A Prototype Design and Experiment of Time Division Duplex (TDD) Underwater Small Area Acoustic Network (USAAN) System

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Summary

Underwater wireless acoustic networking is being demanded for many applications to reduce cable cost, impractical or too time consuming to deploy, as well as radio wireless technologies have enabled the information technology to spread over our real life such as high bandwidth data transfer between humans and machines. Because of the long propagation delays of the underwater acoustic channel, Media Access Control (MAC) design is challenging. Although many radio access MAC protocols are based on handshake type between the sender and the receiver such as IEEE 802.11, it is not efficient in underwater acoustic network and handshake-free MAC protocols are getting important. In this paper, we propose a TDD USAAN communication system, which uses SC-FDMA modulation. The target applications are 1) underwater civil engineering machine control and view monitoring, 2) marine aquaculture monitoring such as underwater environment data and fishes, 3) human monitoring and position tracking at marine leisure such as diving, 4) controlling a remotely operated vehicle (ROV) wirelessly to exterminate harmful creatures such as acanthaster in coral reef and so on. The proposed system assumes small service area less than 100 m diameter. Then USAAN system can avoid a hand-shake protocol and instead use TDD protocols. There is one base station and several user stations. Both Down Link (DL) communication from the base station to the user stations and Up Link (UL) communication from the user stations to the base station are supported as Time Division Duplex (TDD) method.

To realize a stable TDD operation with assuming User Equipment movement, twice repeating chirp preamble signal is proposed. The prototype system uses 16-24 kHz ultrasonic channel and total of 169 subcarriers are used in 8 kHz bandwidth to deliver 10.35Kbps by QPSK modulation. The TDD operation has been confirmed by field experimentation using the prototype system at a Dam Lake in Shizuoka prefecture, Japan. The Lake experiment demonstrated vertical downward DL and upward UL two way TDD communication. The synchronization robustness has been confirmed by the experiment of User Equipment vertical up and down moving. The proposed chirp preamble method realized stable TDD synchronization in water with maximum moving speed of 0.7m/sec.

Key words:

SC-FDMA, OFDM, TDD, Underwater Network, Digital Communication

1. Introduction

Underwater wireless acoustic networking is being demanded for many applications to reduce cable cost, impractical or too time consuming to deploy, as well as radio wireless technologies have enabled the information technology to spread over our real life such as high bandwidth data transfer between humans and machines. The typical applications of underwater acoustic network include surveillance of areas as harbors, ports and coastlines, or monitoring of fishes and excavation sites such as oil wells, trenches and so on [1]. The design of protocol stack for the underwater network must take underwater channel property and strict requirements of acoustic communications into account [2]. Especially because of the long propagation delays of the underwater acoustic channel, Media Access Control (MAC) design is challenging. Although many radio access MAC protocols are based on handshake type between the sender and the receiver such as IEEE 802.11, it is not efficient in underwater acoustic network. In the paper [3], three handshake-free MAC protocols are evaluated and compared for underwater acoustic networks.

In this paper, an Underwater Small Area Acoustic Network (USAAN) System is proposed to simplify the underwater channel access controls. Fig. 1 shows three application examples. The first is underwater civil engineering machine control and view monitoring. The second is marine aquaculture monitoring such as underwater environment data and fishes. The third is human monitoring and position tracking at marine leisure such as diving. Another application is to control a remotely operated vehicle (ROV) wirelessly to exterminate harmful creatures such as acanthaster in coral reef.

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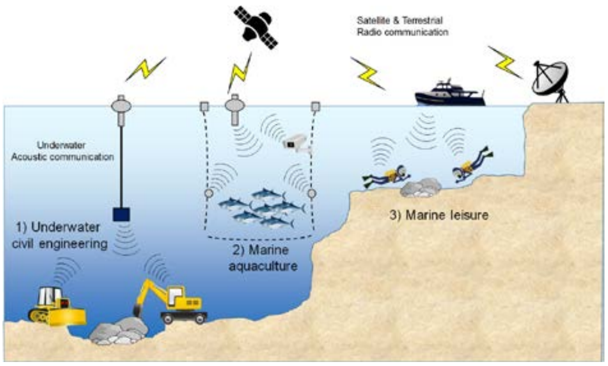

Fig. 1: Target applications for USAAN

The targeting underwater service area of USAAN is defined as shown in fig. 2. The diameter of supported service area is 100 m. There is one base station and several user stations. Both Down Link (DL) communication from the base station to the user stations and Up Link (UL) communication from the user stations to the base station are supported as Time Division Duplex (TDD) method. Since a frequency assignment rule in underwater is not well established and there are many acoustic noise sources available such as creature noise, ship engine noise, other acoustic machines and so on, the system shares the same Down Link (DL) and Up Link (UL) frequency band by use of TDD method to minimize interference with outside noises. Since all UL communication are time-scheduled by the base station, no hand-shake protocol is needed. In addition, in order to support both higher digital communication bandwidth and lower signal Peak-to-Average Power Ratio (PAPR), Single Carrier Frequency Division Multiple Access (SC-FDMA) is utilized [4, 5].

In section 2, the prototype USAAN design detail is disclosed. The prototype system is developed by the combination of a FPGA board and off-the-shelf Personal Computer with Matlab software. In one frame, there is one DL stream and several UL streams. Both streams are configured by SC-FDMA signaling. The signal design of SC-FDMA is also shown in section 2. Field experiment at Dam Lake has been performed to evaluate real time DL signal synchronization and generation of UL signal using the prototype system. In section 3, the experimental results will be shown. Finally, conclusion is given in Section 4.

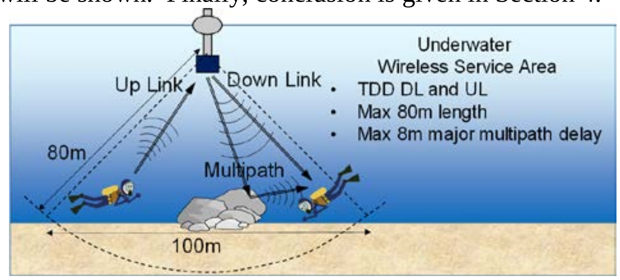

Fig. 2: Wireless Service Area of USAAN

2. Proposed system

2.1 Communication System Architecture

Fig. 3 shows the proposed TDD timing diagram assuming two UL users. In one frame, one DL signal and two UL signal is assigned. The frame length is 102400 sampling point with sampling frequency Fs of 96 kHz. Both DL signal segment and UL signal segment are composed of three parts such as silent period, chirp preamble and SC-FDMA signals. In order to distinguish DL signal from UL, the frequency band of those chirp signals are different. The DL chirp uses upper 4kHz band out of 8kHz communication bandwidth, while the UL chirp uses the lower 4kHz. The length of the SC-FDMA composed of 2048 points symbol and 512 points Guard Interval (G). In DL and UL, there are 13 SC-FDMA symbols and 9 SC-FDMA symbols, respectively.

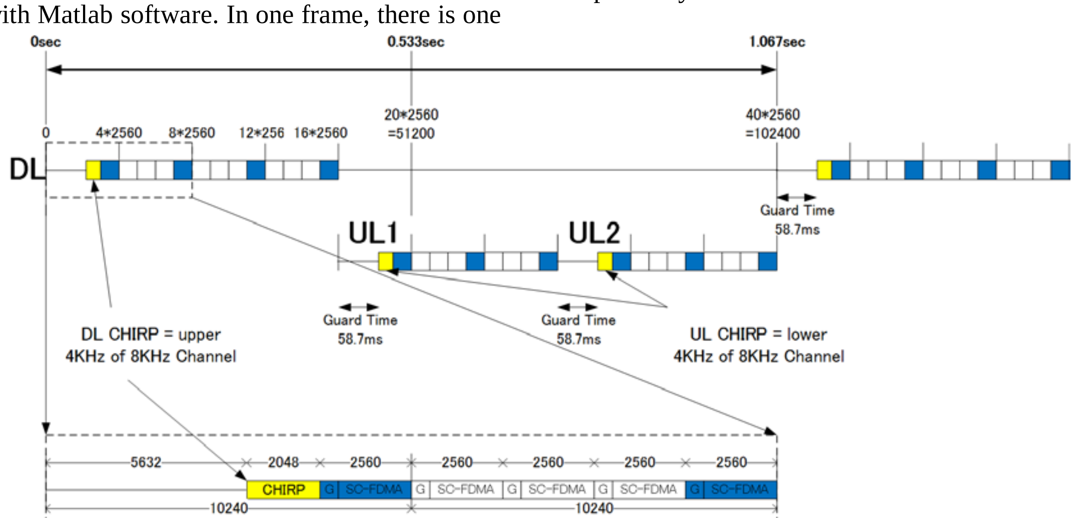

Fig. 3: Frame Design of USAAN

The white and blue SC-FDMA symbols are corresponds to different pilot configurations as shown in fig. 4. In every 4 SC-FDMA symbols, one blue-coloured SC-FDMA symbols are asserted.
The blue SC-FDMA symbol, which is called as SP symbol, consists of 85 Scattered Pilots (SP) and 84 data sub-carriers as shown in fig. 4. The white SC-FDMA symbol, which is called as CP symbol, consists of 13 Continuous Pilots (CP) and 156 data sub-carriers. The scattered pilots, which are placed every even number sub-carriers, are used to measure Channel Transfer Function (CTF). The value of the SP is Zadoff-Chu sequences, whose amplitudes are 1.0 [6].

In order to get whole CTF values in Time-Frequency Diagram as shown in fig. 4, the measured CTF values only on the blue sub-carriers are two dimensionally interpolated. The 13 Continuous Pilots, which are placed on only even number Sub-carriers of both edges (7 in Upper and 6 in Lower frequencies).
The value of CP is also Zadoff-Chu sequences. Using the CP and SP, the time-variation of CTF at such sub-carrier frequency bin can be monitored to evaluate the Doppler shift effect.
Table 1 summaries system parameters.

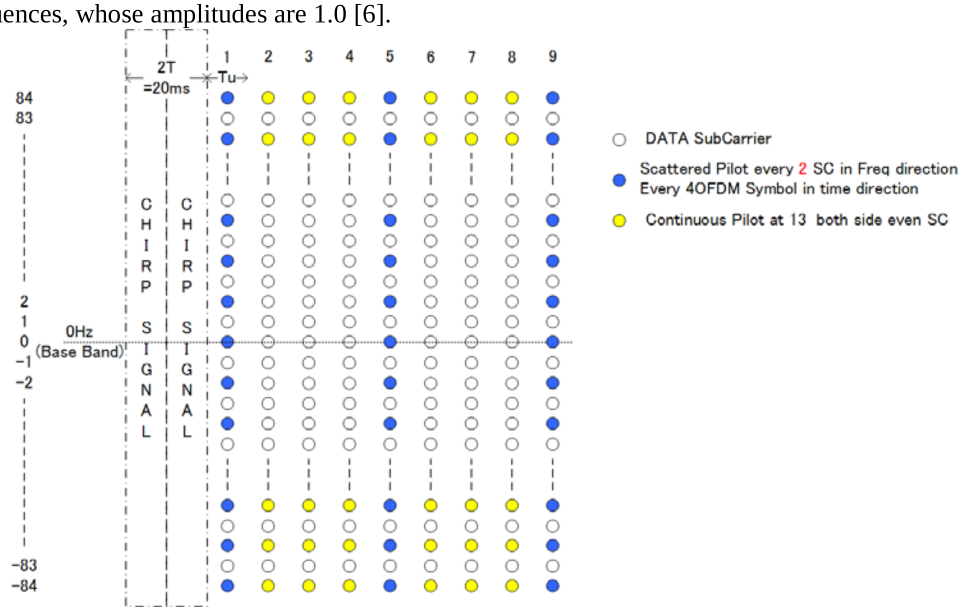

Fig. 4: Time-Frequency Diagram of USAAN

Table 1: System Parameters

SC-FDM Parameters	Value
TX-RX Elements	1 TX and 1 RX Transducer
Sampling Frequency	96000 Hz
TX Center Frequency	20000 Hz
Band Width	8000 Hz
FFT Size	2048
OFDM symbol length T	21.333 ms (2048 points)
GI length Tg	5.333ms (512 points)
Effective Symbol length Tu=T+Tg	26.667ms (2560 points)
Chirp Signal Length	21.333ms (2048 points)
Guard Time between DL/UL packet	58.666ms (5632 points)
Sub Carrier Spacing	47.619 Hz
Number of Sub Carrier	169
DFT precode size	84 for SP symbol and 156 for CP symbol
Pilot	Zadoff –Chu, N_{ZC}= 85 and 13
Data Rate	10.35kbps (QPSK)

Fig. 5 shows the Transmitter TX and Receiver RX signal processing diagram. In TX, digitally modulated symbols in Map block are spread by Discrete Fourier Transform.
The outputs of the DFT Spread correspond to the data sub-carrier as shown by white circles in fig. 4. The sizes of DFT spread are 84 for SP and 156 for CP symbols.
By combining the DFT spread function with IFFT modulation, SC-FDMA signal generation is performed. Excluding the DFT spread and IDFT de-spread, the system becomes OFDMA communication system described in the paper [7].
After the IFFT modulation, Guard Interval (GI) is added to reduce inter symbol interference. Then in front of all modulated symbols, a chirp signal is prepended for RX to detect the starting point of the signal.

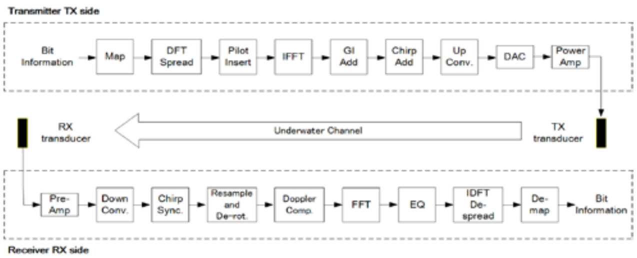

Fig. 5: Transmitter and Receiver Block Diagram

The chirp signal is linearly frequency sweeping signal as shown in fig. 6. In the figure, DL baseband Preamble chirp signal is shown. For DL, the sweeping range is 0Hz to 4 kHz in baseband, as well as UL Chirp sweeps 4 kHz to 0Hz. There are twice 1024 points sweeps to realize easy synchronization. After the chirp append, the signal is up-converted to 20 kHz center frequency and transmitted by TX transducer into underwater channel. Since the signal bandwidth is 8 kHz, the passband signal occupies from 16 kHz to 24 kHz.

The transmitted signal propagates in underwater channel and is received at RX transducer. At the RX side, the signal starting point is detected by the chirp signal and the modulation process, which is the reverse process of TX, is performed as shown in lower side of fig. 5.

To mitigate Doppler shift effect, Resample and De-rotation, Doppler Compensation signal processing is inserted. The detail signal processing of the compensation is explained in paper [7].

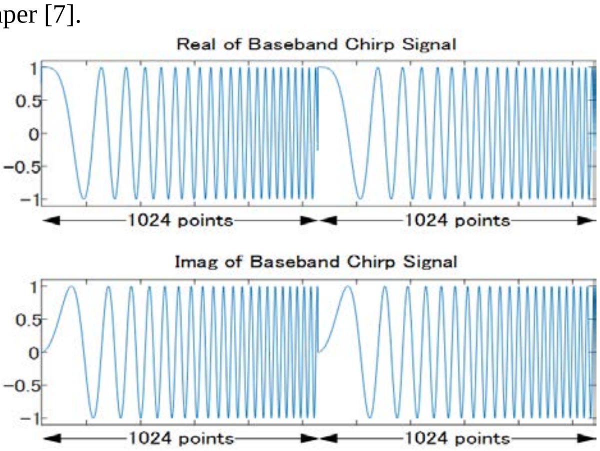

Fig. 6: Baseband down Link Preamble Chirp Signal

Fig. 7 shows the comparison of Peak-To-Average-Power (PAPR) reduction of SC-FDMA with OFDMA. By inserting the DEF Spread and IDFT De-spread as shown in fig. 5, SC-FDMA can be realized from OFDMA. The horizontal axis is PAPR in dB and the vertical axis is probability in time domain signal. At 0.01% probability point, 1.3 to 2.1 dB PAPR reduction has been accomplished depends on three modulations such as QPSK, 16QAM and 64QAM. The reduction of PAPR can reduce signal distortion at high power range of the amplifier and can improve bit error rate reduction at such high power range [5].

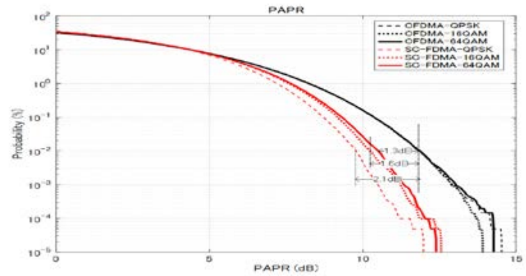

Fig. 7: Peak-to-Average-Ration (PAPR) reduction by SC-FDMA

2.2 Prototype System Implementation

To verify the function of proposed TDD USAAN communication system, a prototype system has been designed and implemented as shown in fig. 8. The prototype system assumes that there is one Base Station and one User Equipment. For the Base Station side, Down Link signal has been prepared in DL-TX PC with the Matlab software and the PC drives outside Digital to Analog converter and Power Amplifier. Then, the DL signal is transmitted from BS-TX transducer.

For User Equipment side, a Board (ZedBoard [8]), which carries CPU-embedded FPGA Zynq device [9] and an Audio Codec device, is used to realize real-time synchronization to the DL signal and to generate Up Link signal. At the Audio Codec with sampling frequency Fs=96 kHz, the received DL signal is converted to digital signals and the digitally generated UL signal is converted to Analog UL signals. The CPU in the FPGA runs Linux OS system and controls the operation of the logic circuits in the FPGA. The controller PC for Zynq Board can monitor and control the devices. The UL signal and the DL signal both are monitored by UL-RX PC. The demodulation operation for UL signal is performed by the Matlab software in UL-RX PC.

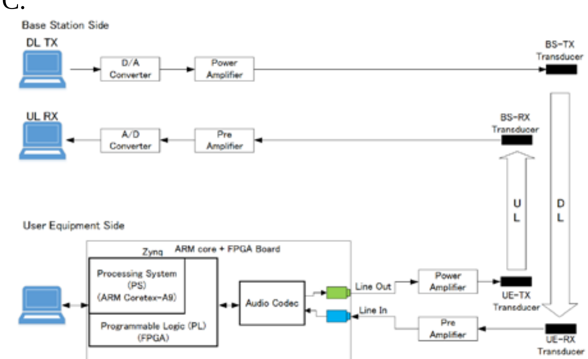

Fig. 8: Prototype USAAN System Diagram

Fig. 9 shows a photo of the prototype TDD USAAN communication system in laboratory. At the Left side, two pre-amplifiers for the receiving transduces for BS-RX and UE-RX, a D/A converter for DL-TX PC and two power amplifiers are placed. The two smaller PCs for BS-TX and -RX are placed at center. The right-hand side larger PC controls the Zynq board. Four TX and RX transducers are in the far-right blue bucket and those are connected to the two pre-amplifiers and two Power amplifiers.

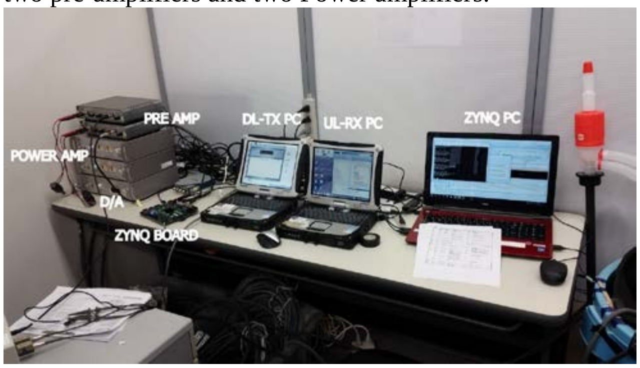

Fig. 9: Prototype System Setup in lab

Fig. 10 shows the chirp signal detection signal processing diagram which is implemented by Programmable Logic in Zynq FPGA. The output DL digital signal from the Audio Codec comes from the left-hand side. After the gain adjustment in Digital AGC block, a down conversion is performed to generate complex baseband signals. To detect DL chirp preamble signal, 1024 points complex FIR filter is implemented. The chirp signal template memory possesses the complex conjugate of the DL chirp signal. The FIR filter then calculates a correlation (Xcorr in the figure) of the down converted input signal with the chirp preamble template. In parallel with the correlation, the averaged signal powers are also calculated. Since the chirp signals are repeated twice with interval of 1024 points as shown in fig. 6, 1024 points delayed correlation signal are summed with the non-delayed correlation signal to further enhance the correlation peak. Using the both averaged power and the enhanced correlation peak (Xcorr2 in the figure), DL chirp preamble timing can be detected. After some timer process, Up Link signal can be initiated by the trigger timing. The output UL signal is input to the Audio Codec device. Then the UL signal is transmitted from UE-TX transducer.

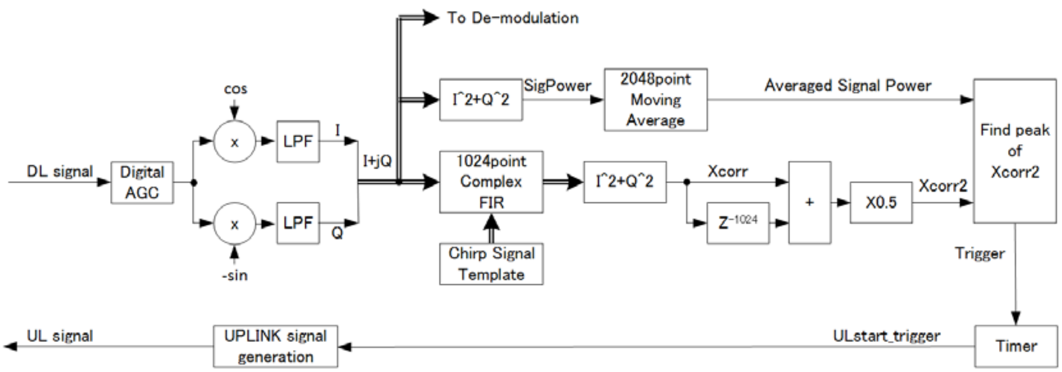

Fig. 10: Preamble Chirp Signal Detection Processing Diagram using Logic in FPGA

3. Experimental results

To evaluate the communication function and Doppler resistance of the TDD USAAN system, a field experiment at Nagase Dam Lake in Izunokuni city, Shizuoka prefecture has been performed. The size of the Dam Lake is roughly 50 m x 50 m with water depth of 6 m. A floating barge at the center of the Lake was used to setup vertical communication experiment as shown in fig. 11.

Fig. 11: Floating Barge in Nagase Dam

The details of the field experiment parameters are shown in Table 2. The cross-sectional view of the experiment is shown in fig 12. All TDD USAAN prototype system are prepared on the barge and four transducers are connected by cables. BS-TX and -RX transducers are set at the depth of 3 m, and UE-RX and -TX transduces are set at the depth of 5m in the lake. The UE transducers can be moved up and down by pulling the hanging rope to evaluate Doppler Shift condition. The depth of the lake is roughly 6 m and the distance between TX-RX transducers are 0.3 m. Photographs of TX and RX transduces for Base Station and User Equipment are shown in fig. 13(a) and (b). Since the UE transduces moves up and down, the UE transduces are set on heavier metal frames.

Table 2: Field Experiment Parameters

Parameters	Value
Experiment site	Nagase Dam Lake in Shizuoka
Number of Transducers	1 TX and 1 RX for BS and UE
Depth	3m (BS), 5m(UE)
Modulation	QPSK
TX-RX Transducer Distance	0.3 m
Transmission Direction	Vertical
Lake Depth	6 m
UE moving speed	0.7m/sec, 0.3m/sec, 0.15m/sec

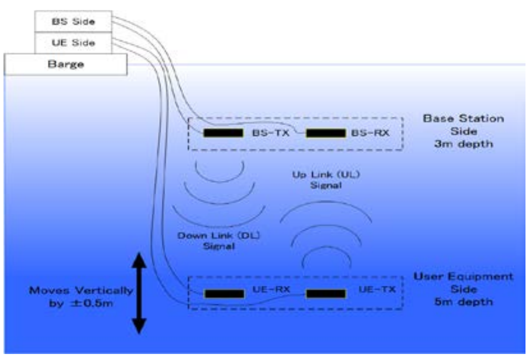

Fig. 12: Vertical Two-way Communication Experiment Setup in the Dam

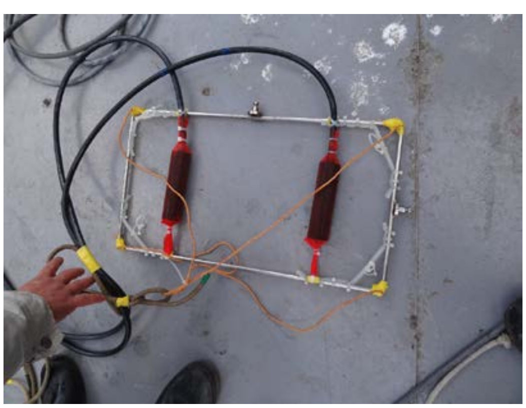

Fig. 13(a): TX and RX transducers at Base Station

Fig. 13(b): TX and RX transducers at User Equipment

Fig. 14 shows the measured DL and UL signal by BS-RX PC when UE transduces are not moving vertically. As described in section 2.1, the DL chirp signal is used to synchronize and UL signal is successfully generated by the synchronization. The time interval between DL chirp and UL signal is pre-programed in the Zynq FPGA as a parameter. By changing the interval parameter, UL start timing can be controlled. Since this measured data were taken at the BS-RX transducer and BS UL-RX PC, the signal amplitude of DL is much larger than that of UL signal because the transducer distances are different. In actual two-way communication, only the UL signal is only demodulated while the DL signal is ignored.

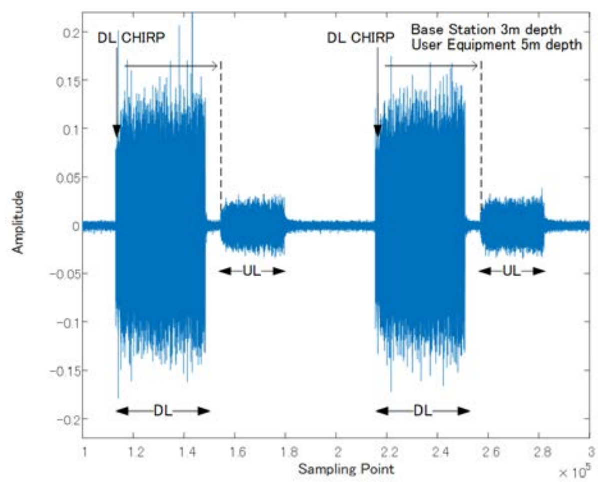

Fig. 14: DL and UL Signal Measure at Base Station RX

Fig 15 shows the UL SC-FDMA demodulated constellation which are decoded by UL-RX PC with Matlab software in fig. 8. QPSK constellations have been successfully obtained. The QPSK modulation corresponds to peak data rate of 10.35 kbps. Because of larger background noise existed in the experiment, the QPSK constellation looks like suffering lower SNR conditions. Therefore, the basic operation of TDD USAAN system has been confirmed.

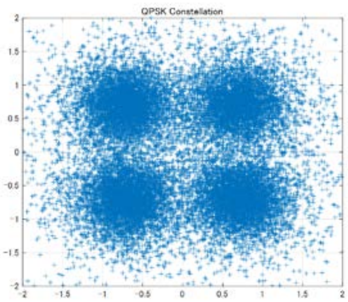

Fig. 15: UL Signal Demodulation Result

Next, to check the robustness of synchronization of the system under the UE moving case, the UE-transducers have moved up and down repeatedly with changing moving velocity such as 0.15 m/sec, 0.3 m/sec and 0.7 m/sec. As shown in fig. 3, the frame length of TDD USAAN system is 1.067 second (= 102400 sampling points). Therefore, the chirp synchronization process has performed every 1.067 second. Then the synchronization trigger timings are detected every 1.067 second. As explained in section 2.2, the controller PC for Zynq Board can take real-time log of the trigger timing. Fig. 16 shows the difference (= Sync Position Shift) between current frame trigger timing and previous frame trigger timing. The Sync Position Shift of 0 corresponds to the situation that BS and UE distance is stable. The positive Shift corresponds to the increase of the distance and vice versa. In the experiment, the positive Shift means the UE transduces move downward and the negative Shift corresponds to upward moving case. The total moving distance is limited by ±0.5 m as shown in fig. 12. Figs. 16(a), (b) and (c) show the logged results of Sync Position Shift for three moving speed of 0.15 m/s, 0.3 m/sec and 0.7 m/sec, respectively. UE moving operation has successfully detected until maximum speed of 0.7 m/sec. The proposed chirp preamble method has shown robustness in TDD synchronization with User Equipment moving cases.

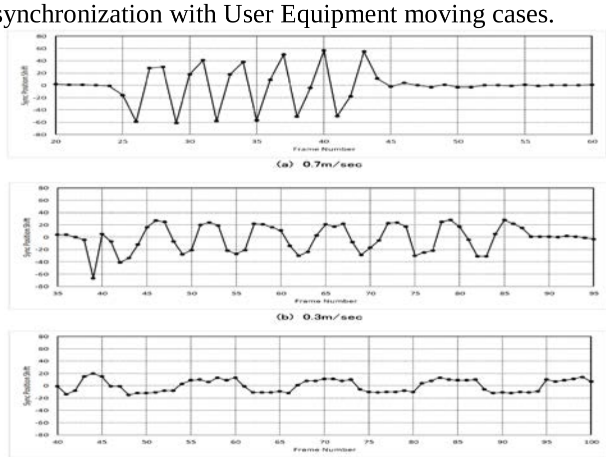

Fig. 16: Measured Time domain Synchronization Point shifts

4. Conclusion

In this paper, we propose a TDD USAAN communication system, which uses SC-FDMA modulation. The target applications are 1) underwater civil engineering machine control and view monitoring, 2) marine aquaculture monitoring such as underwater environment data and fishes, 3) human monitoring and position tracking at marine leisure such as diving, 4) controlling a remotely operated vehicle (ROV) wirelessly to exterminate harmful creatures such as acanthaster in coral reef and so on. The proposed system assumes small service area less than 100 m diameter as shown in fig. 2. Then USAAN system can avoid a hand-shake protocol and instead use TDD protocols. There is one base station and several user stations. Both Down Link (DL) communication from the base station to the user stations and Up Link (UL) communication from the user stations to the base station are supported as Time Division Duplex (TDD) method.

To realize a stable TDD operation with assuming User Equipment movement, twice repeating chirp preamble signal is proposed. The prototype system uses 16-24kHz ultrasonic channel and total of 169 subcarriers are used in 8kHz bandwidth to deliver 10.35Kbps by QPSK modulation.

The TDD operation has been confirmed by field experimentation using the prototype system at a Dam Lake in Shizuoka prefecture, Japan. The Lake experiment demonstrated vertical downward DL and upward UL two way TDD communication. The synchronization robustness has been confirmed by the experiment of User Equipment vertical up and down moving. The proposed chirp preamble method realized stable TDD synchronization in water with maximum moving speed of 0.7m/sec.

Acknowledgments

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