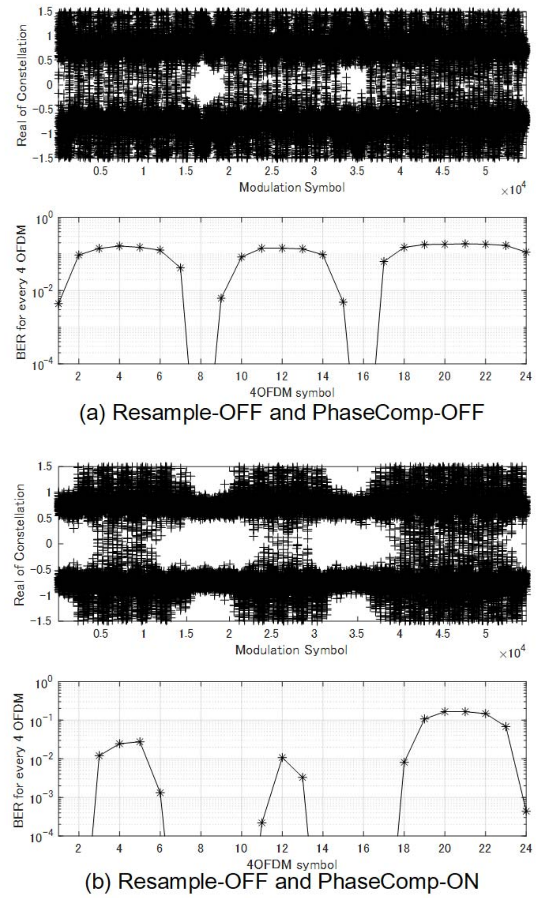

Fig. 7: Simulated Real part of constellations time dependence and Bit Error Rate for every 4 OFDM symbols in case that Resample and De-rotation are OFF and Phase Compensation OFF (a) and ON (b).

III. TIME DOMAIN DOPPLER COMPENSATION

In order to show the effect of the time-domain Doppler compensation, a computer simulation results are shown. Fig. 6 shows simulated receiver velocity change over 94 OFDM symbols (approximately 2.1 sec) with Carrier to Noise ration of 20dB and 3.2Hz frequency error (60ppm sampling clock error) between transmitter and receiver. Used digital data modulation is QPSK. Maximum moving velocity is 0.75m/s.

Fig. 7 shows the simulated time dependence of Real part of QPSK and Bit Error Rate (BER) when Resampler and De-rotater are OFF. Fig.7(a) and (b) correspond to the cases of phase compensation off and on, respectively. When the velocity is high, QPSK constellations are disturbed and high BER is observed. By enabling the phase compensation, BER is improved. However, even 0.5m/s velocity causes severe damage to increase BER more than 0.1. Fig. 8 shows the smilar time dependence of Real part of QPSK and BER as Fig. 7 with enabled Resampler and De-rotater. By using the shrink or expand processing, both constellations and BER are drastically improved. Fig. 9 shows the 4 cases of QPSK constellations with Zadoff-Chu pilots. Fig. 9(d) corresponds to enabled time domain

Doppler compensation. According the computer simulation, Resample and De-rotation are effective to high velocity and

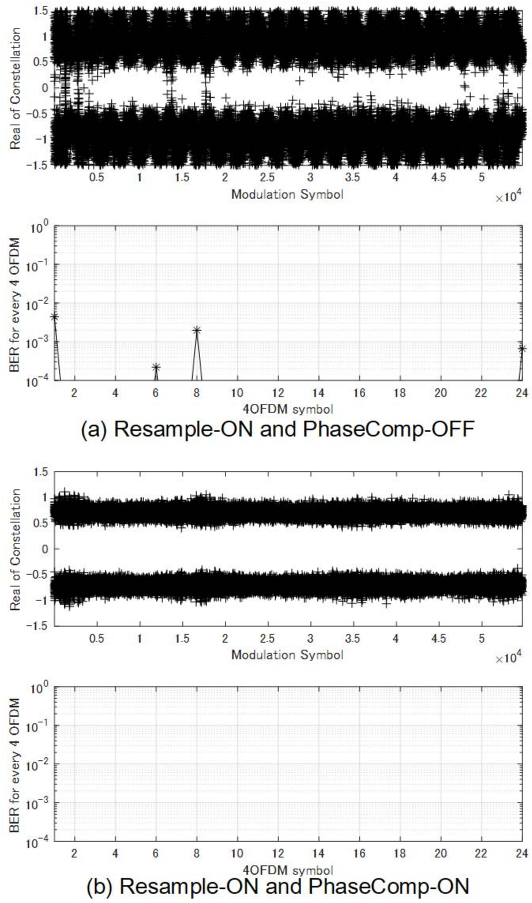

Fig. 8: Simulated Real part of constellations time dependence and Bit Error Rate for every 4 OFDM symbols in case that Resample and De-rotation are ON and Phase Compensation OFF (a) and ON (b).

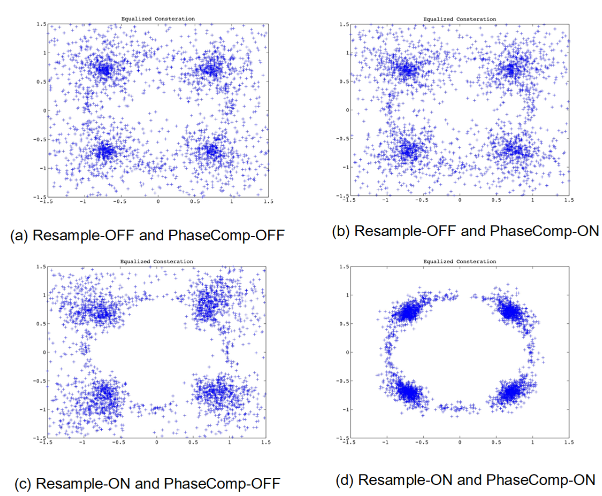

Fig. 9. Simulated QPSK constellations. They get clear by enabling the time-domain Doppler compensation.

Fig. 10: 8 branches diversity integrated receiver system.

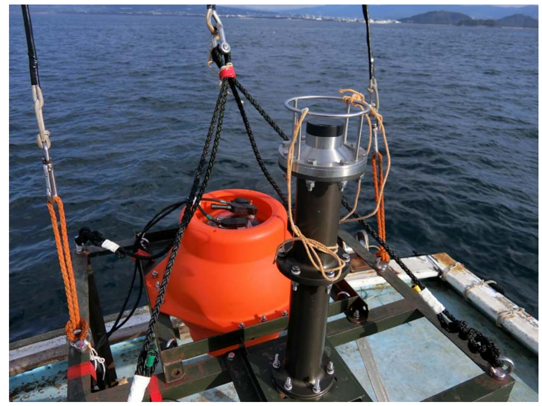

Fig. 11: Transmitter system.

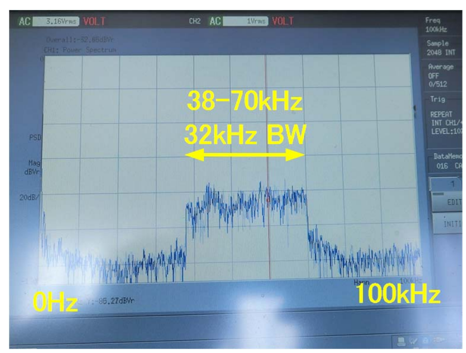

Fig. 12 Measured signal spectrum at near water surface which shows a 32KHz Bandwidth OFDM signal..

phase compensation can contribute to compensate carrier frequency errors.

IV. Ocean Experiment Results

Ocean experiment was performed at Uchiura-bay at Shizuoka prefecture, Japan. The depth of the experiment point is rouly 300m. Fig. 10 shows a receiver system with 8 diversity. In side the gold body, signal processing circuit system is housed. Fig. 11 shows a transmitting system. The top black portion is transducer and the red case includes high-pressure glass container, which carries control system, camera and batteries etc. The transmitter system was submerged to 100m depth to measure constelleations and Bit Error Rates (BERs).

Fig. 12 shows the observed signal spectrum at near water surface. Clear 32KHz Bandwidth OFDM signal is observed. Fig. 13 shows 64QAM measured constellation at 100 m depth. Although the rocking of the ship is happening, stable constellation has been obtained. Fig. 14 shows measured time dependence of Real part of 16QAM constellation with (a) compensation OFF and (b) compensation ON. The X-axis corresponds roughly 2 sec time period. Without the time domain Doppler conpensation, such clear constellation cannot be observed. 8 reciver transducers are illustrated in Fig. 15(a) and three QPSK constellations with changing the number of used branches are shown in Fig. 15(b-d). The BPSK constellation corresponds to First control data symbol. Using the distribution of the QPSK constellation, Modulation Error Ratio (MER) measurement is performed. Measure MERs are 24.1dB / 27.7dB / 28.8dB for only 1branch / 4 branchs / 8 branches, respectively. According to the mesured result, 4.7dB diversity gain has been observed to use 8 branch diversity. When random noises are added to each branch, roughy 9dB diveristy gain was expected. However, roughly half diversity gain has been observed in the ocean experiment.

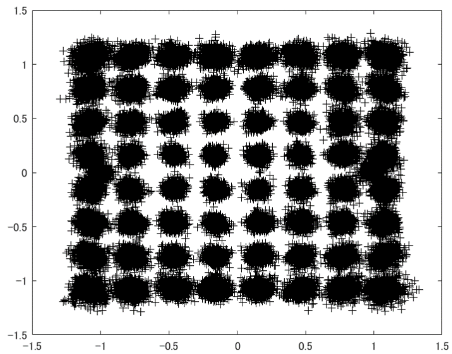

Fig. 13: Measured 64QAM constellation at 100m depth.

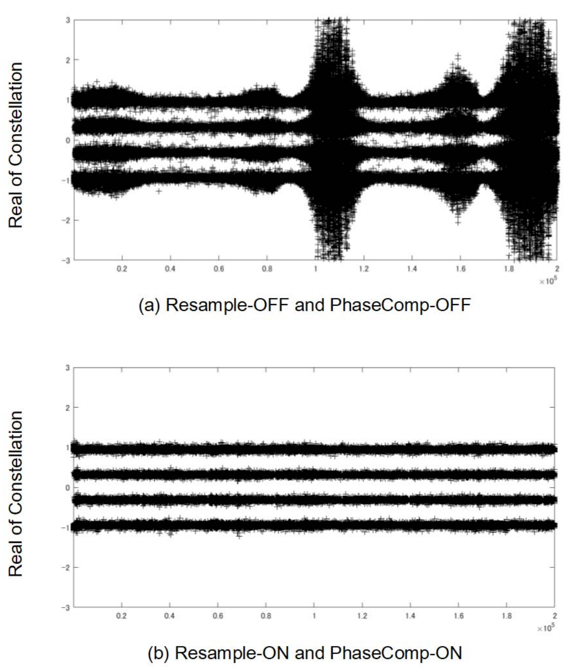

Fig. 14: Measured time dependence of Real part of 16QAM constellation with (a) compensation OFF and (b) compensation ON.

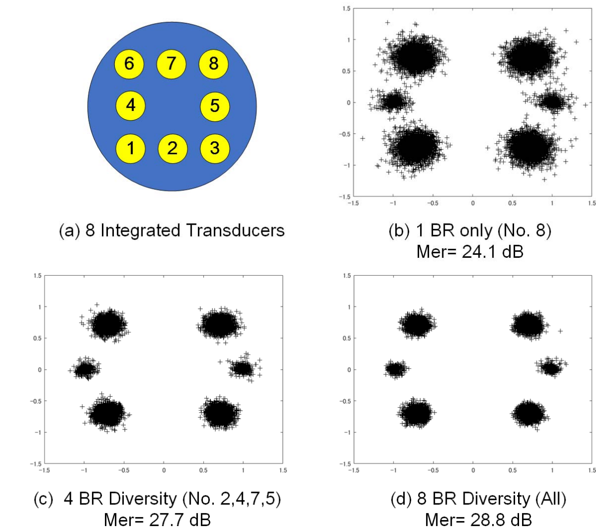

Fig. 15: (a) 8 receiver transducers and (b-d) three QPSK constellations with changing the number of used branches.

V. Conclusion

A 32 kHz bandwidth, 8 branch diversity underwater acoustic OFDM communication system is developed. The transmission data rate is 150 kbps without error correction using 64QAM modulation and 641 sub-carriers. To realize a stable data communication with moving environment, two stage time domain Doppler compensation is applied. The 1st stage is time domain signal shrink or expansion and the 2nd stage is phase shift compensation. The system is verified by Ocean experiment at Suruga Bay with 100m depth of transmitter in Shizuoka, Japan. By enabling the Doppler compensation signal processing, a stable data communication was confirmed. The approximately 4.7dB of diversity gain using the 8 branches diversity was measured.

References

[1] Sassan Ahmadi, LTE-Advanced A Practical Systems Approach to Understanding 3GPP LTE Releases 10 and 11 Radio Access Technologies, ACADEMIC PRESS, 2014.

[2] Taisaku Suzuki, Tomohisa Wada, Hiromasa Yamada, and Shigeo Nakagawa, "An Underwater Acoustic 64QAM OFDM Communication System with Robust Doppler Compensation," MTS/IEEE OCEANS 2016, Monterey, CA, USA, September 19-23rd 2016.

[3] Taisaku Suzuki, Tomohisa Wada, Hiromasa Yamada and Shigeo Nakagawa "A 31.8kbps/8KHz Underwater Acoustic Single Carrier Frequency Division Multiplexing (SC-FDM) Communication System with Forward Error Correction,", MTS/IEEE OCEANS 2017, Anchorage Alaska USA, September 18-21nd 2017.

[4] Taisaku Suzuki, Tomohisa Wada, Hiromasa Yamada, Shigeo Nakagawa "An Underwater Acoustic OFDM Communication System with Robust Doppler Compensation," IJICSNS International Journal of Computer Science and Network Security, VOL.17, No.9, September 2017.

[5] Stefania Sesia, Issam Toufik, Matthew baker, LTE The UMTS Long Term Evolution FROM THEORY TO PRACTICE, WILEY, 2009.