Comparison of SC-FDM with OFDM in Underwater Acoustic Communication System

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***Abstract*— This paper compares Single Carrier Frequency Division Multiplex (SC-FDM) with Orthogonal Frequency Division Multiplex (OFDM) for underwater acoustic communication. One of the drawbacks of OFDM transmission is the large variations in the instantaneous transmit power. This implies a reduced efficiency in power amplifiers and results in lower average power of the transmission signal. SC-FDM is utilized for 4G radio access technology such as Uplink communication of Long Term Evolution (LTE) in order to mitigate the above drawback of OFDM. Among the modulations in this communication system are QPSK, 16QAM and 64QAM. Zadoff-Chu sequence is used as Pilots for SC-FDM both for Channel Estimation and Phase Compensation of Doppler shift. Both Field Experiment at sea port in Okinawa, Japan and computer simulation show the quantitative merits of SC-FDM than OFDM. Peak-to-average Power Ratio (PAPR) of the transmitted signal has been successfully reduced by 1.5-2.0 dB for various modulations and roughly 50% of communication distance can be extended.**

Keywords—Underwater, Acoustic Communication, PAPR, SC-FDM, OFDM

I. INTRODUCTION

Underwater wireless communication system will offer a wide variety of applications such as natural disaster warning, remote control of offshore objects, discovery of new resources at the bottom of ocean, and so on. Emerging underwater wireless network devices can be equipped onto underwater vehicles or robots with sensors and video cameras. Then system in ships can access to those sensors and video cameras through underwater wireless network by acoustic wireless link. Figure 1 shows an example to control a bottom sea ROV (remotely operated vehicles), which engages exploring natural resources by sensors, from water surface operator in ship through underwater network.

In order to support long range distance communication such as more than several thousand meters from ROV to surface ship, the transmitter in bottom should emit higher power signal to increase SNR at the receiver. OFDM based communication systems has been proposed [1-3]. One of the drawbacks of OFDM transmission is the large variations in the instantaneous transmit power. This implies a reduced efficiency in power amplifiers and results in lower average power of the transmission signal.

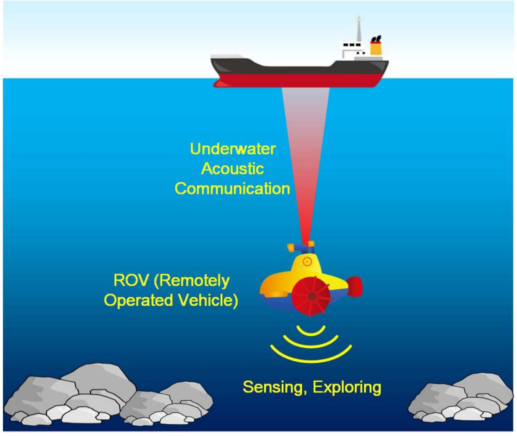

Fig. 1. Application of long range underwater acoustic communication

In this paper, we have compared Single Carrier Frequency Division Multiplex (SC-FDM) with Orthogonal Frequency Division Multiplex (OFDM) for underwater acoustic communication. The both SC-FDM and OFDM systems support one TX (transmitter) and one RX (receiver) transducers with center frequency of 20 KHz, 7.6 KHz bandwidth 81 subcarriers ultrasonic sound. In order to lower the Peak to Average Power Ratio (PAPR) of transmitting signal, SC-FDM introduces DFT Spread pre-coding [4]. Section II describes the detail processing of both SC-FDM and OFDM transceiver architectures and system parameters. The design is based on the underwater acoustic OFDM system with robust Doppler compensation in reference [5]. Section III shows the comparison results obtained by computer simulations in terms of PAPR and Bit Error Rate (BER) by limiting signal amplitude of transmitting signals. Then, sea experimental results performed in Ojima fishing port in Okinawa, Japan will be disclosed in Section IV. Finally, the conclusion is given in Section V.

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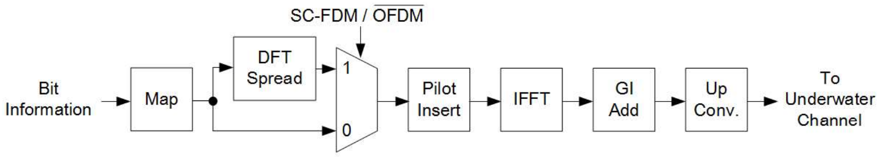
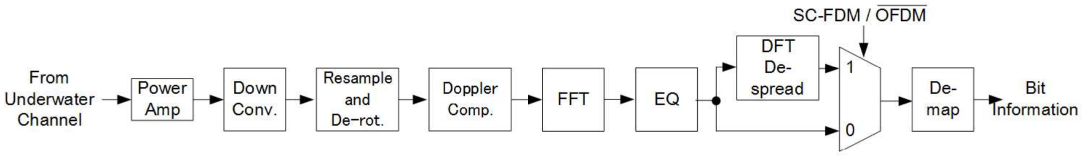


(a) TX Signal Processing



(a) RX Signal Processing

Fig. 2. Signal Processing in Transmitter and Receiver supporting both SC-FDM and OFDM

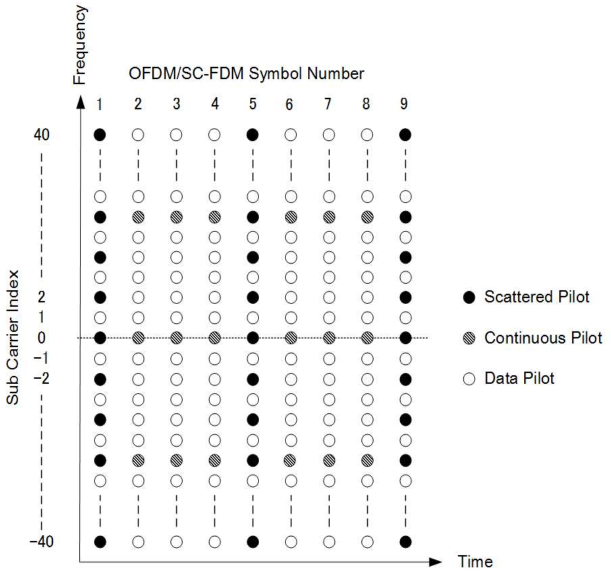


Fig. 3. Pilots and Data arrangements

II. SC-FDM AND OFDM SYSTEMS

Figure 2 shows the signal processing block diagram of the proposed communication systems. The upper side is transmission signal processing, which utilizes conventional OFDM signal generation. In order to support SC-FDM mode, additional Discrete Fourier Transform (DFT) pre-coder is multiplexed. The lower side corresponds to receiver side which is also capable of OFDM and SC-FDM modes. The receiver adopted time-domain re-sampler and de-rotator, and Doppler compensation before FFT in order to support TX or RX moving case [5]. Figure 3 shows Time-Frequency diagram of the system. One OFDM symbol in series of 4 OFDM symbols possesses Scattered Pilots (shown in black circle), which is used for channel estimation and the other three OFDM symbols includes 13 continuous pilots to detect time-domain Doppler shift estimation.

Table I shows the detail of the communication system parameters. The OFDM bandwidth is 7.6KHz with center frequency of 20KHz. One symbol length of OFDM is 10.667 ms, which corresponds to 1024 point of samples. Total number of subcarrier is 81. Although both scattered and continuous pilots in OFDM mode are BPSK modulated signals such as 1 or -1, Zadoff-Chu sequences are used for SC-FDM mode. Since the length of Scattered Pilots (SP) are 41 and the length of Continuous Pilots (CP) are 13, two sets of Zadoff-Chu sequences are generated using equation (1).

$$\mathrm{ZC(n)} = \exp\left[-j2\pi q\,\frac{n(n+1)}{2N_{ZC}}\right] \tag{1}$$

Here, N_{ZC}=41 for SP symbol and 13 for CP symbol, n is index from 0 to N_{ZC} -1 and q is integer between 1 and N_{ZC} -1. The sizes of DFT Spread (pre-code) and De-spread (post-code) are 40 for SP symbol and 68 for CP symbol. The system support maximum data rate of 26.78Kbps for 64QAM modulations.

TABLE I. SYSTEM PARAMETERS

Parameters	Value	
	SC-FDM	OFDM
TX-RX Elements	1 TX and 1 RX Transducer	
Sampling Frequency	96000 Hz	
TX Center Frequency	20000 Hz	
Band Width	7600 Hz	
FFT Size	1024	
OFDM symbol length	10.667 ms (1024 points)	
GI length	3.0ms (288 points)	
Sub Carrier Spacing	93.75 Hz	
Number of Sub Carrier	81	
DFT precode size for SC-FDM	40 and 68	none
Pilot	Zadoff-Chu N_{ZC}= 41 and 13	BPSK
Maximum Data Rate	26.78Kbps (64QAM)	

III. PAPR AND BIT ERROR RATE SIMULATIONS

The effect of Peak to Average Power (PAPR) ratio is calculated by analyzing both OFDM and SC-FDM transmission signal amplitude distributions. Figure 4 summarizes the analysis results for 3 data modulations such as QPSK, 16QAM, 64QAM for both OFDM and SC-FDM. Although OFDM shows almost same PAPR distributions for all modulations, QPSK case shows more than 2dB reduction and roughly 1.6dB reduction in both 16/64QAM are shown for SC-FDM.

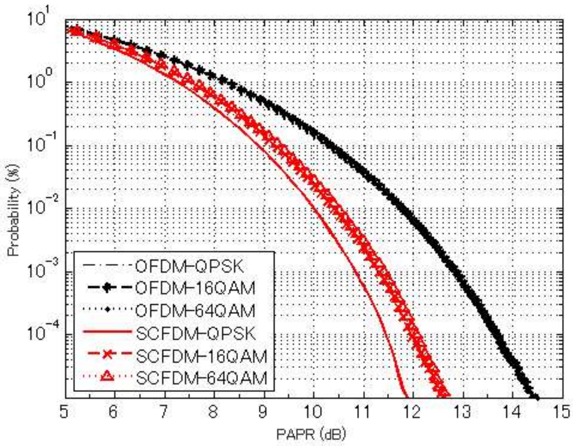


Fig. 4. Comparison of SC-FDM and OFDM PAPRs

The purpose to use SC-FDM instead of OFDM is to decrease PAPR and increase average transmission signal power to improve Signal Power to Noise Power Ratio (SNR) at the receiver. Then the performance evaluation by applying the maximum power limitation for the transmission signal is important. In the following simulation, the level of transmit signal power became a parameter to measure Bit Error Rate (BER). Figure 5 (a), (b), (c) show BER for three modulations such as QPSK, 16QAM, and 64QAM with changing transmitting signal power saturation level from 0dB (no signal saturation) to -20dB (maximum transmit power is 20dB lower). The lower the saturation signal power, the higher the BER became. When using QPSK, at BER of 0.005, approximately 1dB gain has been obtained. When using 16/64QAM at BER of 0.01, the gain of 0.8dB and 1.0dB has been obtained, respectively.

IV. FIELD EXPERIMNET

Sea experiment was performed to demonstrate the difference between SC-FDM and OFDM. The experiment site

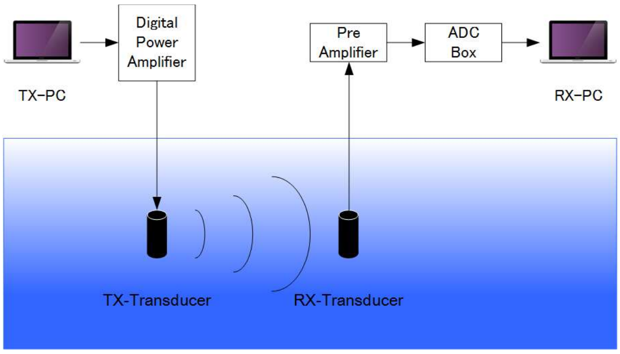
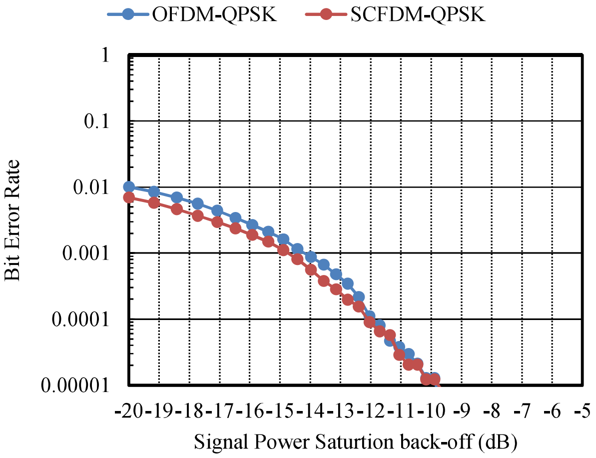
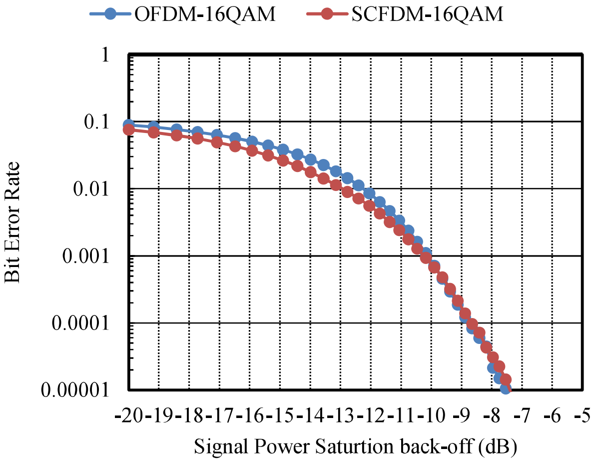


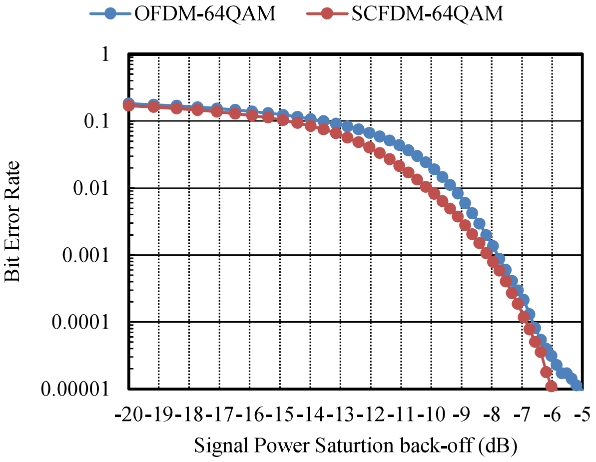
Fig. 6. Sea experiment setup at fishing port



(a) QPSK (CNR=15dB)



(b) 16QAM (CNR=23dB)



(c) 64QAM (CNR=30dB)

Fig. 5. Simulated BER for limiting the maximum signal power

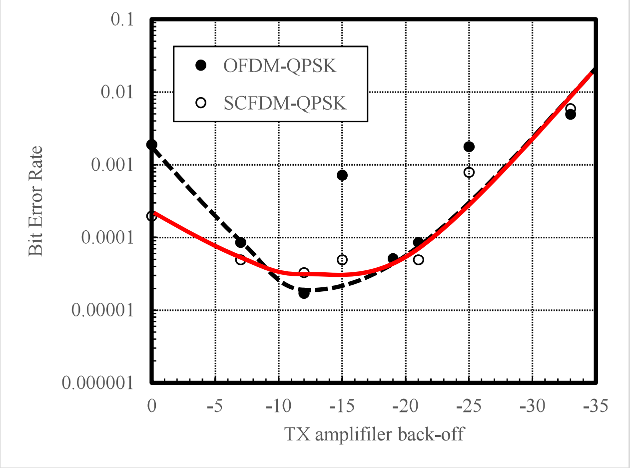
is Ojima fishing port, south part of Okinawa main island, Japan. Figure 6 shows the experiment setup used at the port. Computer generated transmission (TX) signal is stored in TX-PC, which is connected to Digital Power Amplifire through USB cable. Wave file with sampling frequency of 96KHz is used to generate TX signal. TX signal is emitted from TX-Transducer into water and is received by RX-Transducer through underwater channel. Since the purpose of the experiment is to observe the signal saturation of the TX signal, the channel length used in the experiment is 1 – 2 m short distance. Detail Sea experiment parameters are listed in Table II. The received signal is amplified by the pre-amplifier and analog-to-digital conversion (ADC) is performed, then the digital signal is transferred to RX-PC to demodulate the received signal. Two transducers are sank in the sea 2m below sea surface by using the metal bar as shown in figure 7.

TABLE II. SEA EXPERIMENT PARAMETERS

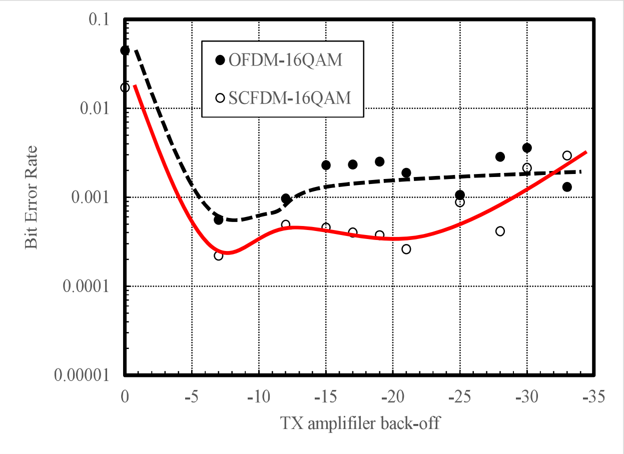
Parameters	**Value**
Experiment site	Ojima Fishing port in Okinawa
Number of Transducers	1 TX and 1 RX
Transducer Depth (TX / RX)	2 m / 2 m
Modulation	QPSK / 16QAM / 64QAM
TX-RX Distance	2 m (QPSK) and 1m (16/64QAM)
Transmission Direction	Horizontal
Ocean Depth	5 m

Fig. 7. Photo of sea experiment at Ojima fishing port in Okinawa

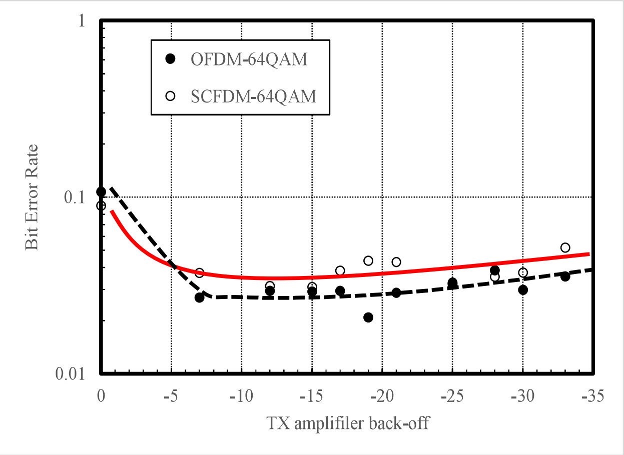
The measured BERs are shown in figure 8 (a), (b), (c). The horizontal axis corresponds to TX power amplifier back-off and 0dB corresponds the maximum output power. Values of TX amplifier back-off are determined by power amplifier used in experiment. QPSK measured BER is shown in figure 8(a). The red solid and black dashed lines smoothly connect measured points. Some points which are far from the lines are ignored since the experimentation field sometimes suffers from noises caused by ships. The small the TX power becomes in x-axis to right direction, the worse the BER becomes because of lower SNR. Then, if there is no distortion caused by TX power amplifier, the measured carve should be monotonous increasing curve. However, The higher the TX power become, the worse the BER gets similarly. This downward-convex shape is caused



(a) QPSK



(b) 16QAM



(c) 64QAM

Fig. 8. Sea experiment at fishing port

by output TX signal distortion because of the non-liminality of the power amplifier system. Comparing SC-FDM with OFDM, BER of SC-FDM is lower than OFDM by one order of magnitude at TX amplifier back-off = 0dB. In figure 8(b), 16QAM result is also shown. At the region of high TX power (left side), SC-FDM shows better result than OFDM. Finally, 64QAM measured result is shown in figure 8(c). Some small merit is observed but BER level are not good entirely because of higher modulation level and high level marine creature generating impulsive noise circumstance.

V. CONCLUSION

In this paper, we have compared SC-FDM with OFDM acoustic underwater communication system by sea experiments and computer simulations. According to the computer simulation, PAPR of the transmitted signal has been successfully reduced by 1.5-2.0 dB for various modulations. Approximately 1dB transmission power gain has been obtained for QPSK at BER of 0.005, 0.8dB and 1.0dB transmission power gain has been obtained for 16/64QAM at BER of 0.01, respectively. From the see experiment measured data, QPSK BER is decreased by one order of magnitude from OFDM to SC-FDM at the highest transmission power level. Then SC-FDM has successfully lowered the distortion of the power amplifier.

The SC-FDM is advantageous than OFDM for long-distance transmission because the peak value of transmission signal power in a time-domain is lowered by DFT spread pre-cording and it is expected that the communication distance can be extended by roughly 50%.

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