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Adaptive symbol time adjustment for underwater acoustic communication with nonuniform Doppler shift

非定常ドップラーシフトを伴った水中音響通信における逐次的シンボル時間調整処理

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1. Introduction

In underwater acoustic communication (UWAC), the Doppler shift degrades demodulation performance severely due to the low propagation speed. Particularly, the nonuniform Doppler shift can be one of the severest challenges.[1,2] Meanwhile, demand to survey a sea bed with an autonomous underwater vehicle (AUV) and a small surface vehicle has grown recently. In this survey system, the nonuniform Doppler shift can degrade acoustic signals severely even if no multipath signal is received.[2]

The nonuniform Doppler shift causes two challenges for UWAC: time-varying phase shifts and change in received time of data symbols. To deal with such phase shifts, a decision feedback equalizer (DFE) has been utilized in UWAC.[1-3] However, when the nonuniform Doppler shift affects acoustic signals severely, the received time of data symbols also change largely. In some cases, the change in the received time causes in degradation of demodulation performance even if the DFE is applied. In this study, an adaptive processing to estimate and compensate for the change in the received time of the data symbols is proposed. In addition, improvement of demodulation performance that the proposed processing yields is investigated by simulation.

2. The Doppler shift and symbol time adjustment

When no multipath signal is recceived, a received signal $y(t)$ is written as

$$y(t) \;= a\,x(t-\delta\tau(t)) + \upsilon(t), \qquad (1)$$

where a, x, $\delta\tau$ and υ denote an amplitude, a transmitted signal, the time-varying propagation time and a noise component, respectively. Assuming that the baseband signal including data symbols and the carrier frequency are denoted as $X(t)$ and f_c, the transmitted signal $x(t)$ can be written as $x(t) = \mathrm{Re}\{X(t)\exp[if_\mathrm{c}t]\}$. Therefore, the received signal $y(t)$ is derived as

$$\begin{aligned} y(t) \;&= a\,\mathrm{Re}\{X\big(t-\delta\tau(t)\big) \\ &\quad\times \exp[if_\mathrm{c}t - j\varphi(t)\,]\} + \upsilon(t), \end{aligned} \qquad (2)$$

where $\varphi(t) = f_\mathrm{c}\delta\tau\,(t)$ denotes the phase shift caused by $\delta\tau$.

As stated in Sect. 1, the DFE is commonly utilized for demodulation in UWAC. It is composed of a feedforward filter, a feedback filter and a digital phase lock loop (DPLL). The feedforward filter and the DPLL compensate for a channel response of the direct signal, and the feedback filter compensates for responses of multipath signals. Taps of both filters and a compensation phase of the DPLL are adaptively updated at a symbol rate.[1, 2] Specifically, the pahse shift of the direct signal φ is adaptively estimated and compensated for by the feedfoward filter and the DPLL. It means that the estimate $\tilde{\varphi}$ can be derived from the estimates of the feedfoward filter and the DPLL.[1]

In this study, the estimate of $\delta\tau$, which is denoted as $\widetilde{\delta\tau}$, is calculated according to $\widetilde{\delta\tau} = \tilde{\varphi}/f_\mathrm{c}$. Furthermore, the input timing for the DFE is adjusted at the digital down converter (DDC) by using the estimate $\widetilde{\delta\tau}$. It yields capability to track change in received time of data symbols and improves the demodulation peformance. In this paper, the DFE with the input timing adjustment is called the adaptive symbol time adjustment DFE (ASTA-DFE). The Block diagram of the ASTA-DFE is decpited in **Fig. 1**. It is worth to note that the ASTA-DFE coincides with a conventional DFE when $\widetilde{\delta\tau}$ is fixed as 0.

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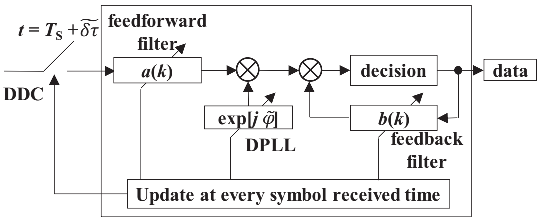
3. Simulation description

In this study, simulations of UWAC communication between a moored source and a receiver of a surface vehicle with a roll motion were



T_S: an inverse of a symbol rate
$\widetilde{\delta\tau}$: estimated change in received time of each symbol

Fig. 1 Block diagram of ASTA-DFE.

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carried out. Figure 2 shows the simulation condition. In this simulation, the roll motion of the vehicle was assumed as a simple harmonic motion (SHM) with a roll angle $\theta_r = \theta_{max} \sin(2\pi\ t/T_r + \phi)$, where θ_{max}, T_r and ϕ denote the maximum of the angle, a roll period and an initial phase of the SHM, respectively. In propagation simulation, a propagation time of the direct signal at each discrete time was calculated according to the ray theory. Received signals were derived by the propagation time and transmitted signals. In addition, no multipath signal was assumed in this study. The signal configuration is depicted in **Fig. 3**.

As updating algorithm for the DFE, recursive least square (RLS) algorithm was adapted. In addition, an output signal-to-noise ratio (SNR) was utilized to evaluate demodulation performance.[1-3] The simulation parameters are listed in **Table 1**.

4. Results and discussion

Figure 4 shows output SNRs for various initial phases of the SHM ϕ. As shown in **Fig. 4**, the ASTA-DFE marks demodulation performance better than that of the conventional DFE. It indicates that the ASTA-DFE works well in all cases in this simulation. However, difference between output SNRs of the ASTA-DFE and the conventional DFE is not constant. Specifically, the difference at ϕ=30° is small in comparison with the results at ϕ=90°, 200° and 310°. It comes from the dominant factors to degrade demodulation performance. According to a previous study, the dominant factor is the time-varying phase shift when ϕ=30°.[2] Meanwhile, phase tracking performance of the ASTA-DFE essentially equals to that of the conventional DFE. Therefore, the output SNR of the ASTA-DFE marks near that of the conventional DFE when the dominant factor is the time-varying phase shift.

On the other hands, when ϕ=90°, 200° and 310°, phase shifts vary slowly and the effects are suppressed effectively by the DPLL.[2] In the cases, the nonuniform Doppler shift degrades the demodulation performance via change in the received time of each data symbol. In case of the conventional DFE, the feedforward filter has to track the change. On the other hands, in case of the ASTA-DFE, the DDC tracks the change based on compensation phases of the DPLL. Therefore, it can track the change in the received time of each symbol as fast as phase shifts, and it results in improvement of the demodulation performance.

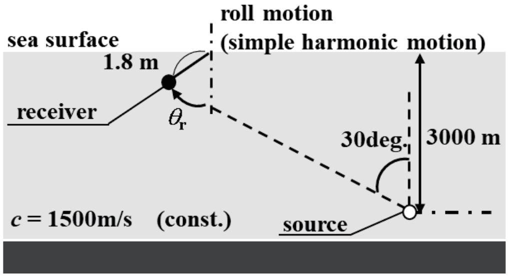

Fig. 2 Simulation condition.

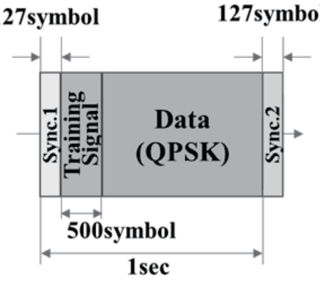

Fig. 3 Signal configuration.

Table 1 simulation parameters

parameters	description	value
F_{sym}	Symbol rate	5kHz
F_s	Sampling rate	400 kHz
θ_{max}	Maximum of θ_r	20°
T_r	Roll period	3 s
ϕ	Initial phase of SHM	0° to 355° at every 5°
f_c	Center frequency	20 kHz

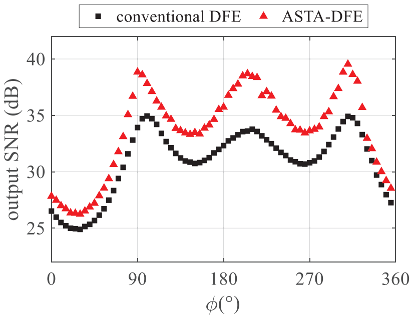

Fig. 4 output SNRs of the conventional DFE and the ASTA-DFE.

5. Summary

In this study, a signal processing to estimate and compensate for change in received time of each data symbol was proposed in order to suppress the nonuniform Doppler shift of a direct signal. In addition, it was confirmed that the proposed processing improves demodulation performance by simulation.

Acknowledgment

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