EXPERIMENTAL DEMONSTRATION OF EQUALIZATION AGAINST DOPPLER SHIFTS OF MULTIPATH SIGNALS IN UNDERWATER ACOUSTIC COMMUNICATIONS

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Abstract: *In underwater acoustic communications, multipath signals, including direct signals, are affected by the corresponding temporal fluctuations and phase shifts. To follow the temporal fluctuation of a direct signal, an adaptive digital down-conversion has been proposed. Moreover, each multipath signal in an underwater acoustic channel is affected by the corresponding Doppler shift, depending on the direction of arrival and motions of terminals. To suppress the effects of phase shifts caused by the Doppler shifts individually, equalization with digital phase lock loops for multipath signals has been proposed. Previous studies have shown that both processing methods effectively work through simulations in communication between surface and underwater vehicles. In this research, both methods were applied to acoustic data from an at-sea experiment. The demodulation results shows that both methods effectively work in the real world. Particularly, the digital phase lock loops for multipath signals greatly improved the performance, indicating that the Doppler shifts of the multipath signals degraded the performance.*

Keywords: *Underwater acoustic communications, decision feedback equalizer, the Doppler shift, autonomous surface vehicle, autonomous underwater vehicle*

1. INTRODUCTION

Recently, concerns regarding mineral sources in the seabed have been growing. To efficiently survey the seabed, an operation system for multiple autonomous underwater vehicles (AUVs) along with an autonomous surface vehicle (ASV) has been proposed [1]. In this system, the ASV monitors the status and location of the AUVs using underwater acoustic (UWA) communications and positioning systems [2][3]. From an economical and operational perspective, the ASV is relatively small, measuring only a few meters in size. As a result, the ASV rolls, pitches, and heaves significantly during operation in comparison with a large mothership. The motions tend to have a period of a few seconds and cause the nonuniform Doppler shifts. Therefore, it is necessary to suppress the effects of nonuniform Doppler shifts to establish robust and high-rate UWA communication in the operation system.

In the ray theory framework, the Doppler shift of each multipath signal originates from the changes in path length caused by the movement of terminals or propagation media. These changes cause fluctuations in the received time and phase shifts through variations in propagation time. Because the relationship between the direction of arrival (DOA) of the signal and the terminal motions determines how the path length changes, a multipath signal is affected by temporal changes and time-varying phase shifts based on the DOA.

In a previous study, an adaptive down-conversion (ADDC) was proposed to suppress the effects of received time fluctuation of the direct signal for UWA communication using single-carrier modulation [4]. ADDC adjusts to changes in the received time of the direct signal according to the estimated phase shift in the decision feedback equalizer (DFE). In contrast, the DFE with additional digital phase-lock loops (DPLLs) for multipath signals was proposed to suppress the effects of phase shifts of signals other than a direct signal [5]. Both proposed techniques were individually reported to improve the demodulation performance in simulations of UWA communication between small surface and underwater vehicles in previous studies.

In this study, ADDC-DFE and DFE with additional DPLLs were extended to handle multiple channels. In addition, both techniques were applied to acoustic data from an at-sea experiment to confirm their validity.

The rest of the paper is organized as follows. Section 2 describes the extension of both techniques for multiple channels. Section 3 presents the details of the at-sea experiment. The demodulation results and discussion are presented in Section 4. Finally, the conclusions are presented in Section 5.

2. SIGNAL PROCESSING

Block diagrams of the conventional DFE, DFE with ADDC, and DFE with additional DPLLs for multipath signals are shown in Fig. 1. The equalization parameters are listed in Table 1.

As shown in the top figure of Fig. 1, the conventional DFE consists of feedforward and feedback filters and a DPLL [6]. The feedforward filter and DPLL handle the signal with the highest power; here, the peak-tap index of the feedforward filter corresponds to the received time of the signal. In vertical UWA communication, this signal corresponds to the direct signal in most cases. In contrast, the feedback filter deals with signals delayed from the signal corresponding to the peak tap of the feedforward filter. In this study, the taps of both filters were updated according to the recursive least squares (RLS) algorithm, whereas the compensation phase of the DPLL was second-order and updated according to the least mean square (LMS) algorithm.

The ADDC-DFE shown in the middle figure of Fig. 1 is the modified DFE that adjusts the DDC timing according to the DFE estimates [4]. The adjustment time $\tilde{\tau}_n$ is calculated based on the compensation phases of the DPLLs and the phases of peak taps of the feedforward filters [4][7]. In this study, the adjustment mechanism was installed in a multichannel DFE, whereas it had only been installed in a single-channel DFE in a previous study.

Finally, the DFE with additional DPLLs for multipath signals shown in the bottom part of Fig. 1 is an extended version of the DFE that compensates for phase shifts of multiple multipath signals [5]. It can handle the phase shifts of multipath signals individually because each additional DPLL is applied to the corresponding tap of the feedback filter. In this study, the additional DPLLs were of the second order and updated according to the LMS algorithm. While the additional DPLLs were installed in a single-channel DFE in a previous study, they were installed in a multichannel DFE in this study.

Notably, the ADDC can be installed in a DFE with additional DPLLs for multipath signals. The adjustment mechanism in the ADDC is calculated based on the feedforward filter, and the DPLL applied to the filter output. If the additional DPLLs improve the estimation accuracy of the feedforward filter and the other DPLL, the accuracy of the adjustment time $\tilde{\tau}_n$ is also improved; otherwise, the additional DPLLs do not affect the ADDC.

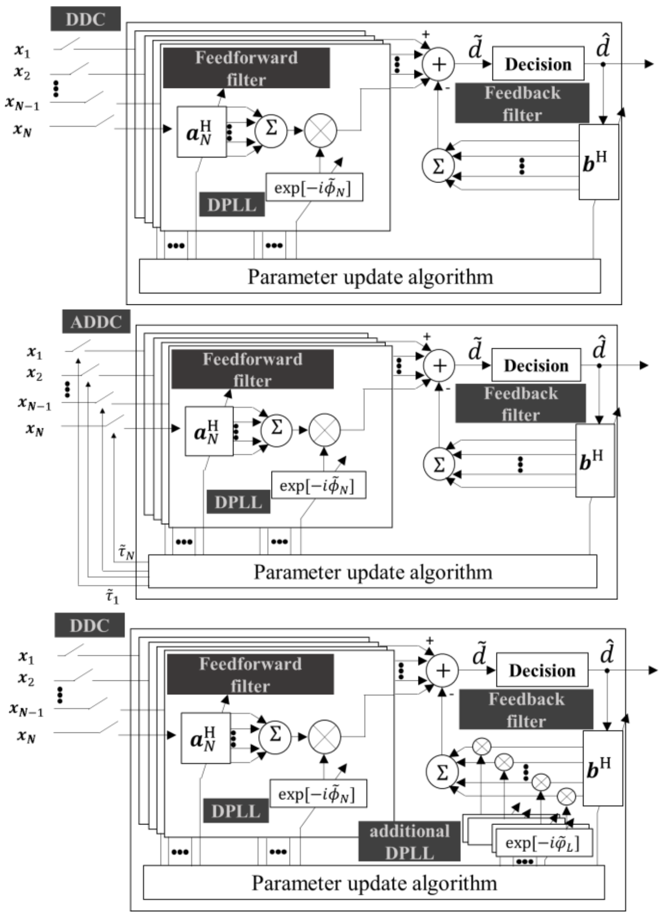

Fig. 1: Block diagrams of the conventional DFE, ADDC-DFE, and DFE with additional DPLLs in order from top.

Variables	Description
$\boldsymbol{x}_n$	Input data for the *n*th channel
$\boldsymbol{a}_n$	Taps of a feedforward filter for the *n*th channel
$\boldsymbol{b}$	Taps of a feedback filter
$\tilde{d}$	Estimates of the data symbol
$\hat{d}$	Decision of the data symbol
$\tilde{\phi}_n$	Compensation phase of the DPLL applied to the output of the feedforward filter for the *n*th channel
$\tilde{\tau}_n$	Adjusted time of the ADDC for the *n*th channel
$\tilde{\varphi}_k$	Compensation phase of the additional DPLLs applied to the *k*th tap of the feedback filter

Table 1: Equalization parameters.

3. AT-SEA EXPERIMENT

In this study, acoustic data recorded in a previous at-sea experiment were evaluated.

In the experiment, the source was moored at a depth of 1720 m and a receiver array with five elements was embedded at the bottom of the small ASV, as shown in Fig. 2. The experiment was conducted to investigate the vertical UWA communication.

During the measurement, the source transmitted a test signal at intervals of 10 s, while the receiver side recorded the data continuously. The ASV cruised along a programmed circular line. The rotational speed of the thruster was controlled as the ASV operated at speeds of 2, 3, 4, and 0 knots under a static condition.

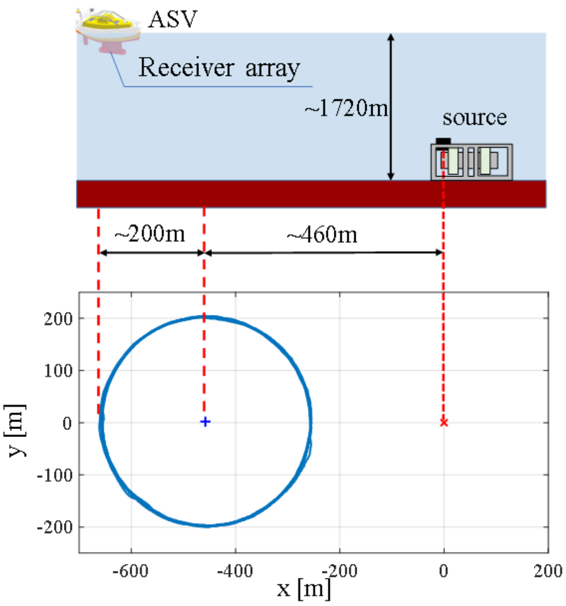

Fig. 2: Relationship among a source, a receiver array, and the cruising line.

The carrier frequency and bandwidth of the test signal were set to 20 and 8 kHz, respectively, and the length of the signal was 820 ms. Furthermore, synchronization signals, specifically Zadoff-Chu signals, were located at the start and end of the signal to detect and measure the received signal length caused by the uniform Doppler shift of the direct signal. For demodulation, down-conversion timing in the DDC and replica frequency were adjusted based on a uniform Doppler shift [4]. In addition, a linear frequency modulation (LFM) signal was transmitted between the test signals to measure channel responses. The central frequency and bandwidth were set to the same values as the test signals.

4. EXPERIMENTAL RESULTS AND DISCUSSION

The measured channel response for an element of the receiver array is depicted in Fig. 3, where the amplitudes of the multipath signals are represented in decibels with reference to the direct signal at a delay of 0 ms. Fig. 3 clearly shows that direct and other multipath signals were received. Based on the geometry, the responses with delays of 2 and 9 ms corresponded to the surface-reflected and bottom-reflected signals, respectively. Because the ASV ran along a circular line, as shown in Fig. 2, the DOA of the signals for the receiver array depended on the course of the ASV. Therefore, the responses in Fig. 3, specifically that of the bottom-reflected signal, varied periodically.

For the demodulation performance with DFEs, the output SNRs at different times of day and histograms are shown in Figs. 4 and 5, respectively. They clearly show that the additional DPLLs for multipath signals improve the demodulation performance, while the output SNRs of ADDC-DFE are close to those of the conventional DFE. The results indicate that the phase shift of the multipath signals severely affects demodulation with the conventional DFE in comparison with the temporal instabilities of the direct signal.

Some output SNRs of the ADDC-DFE were lower than those of the conventional DFE. It is because the DFE cannot estimate the phase shift of the direct signal with sufficient accuracy. The ADDC follows the fluctuation of the received time based on the estimated phase shift; hence, ADDC can degrade the demodulation performance when it is difficult for the DFE to estimate the phase shift [4].

As shown in Fig. 5, ADDC-DFE with additional DPLLs for multipath signals offers better demodulation performance than the other DFEs. It implies that the additional DPLLs can be combined with the ADDC, which is in accordance with the principle. As ADDC requires the correct estimation of the phase shift of the direct signal for DFE, the best combination among the processing methods will depend on the actual channel responses for UWA communication.

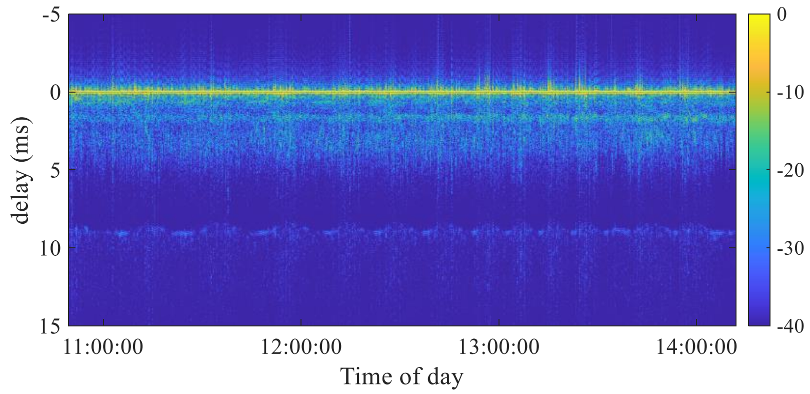

Fig. 3: A time-series channel response for an element of the receiver array.

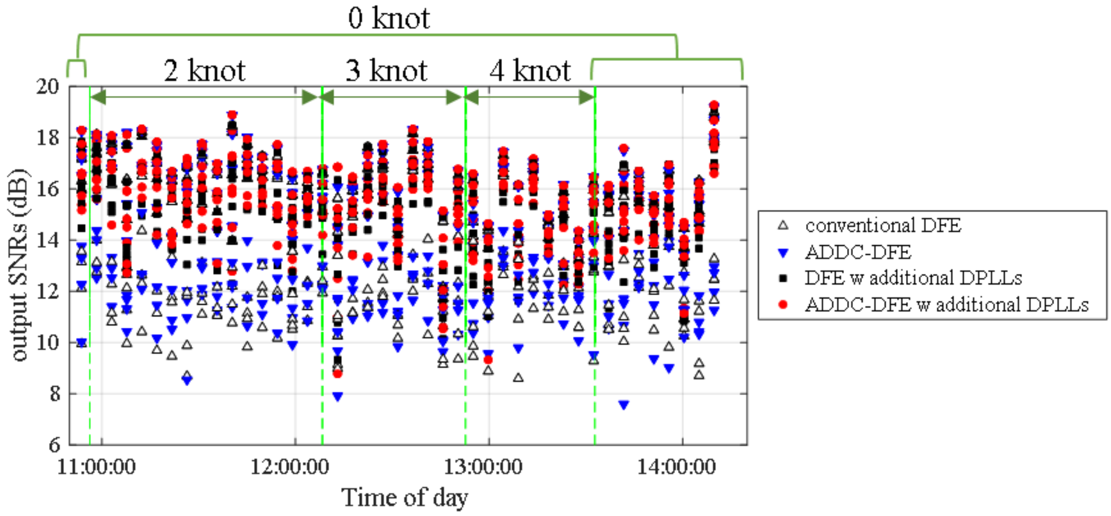

Fig. 4: Output SNRs at various times of the day.

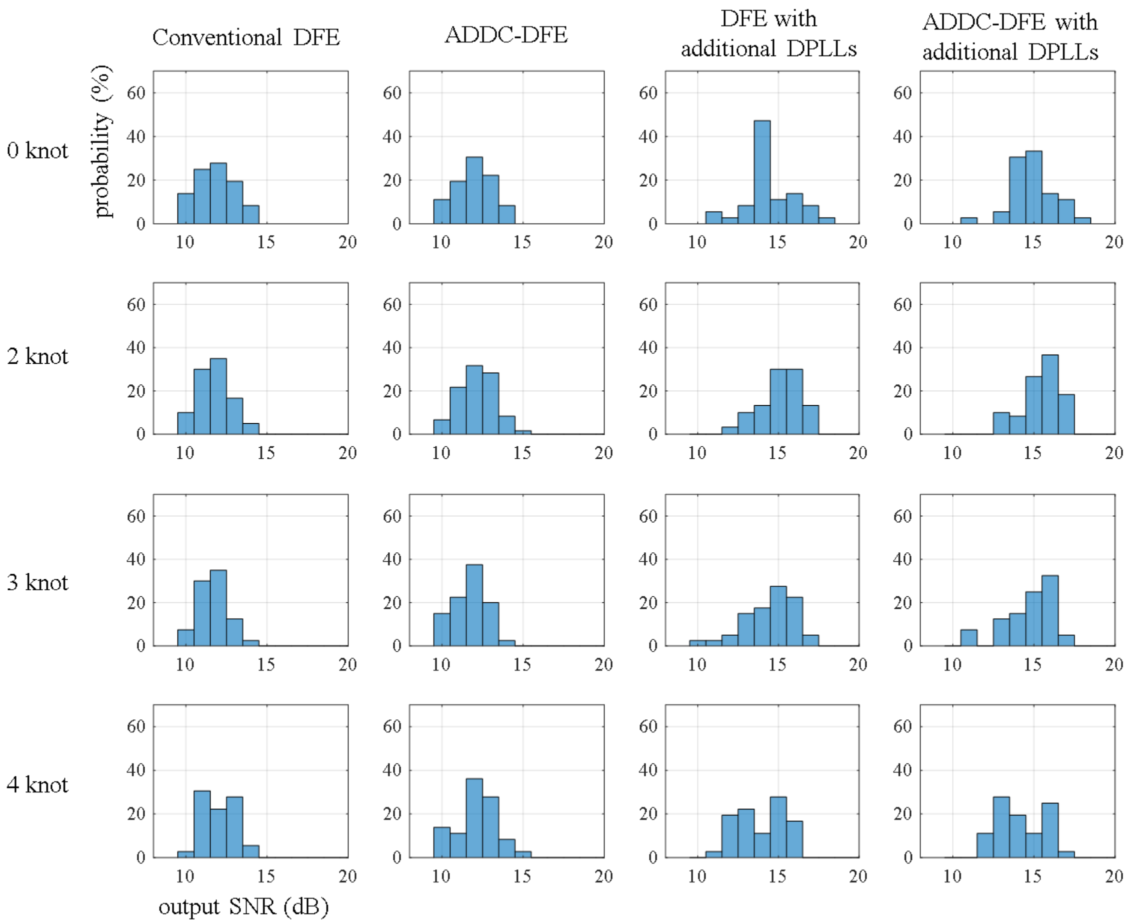

Fig. 5: Probability distribution of output SNRs for DFEs on demodulation at various thruster speeds.

5. CONCLUSION

Recently, an adaptive digital down-conversion and decision feedback equalizer with additional digital phase-lock loops for multipath signals have been proposed to suppress the effects of the received time instabilities of the main power signal and the phase shifts of the other signals, respectively.

In this study, both processing methods were extended for multiple receivers, whereas methods used in previous studies were derived for a single receiver. In addition, both methods were applied to acoustic data from an at-sea experiment, and were found to be effective in demodulation. Furthermore, using additional digital phase-lock loops significantly improved the demodulation performance compared to adaptive digital down-conversion. These results indicate that the dominant factor that degrades demodulation is the phase shift of multipath signals other than that of the main power signal. Furthermore, the demodulation results showed that both processes could be combined. Therefore, this study indicates that the best combination of processing methods depends on the channel responses.

ACKNOWLEDGMENTS

This work was supported by JSPS KAKENHI, Grant No. 18K13946.

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