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Towing Experiment for Shallow Underwater Acoustic Communication Using QPSK and DPLL

DPLL を用いた QPSK 方式による浅海域音響通信の曳航試験

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1. Introduction and Objective

The use of unmanned underwater vehicle (UUV) has increased in recent years. UUV can cover large areas using fewer resources, both budgetary and human, especially in the detection and elimination of risks on the seafloor, such as mines.

For fast and efficient sweeping on the seafloor, acoustic communication is an essential technology. To establish underwater acoustic communications in actual use, it is necessary to increase the communication speed. A speed of more than 10 kbps is needed for efficient SONAR image transmission. Recently, experiments using speeds over 120 kbps, which is close to the theoretical limit, have been carried out successfully in the deep ocean [1,2].

A continuous data link under shallow and towing conditions is also essential for UUV operation. In shallow water, inter-symbol interference (ISI) due to multipath fading strongly distorts the carrier signal. In addition, the phase of the signals shifts considerably due to the Doppler shift at a high relative speed (~ 5kt) between the mother ship and the UUV. The communication performance degrades significantly compared to static communication. Actually, a 1-kt relative speed between the transmitter and receiver causes a phase shift of more than 2 π within 1000 symbols of transported data [3].

In this study, we investigated QPSK acoustic telecommunication systems that incorporate a digital phase lock loop (DPLL) [3-5] for the Doppler shift compensation. A towing experiment was conducted in shallow water, and the performance of the system was evaluated.

2. Acoustic Telemetry Systems

Fig. 1 is a block diagram of our QPSK system that incorporates the DPLL. To correct ISI, a multi-channel decision feedback equalizer (MDFE) is added. To improve the bit error rate (BER), a turbo coder and decoder is included. To improve the frame synchronization, we applied two original schemes [6], the self-correlation both in I and Q signals using Barker code to eliminate phase error in the carrier, and multi-channel SNR averaging to detect the synchronous data placed at the data head. The DPLL is implemented in the MDFE process. Additionally, a stabilized fast transversal filter (SFTF)［7-9］ is incorporated to prevent numerical instability in the least squares routine due to the large channel inputs and taps in the DFE.

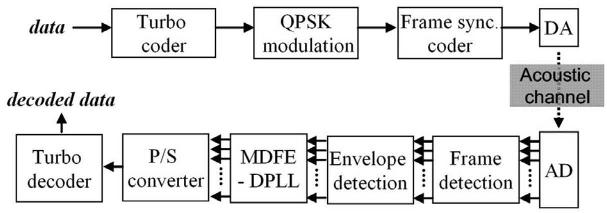

Fig. 1 QPSK systems with MDFE-DPLL.

3. Experimental Schematics

Fig. 2 is a schematic of the towing test at-sea. A towing float is wired between the barge and the ship. Previously coded and modulated signals are sent from the transmitter, and then the multi-channel hydrophone array (max. 8 ch.) receives the acoustic signals. The acquired data are stored in a PC and demodulated and decoded by an off-line MATLAB program by the algorithm depicted in Fig. 1. The center frequency of the carrier wave was 70 kHz, and the bandwidth was 20, 30, and 40 kHz. Considering the redundancy, such as the frame synchronization code, training sequence for the DFE, the puncturing of the turbo codes, and the time interval between the sequences, the actual communication speed was 17.6, 25.4, and 35.2 kbps, respectively. The distance between the transmitter and receiver was 50 – 200 m, and the towing speed was altered from 0.8 to 2.1 kt.

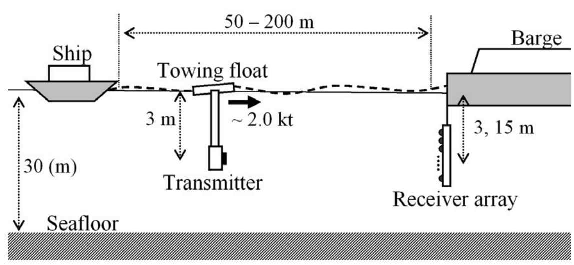

Fig.2 Schematic of acoustic telemetry experiment.

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4. Results and Discussion

Figs. 3 and **4** show the results of mean-square-error (MSE) of the equalized data and the constellation of the demodulated data, before the decoding of the turbo codes. In both, the towing speed was 1.72 kt, and the transmitter and receiver depths were 3 m. Without the DPLL, Fig. 3(a), the MSE does not converge within the 255 symbols of training sequence. In Fig. 3(b), the DPLL shows good error correction performance, and the MSE is less than 1 throughout almost all of the 2000 symbols. In Fig. 4, the constellation also shows the effect of the MDFE-DPLL. The amplitude and phase of the symbols are clearly divided into four phases of QPSK. The slight error seen in Fig. 4(b) is completely corrected by the turbo decoder that follows. **Fig. 5** shows the reconfigured image of the towing test. The original data are completely reproduced at 17.6 and 26.4 kbps. At 35.2 kbps, errors are seen in the image, and the BER on this case is 1.90×10^{-3}.

Table 1 summarizes the BER results of each towing speed and communication speed. When the receiver depth was 15 m from the surface, all of the transmitted data were completely reproduced after applying our acoustic communication algorithm. When the receiver was 3 m deep, at speeds of 1.49 and 2.02 kt, we see a considerable number of errors.

There is still room to improve the communication performance, especially in the number of taps and the length of the training sequence in the equalizer block. The degradation of DPLL performance at high speed is mainly because of the small number of taps, less than 20, which is far smaller than that in other studies [3]. The lower performance at the receiver depth of 3 m case was due to multipath fading. An increase in the training sequence, currently 255 bits, is expected to result in a greater ability to eliminate the multipath fading that appears in the long time sequence.

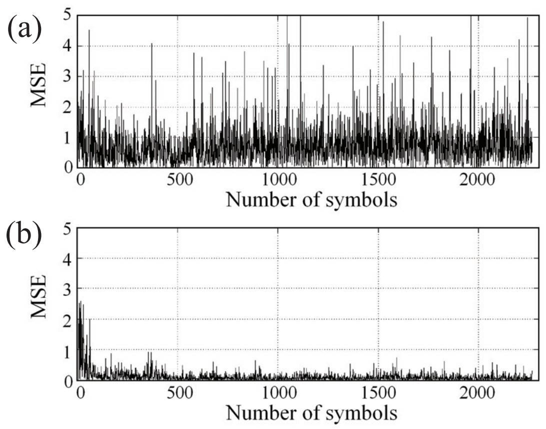

Fig. 3 Mean square error of the equalized signal (speed: 1.55 kt), (a) MDFE (b) MDFE-DPLL.

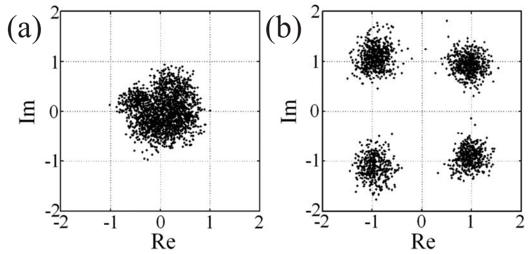

Fig. 4 Constellation of the towing test, (speed: 1.55 kt) (a) before equalization, (b) after equalization.

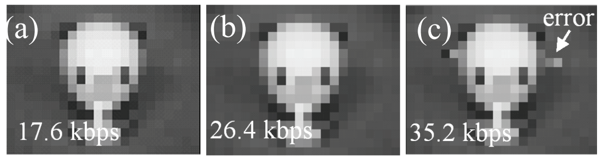

Fig. 5 Reconfigured image of the towing test, speed 1.72 (kt), Transmitter: 3 (m), receiver: 3 (m); (a) 17.6 kbps, (b) 26.4 kbps, (c) 35.2 kbps.

Table 1. BER results of towing test

Transmitter 3 (m), Receiver 15 (m)

	0.90 kt	1.55 kt	2.05 kt
17.6 kbps	No error	No error	No error
27.4 kbps	No error	No error	No error
35.2 kbps	No error	No error	No error

Transmitter 3 (m), Receiver 3 (m)

	0.82 kt	1.49 kt	2.02 kt
17.6 kbps	No error	No error	1.90×10^{-3}
27.4 kbps	No error	1.0×10^{-4}	2.97×10^{-1}
35.2 kbps	No error	2.0×10^{-3}	4.95×10^{-1}

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