■ Paper

Experiment of Underwater Acoustic Communication with an Orthogonal Signal Division Multiplexing Scheme in a Harbor

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Abstract:

Underwater acoustic (UWA) communication is still a challenging area of research, as methods to deal with large intersymbol interference and Doppler spread are needed. We previously evaluated the performance of an orthogonal signal-division multiplexing (OSDM) scheme in a UWA communication system in a test tank and found that OSDM achieved better bit-error-rate (BER) performance than the single-carrier with decision-feedback-equalizer (DFE) method and the orthogonal frequency-division multiplexing (OFDM) method. However, no experiments have yet been conducted in an actual sea environment, which is much more complex than a test tank. In this paper, we report an initial demonstration of OSDM communication in an actual sea environment. The experiment was performed at a harbor for about 85 h by changing the transmission level. We also performed the communication using single-carrier DFE and OFDM, and confirmed that OSDM with a multichannel receiver is attractive to existing schemes; as in the test-tank results, OSDM achieved the best bit-error-rate performance compared to other schemes with practical complexity. We confirmed that OSDM can achieve a highly reliable communication for UWA channels, such as in shallow water.

Classification: signal processing

Keywords: underwater acoustic communication, multipath, Doppler

1. Introduction

Underwater acoustic communication (UWA) plays an important role for ocean exploration activities, such as data transmission for maritime observation and construction; and indeed, communication systems using phase-coherent modulation

techniques to deal with the two major challenges of intersymbol interference (ISI) and Doppler spread are a topic of active research. Multipath-induced channel spread over time causes heavy ISI to extend to over 100 symbols. Moreover, movements of the sea surface and communication platforms

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cause Doppler shifts and multiple Doppler scaling paths in the channel results for Doppler spread. Because the effect of the multipaths and Doppler spread in UWA channel is significant (several orders of magnitude compared to the radio communication), UWA communication is still a challenging area of acoustic research.

To achieve reliable communication in UWA channels, two approaches, single-carrier communication with an adaptive decision feedback equalizer (DFE) and multi-carrier communication such as orthogonal frequency division multiplexing (OFDM), have been researched. From around the 1990s, a single-carrier technique has been used to cope with ISI using adaptive equalizers such as DFE¹⁻³⁾. Moreover, it was found that the combination of DFE and array processing can increase communication quality⁴⁻¹²⁾. Although the receiver complexity significantly increases as the effect of ISI increases, the single-carrier technique achieves good communication quality even in UWA channels, and an array-processing technique can be utilized to increase communication quality with practical complexity. To follow small Doppler spreads, a phase-locked loop (also controlled by DFE) can be utilized. To cope with large Doppler spreads, the use of a channel tracker has been proposed^{13,14)}. Around the 2000s, another communication scheme, OFDM, was proposed for the use of UWA communication¹⁵⁾. OFDM is attractive because it can deal with heavy ISI with small complexity, although the resulting communication quality does not exceed that of the single-carrier method. As in the single-carrier case, the combination of OFDM and array processing has been shown to increase the communication quality, by utilizing the spatial diversity. Focusing on the effect of Doppler spread, receivers that deal with the Doppler shift have been considered¹⁶⁻¹⁹⁾.

As an alternative, we have focused on another scheme for UWA communication: orthogonal signal division multiplexing (OSDM)²⁰⁻²³⁾. The use of OSDM for UWA communication has been considered from several aspects, such as performance evaluation for heavy ISI²⁴⁾, for Doppler shift^{25,26)}, and power efficiency²⁷⁾. We have also proposed multichannel OSDM, and compared its performance with single-carrier DFE and OFDM in a test tank with and without surface waves²⁸⁾. As a result, we have found that the OSDM is attractive for UWA communication; it achieved better bit-error-rate (BER) performance than single-carrier DFE and OFDM, although its complexity was less than that of DFE with a recursive least squares (RLS) algorithm. However, no experiments have yet been conducted in an actual sea environment, which is inevitably more complex than that of a test tank.

An actual sea environment is different from a test tank in several points. The sea surface becomes an acoustic reflector which moves and changes its roughness randomly. The existence of underwater inclusions (such as bubbles) scatters the acoustic signal. The underwater noise cannot be modeled by a simple Gaussian model; there is unstable biological noise in addition to the stable noise. Moreover, the tidal effect and change of sea temperature and salinity concentration make the underwater acoustic signal propagation change over time. Therefore, the experimental results of UWA communication in an actual sea environment can help us enhance the practical performance of such a system.

This paper represents an initial demonstration of OSDM for UWA communication in an actual sea environment. The experiment was performed in a harbor for about 85 h. In this experiment, the performance of OSDM was compared to that of single-carrier DFE and OFDM with respect to communication quality under the same data rate

and signal bandwidth. This paper consists of five sections. Section 2 overviews the OSDM, single-carrier DFE, and OFDM. Section 3 shows the experimental setup. Section 4 shows the experimental results and discusses the results. Section 5 provides a conclusion.

2. Overview of OSDM, Single-Carrier DFE, and OFDM

The scope of this paper is to demonstrate communication using OSDM, single-carrier DFE, and OFDM in an actual sea environment; in this section, we provide an overview of these communication schemes.

Figure 1(a) shows a block diagram of the signaling structure of the OSDM. The transmitter calculates a multiplexed sequence by calculating the sum of the Kronecker products between the n -th row of an inverse discrete Fourier transform (IDFT) matrix, f_{Nn} , and the n -th message of length M , x_{tn} ($n=0, 1, \dots, N-1$). The first message, x_{t0} , is a receiver-known sequence and is called the pilot sequence. The sum of the multiplexed sequence is then prepended with a cyclic prefix (CP) of length L , and transmitted from the transducer. Through the UWA channel, the transmitted signal is affected by multipath, Doppler, and noise, and reaches the receiver. We assume that the length

Fig. 1 Block diagram and signaling structure of (a) OSDM, (b) single-carrier DFE, and (c) OFDM.

of the channel impulse response is L , and that the receiver employs K hydrophones. At the receiver, the receiver applies N number of matched filters (MFs) on the CP-removed sequence. The output of the first MF (MF #0) becomes a cyclic convolution of $\mathbf{x}_{t0}$ and the channel impulse response; hence, the receiver can calculate the channel impulse response by calculating the periodical cross-correlation function between the output of MF #0 and $\mathbf{x}_{t0}$. Finally, the receiver combines K sequences, and by utilizing K channel impulse responses, the transmitted messages are obtained by solving linear equations. The complexity of the receiver (multiplications per block) is on the order of $KN(M^3+M^2)$, which is necessary to solve the linear equations.

Figure 1(b) shows a block diagram and the signaling structure of the single-carrier DFE. The transmitter is far more simple than the OSDM, which simply prepends a training sequence of length A (known to the receiver) to a message of length B . The receiver obtains the transmitted message by applying multichannel DFE on K received signals. The multichannel DFE is designed to have total of $K(L+1)$ and K taps for feedforward (FF) and feedback (FB) filters, respectively, to cope with an ISI

of length L^{29} . The receiver first optimizes the taps during the training section (training mode) to minimize the effect of ISI using the RLS algorithm, and continues to update the taps during the message section (decision-oriented mode). The complexity of the receiver is on the order of $(5R^2/2+9R/2)(A+B)$, where R is the total number of the taps, $K(L+1)+L$. After the message is completely received, the receiver resets all coefficients of the taps and starts the equalization on the next block. To avoid inter-block-interference, an unsignalized section of length L is inserted between blocks.

Figure 1(c) shows a block diagram and the signaling structure of the OFDM. The transmitter calculates the inverse fast Fourier transform (IFFT) of a sequence of length PQ , and prepends a CP of length L on the output of IFFT. Focusing on the OFDM symbol in the frequency domain, the OFDM symbol has PQ subcarriers; P pilot subcarriers are inserted into the OFDM symbol uniformly with Q data subcarriers apart from each other (comb-type pilot allocation). The receiver calculates the channel impulse response in the frequency domain by interpolating the pilot subcarriers and obtains the transmitted message by performing

Table 1 Relationships among parameters, complexity, carrier frequency, signal bandwidth, block length, and data rate used in the experiment and the simulation.

Type	Parameters		Complexity	Carrier frequency, signal bandwidth, block length, and data rate
OSDM	M	127	24.7×10^6 ($K=3$)	Carrier frequency: 30 kHz Signal bandwidth: 1.2 kHz Block length: 463.3 ms Data rate (QPSK): 1.6 kbps
	N	4		
	L	48		
Single-carrier DFE	A	127	48.7×10^6 ($K=3$)	
	B	381		
	C	48		
OFDM	P	127	6.8×10^3 ($K=3$)	
	Q	4		
	L	48

Fig. 2 Map of experimental site, Hashirimizu port.

frequency-domain equalization. In the equalization process, K received signals are combined with maximal ratio combining (MRC). The complexity of the receiver is $KPQ/2 \cdot \log_2 PQ$, which remains small compared to OSDM and single-carrier DFE under the same data rate and signal bandwidth. This is because OFDM can cope with ISI only by multiplications at each subcarrier. As a result, OFDM is attractive in terms of complexity.

In this paper, we compare the performance of OSDM, single-carrier DFE, and OFDM using the same data rate and signal bandwidth, as in our previous work in an experimental tank. **Table 1** shows the relationships among parameters, complexity, carrier frequency, signal bandwidth, block length, and data rate used in the experiment. We first determined the carrier frequency and signal bandwidth considering the specifications of transducers and hydrophones. Then, we determined the value of L considering the channel spread in time (about 40 ms). Finally, the rest of parameters were determined to satisfy the same data rate. Quadrature-phase shift keying (QPSK) was used to modulate binary data to complex baseband data. The forgetting factor for the RLS algorithm was set as 0.99, which was found to achieve the best communication quality in this experiment.

Fig. 3 Vertical sectional view of the transducer arrangement in water.

The number of K is important because a large K increases the communication quality in exchange for receiver complexity. However, in previous work, it was found that performance quality plateaued as the value of K increased beyond a certain point⁽²⁸⁾. To achieve a balance between receiver complexity and communication quality, we combined three received signals for demodulation ($K=3$). Because there are four hydrophones at the receiver, we calculated three input signal-to-noise ratios (ISNRs) and BERs from a single trial (number of combinations of four signals taken three at a time).

3. Experimental Setup

3.1 Transmitter and receiver setup

The experiment was conducted in a Hashirimizu port (lat. 35°26'20"N, 139°73'40"E), which faces Tokyo Bay, for about 85 h [from 17:30 August 1 to 10:35 August 2 and from 12:06 August 2 to 9:48 August 5, 2013 (JST)]. Throughout the experiment, the weather was mild. **Figures 2 and 3** show a map of the experimental site and the arrangement of the transducers in the water, respectively. Focusing on the geometry of the experimental site, the distance between the transmitter (Tx) and the receiver (Rx) was about 120 m, as shown in Fig. 2. The sea floor

was about 6–7 m deep, measuring from ground level (GL), and the water level (WL) changed about 1.4 m during the experiment, due to the tidal effect, as shown in Fig. 3.

Focusing on the Tx side, two transducers (BII-7512, Benthowave Instrument) were fixed with a distance of 0.6 m, as shown in Fig. 3. The reason why we employ two transducers is the limitation of the power amplifier. By employing two transducers with two power amplifiers and transmitting the signal from these transducers at the same time, we could cover a wide range of transmission powers without using the non-linear domain of the amplifier. Focusing on the Rx side, four hydrophones (BII-7520, Benthowave Instrument) were placed at a distance of 0.3 m, as shown in Fig. 3. To avoid the movement of the communication platform, these hydrophones were tied up on a rung of an aluminum ladder (the spacing of rung was 0.3 m) fixed to the quay. In a multichannel receiver, the channel impulse response obtained at each hydrophone should be independent of one another, requiring a certain amount of space between hydrophones. Considering the spacing of the rungs and the tidal effect, we decided to make the spacing of the hydrophones 0.3 m. Prior to the experiment, we confirmed that there was no definite correlation among channel impulse responses obtained by the hydrophones.

The transmission signal, which was calculated on a software-defined modulator, was applied to the transducers via a digital-to-analog converter and a power amplifier. The signals received at the hydrophones were stored using an analog-to-digital converter via a pre-amplifier. The signal received from each hydrophone was stored independently to perform multichannel equalization.

3.2 Flow of the experiment

In this experiment, we repeated the following trial 195 times. The interval was 41 min for the first 25 trials and 24.6 min for the rest of the 170 trials.

The sequence of a single trial was as follows:

- Step #1. Transmit and record a probe signal [linear-frequency modulated signal from 26 to 34 (kHz)] for 4 s.
- Step #2. Transmit and record a single tone signal (30 kHz) for 8 s.
- Step #3. Record the environmental noise for 8 s.
- Step #4. Transmit and record OSDM, single-carrier DFE, and OFDM signals. Each signal contains 18 blocks (about 8 s).
- Step #5. Repeat step #1 through #4: the transmission powers of communication signals are -3 dB from sequence #4.
- Step #6. Repeat step #1 through #4: the transmission powers of communication signals are -6 dB from sequence #4.
- Step #7. Wait for the next trial.

The probe signal at step #1 was used to measure the channel impulse response. A single tone signal obtained at step #2 was used to measure the Doppler effect. The noise information obtained at step #3 was used to obtain the energy of the noise, E_n . As shown in steps #4–#6, we performed communications using OSDM, single-carrier DFE, and OFDM, and varied the amplitude of the signal, which resulted in different ISNRs. In this paper, the ISNR is defined as $(E_s - E_n)/E_n$, where E_s and E_n are the energy of the received signal and that of the noise, respectively.

3.3 Channel condition

3.3.1 Intersymbol interference

Figure 4(a) shows the change of the channel response throughout the whole experiment, which was obtained by calculating the cross-correlation

Fig. 4 (a) Obtained channel response in time domain throughout the experiment and (b) example of channel response (dotted line: channel decay profile used in simulation).

function between transmitted and received probe signals. As shown in the figure, we could confirm that the channel response had two major peaks corresponding to the direct wave and the wave reflected from the quay wall (right-hand side of the quay in Fig. 2). Figure 4(b) shows an example of the channel response. In this paper, we assume that the channel spread in time is about 40 ms, which means the length of the ISI becomes 48 symbols. As a result, the signal parameter, L , was determined as 48 in this experiment.

3.3.2 Noise

We recorded and analyzed the noise that was obtained throughout the whole experiment. **Figure 5(a)** shows the complex baseband noise [band-pass filtered (29.4 to 30.6 kHz), frequency down-converted, and sampled] obtained in the experiment. The solid and dotted lines show the real and imaginary parts of the noise, respectively.

Fig. 5 Example of the received and sampled noise (solid line, real part; dotted line, imaginary part) obtained in (a) experiment and (b) noise model in simulation (variance of N_1 : 2.5×10^{-6} and N_2 : 3.0×10^{-4}), and (c) probability density function of (a), solid line, and (b), dotted line.

The observed noise was different from Gaussian white noise; we could confirm biological noise (like a peculiar pulse sound by snapping shrimp) in addition to the Gaussian noise. As a result, a probability density function of the observed noise, as shown in a solid line in Fig. 5(c), has a long tail in addition to the Gaussian function. To simulate the noise obtained from the experiment, we assumed that the noise was the sum of two noises, N_1 and N_2 . N_1 is the static Gaussian noise and N_1 follows a normal distribution, $N(0, \sigma^2)$. N_2 is a peculiar pulse which occurs randomly by the exponential distribution and amplitude of the pulse that follows $N(0, 120\sigma^2)$. Although it has been reported that

Fig. 6 (a) Example of the received signal when a single tone (30kHz) was transmitted from the transmitter, (b) the section of (a), (c) amplitude spectrum of (a), and (d) probability density function of the maximal Doppler shift (f_d) obtained from the experiment.

the snapping-shrimp-dominated noise can be represented accurately by the symmetric alpha-stable noise³⁰⁾, the Gaussian function (also a special case of the symmetric alpha-stable noise) was found to fit the experimental results well in this work. The parameter for exponential distribution, λ , was set to have an average pulse rate of 0.63 per second as obtained in the experiment. Figure 5(b) and 5(c) show a complex baseband noise obtained from the noise model and its probability density function (dotted line), respectively. It was found that the noise model has almost the same tendency as the obtained results, and we used this noise model for the simulation that was performed to confirm the experiment.

3.3.3 Doppler spread

We also investigated the effect of Doppler spread in the experiment. We transmitted and recorded a single tone of 30kHz. **Figure 6(a)** shows a sample of the recorded signal. Although the power of the transmitted signal was uniform, the power of the received signal showed a variation over time,

which was attributed to the effect of sea surface. **Figure 6(b)** shows a part of **Fig. 6(a)**, whose length corresponds to the block length. We could confirm that the power of the received signal still changes frequently. **Figure 6(c)** shows the amplitude spectrum of **Fig. 6(a)**. As shown in the figure, the amplitude spectrum does not have a sharp peak and it seems to broaden. In this paper, we define the maximal Doppler shift, f_d , as the frequency shift at which the value of the amplitude spectrum drops 10dB from its peak. **Figure 6(d)** shows the probability density function of the maximum Doppler shift throughout the experiment. We found that the maximum Doppler shift of 0.3Hz was dominant in the experiment.

4 Results and Discussion

We performed the same communication using OSDM, single-carrier DFE, and OFDM for about 85h. **Figure 7** shows the energy of the received signal in each channel (Ch. #1 to #4), under the same signal transmission level. As shown in this

Fig. 7 Received signal power of Ch. #0–#3 obtained from the experiment.

Fig. 8 ISNRs obtained from the experiment.

Fig. 9 Relationships between ISNR and BER in the (a) experiment, and (b) simulation.

figure, the energy of the received signal changed drastically over time. Moreover, in contrast to the test-tank experimental results, the ISNRs at each channel were also different, which may have played a part in the different performances of the communication systems. One of the reasons is the complex propagation of the signal in the channel. There are several factors that would contribute to such severe fading: the effect of tidal action, changes of temperature and salinity concentration, and the existence of inclusions which cause signal scattering. We did not change the amplitude

of the communication signal that much (0 dB, -3 dB, and -6 dB in power); however, we could obtain a variety of received signal levels due to this energy change in time. **Figure 8** shows the ISNRs obtained in the experiment. As shown in this figure, we could obtain a substantial number of received signals whose ISNR values were distributed from 0 to 20 dB.

Figure 9(a) shows the relationship between ISNR and BER of OSDM, single-carrier DFE, and OFDM, obtained in the experiment. We compared the performances of the communication schemes

without any solutions (*e.g.*, channel tracker), to compare them in the simplest state. OSDM achieved better BER performance than single-carrier DFE although the complexity of OSDM was about 1/2 that of the single-carrier DFE, as shown in Table 1. This means that OSDM may be a viable alternative to single-carrier DFE in terms of both communication quality and complexity. OSDM also achieved better BER performance than OFDM. However, OFDM remains attractive in terms of complexity, because its complexity is less than 1/4000 that of OSDM. The relationships between OSDM, single-carrier DFE, and OFDM were almost the same as those obtained in the test tank, although the amplitude of the received signal at each hydrophone had larger variance. As a result, the communication schemes tested here may not be largely affected even if the ISNRs at each channel are different.

To confirm the experimental results, we also performed a baseband simulation using the parameters shown in Table 1. In this simulation, we assumed that the channel is Rayleigh-distributed, exponentially fading and that its spread time is 40 ms, as shown in the dotted line in Fig. 4(b). To simulate the noise obtained from the experiment, we used a noise model as discussed in 3.3.2. In the simulation, the channel had a maximum Doppler shift of 0.5 Hz. In contrast to the experimental results, the ISNRs at each channel were the same. Figure 9(b) shows the simulation results. Although the obtained results do not fit the experimental results accurately, we can confirm that they have the same tendency, and the advantage of multichannel OSDM was also supported by the simulation. This means that the differential of ISNRs among hydrophones does not greatly affect the communication quality, as discussed above.

To summarize, multichannel OSDM achieved

better communication quality than the other schemes tested here, as it did in our previously reported experiment in a test tank. Considering the factors of communication quality obtained from the experiment and the simulation and calculation complexity, multichannel OSDM was found to be well suited as a UWA communication scheme in shallow water.

5 Conclusions

In this paper, we made an initial demonstration of OSDM communication in an actual sea environment. We performed OSDM communication and compared its performance to that of single-carrier DFE and OFDM with respect to communication quality under the same data rate and signal bandwidth. The experiment was performed for about 85 h, and we measured the effect of ISI, noise, and Doppler throughout the whole experiment. The experiment showed that the ISNRs at each channel change drastically. However, we found that OSDM with a multichannel receiver remains attractive in terms of communication quality; it achieved better BER performance than the other schemes although its complexity is less than that of RLS-DFE. We expect that OSDM can become a viable alternative offering highly reliable communication for an UWA channel with heavy multipath, and can deal with the practical complexity of an actual sea environment.

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