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Effects of nonuniform Doppler shifts on underwater acoustic communication with a rapidly moving terminal in shallow water

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1. Introduction

Generally, underwater acoustic communication (UWAC) is characterized by a multipath environment and Doppler shifts as severe double-selective channels. Specifically, the Doppler shifts severely affect demodulation performance due to a slow propagation speed. In addition, a physical nature of seawater limits a usable bandwidth depending on a communication range, which leads to long signal lengths for UWAC. Such long lengths cause the time-varying Doppler shifts.

In terms of demand, the UWAC with a rapidly moving terminal in shallow water is required to explore the seafloor with underwater vehicles efficiently. For the stable exploration, the UWAC must cover the area as wide as the survey coverage of the vehicle. On the other hand, demodulation performance is highly dependent on positions of the vehicles as well as speeds because the positions significantly affect the Doppler shifts of multipath signals and the temporal instabilities.

In this study, demodulation performances were evaluated by simulations under conditions with various positions of a sending terminal. For the simplicity, the linear uniform motion (LUM) was assumed in this study. The demodulation results show that the configuration of terminals significantly relates to the dominant cause limiting the performance, and that signal processing methods suitable for individual situations are required against the temporal instabilities of signals.

2. Channel model and decision feedback equalizers

Let $x(t)$ and $y(t)$ denote transmitted and received baseband signals, respectively. Then, $y(t)$ can be represented as

$$y(t) = e^{i\phi_{\mathrm{d}}(t)} \sum_m A_m(t) x(t-\tau_m(t)) e^{i\phi_m(t)}, \quad (1)$$

where $A_m(t)$ and $\tau_m(t)$ stand for an amplitude and propagation time for the m th multipath signal, respectively[1]. In addition, $\phi_{\mathrm{d}}(t)$ and $\phi_m(t)$ are defined as the residual phase shifts of a direct signal after a digital down-convertor (DDC) and differences between the phase shifts of the direct and the m th multipath signal. It means $\phi_0 = 0^\circ$ when $m=0$ is defined as an index of the direct signal. Generally, the propagation time of the direct signal $\tau_0(t)$ can be decomposed into the offset τ_{offset}, the linear term $\beta(t-\tau_{\mathrm{offset}})$ and the residual term $\tau_{\mathrm{nl}}(t)$. The term β represents a dilation/compression ratio caused by the uniform Doppler shift and is calculated using the measured signal length. Then, carrier frequency offset is calculated as βf_{c} with the carrier frequency f_{c}, and $\phi_{\mathrm{d}}(t) = -2\pi f_{\mathrm{c}} \tau_{\mathrm{nl}}(t)$ holds.

In general, a LUM nonlinearly changes path lengths of multipath signals. Therefore, the phase shifts $\phi_{\mathrm{d}}(t)$ and $\phi_m(t)$ can also vary nonlinearly. However, the changes in the incident angles of multipath signals are small and can be approximated by linear variations when a horizontal range is large. In contrast, the phase shifts nonlinearly vary through the changes in the angles when the terminals are close to each other.

3. Simulations

Propagation simulations were carried out according to the ray theory. Reflectance and attenuation for multipath signals were calculated based on acoustic impedances and propagation losses according to spherical spreading, reflectively[2]. Only the reflectance of the sea surface was set to -3 dB regardless of the incident angle. The configuration is depicted in **Fig. 1**. As shown in the figure, five multipath signals were considered: direct, surface-reflected (s-reflected), bottom-reflected (b-reflected), bottom-surface reflected (bs-reflected) and surface-bottom reflected (sb-reflected) signals.

As a test signal, binary phase-shifts keying (BPSK) signals were used with a bandwidth of 10 kHz, a carrier frequency of 20 kHz and 9932 data symbols. The preamble length was set to 6.3 ms.

In demodulation procedures, the uniform Doppler shifts were estimated by measuring the signal length with detections of preamble and postamble. Based on the estimates, the replica frequency and down-sampled interval in a DDC were adjusted. As an equalizer, the four kinds of

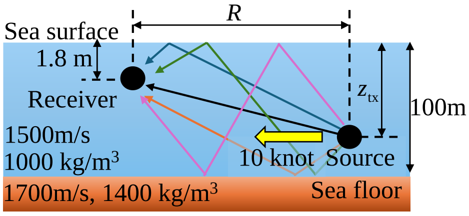

Fig. 1 The simulation condition

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decision feedback equalizers (DFEs) combined with the 2nd order digital phase locked loop (DPLL) were used: a standard DFE, DFE with an adaptive DDC (ADDC)[3], DFE with DPLLs for feedback filter taps (FBDPLL)[4] and the combination (ADDC-FBDPLL)[5]. The ADDC adaptively adjusts down-sampled timing based on an estimate of $\tau_{\mathrm{nl}}(t)$, the FBDPLL compensates for $\phi_m(t)$. The numbers of the feedforward and feedback filter taps were set to 33 and 160, respectively. The taps were updated according to the recursive least square algorithm.

4. Results and discussions

Output signal to noise ratios (SNRs), delays from the direct signals for multipath signals and averages of relative amplitudes A_m / A_0 are listed in **Table 1**, **Table 2** and **Table 3**, respectively.

Table 1 indicates that the ADDC improvement is small when $R = 1000$ m. Although the improvements are apparently different from each other in dB units, they commonly correspond to a 0.3 % decrease in errors with reference to the signal power. This is because the Doppler shift of the direct signal can be regarded as uniform when the terminal is far enough away from the other terminal.

Furthermore, the ADDC could not avoid estimation collapse when $R = 0$ m and $z_{\mathrm{tx}} = 10$ m. In this case, the temporal change in the s-reflected signal dominantly degraded the performance. As shown in Table 2 and Table 3, only the s-reflected signal had a large amplitude, and the delay varied significantly. Notably, even in this case, the ADDC improved the performance when combined with FBDPLL. This is because the FBDPLL sufficiently compensated for the phase shift of the s-reflected signal and avoided the estimation collapse. It means that the ADDC improve the performance when the term $\tau_{\mathrm{nl}}(t)$ limits the performance.

On the other hand, the results also show that it was difficult for the FBDPLL in two cases: one with $R = 0$ m and $z_{\mathrm{tx}} = 90$ m, and the other with $R = 1000$ m and $z_{\mathrm{tx}} = 90$ m. In both cases, delays of the other multipath signals than the direct signal did not vary greatly. In the other words, the FBDPLL effectively worked when the delays of multipath signals which had an impact on the performance varied significantly. It means that the FBDPLL successfully compensated for the time-varying phase shifts of the multipath signals when required.

4. Conclusion

UWAC is characterized by multipath environment and the Doppler shifts. Specifically, motions of terminals cause the nonuniform Doppler shifts based on the configuration of the terminals.

In this study, it was investigated by simulations how the configuration affects the demodulation performance in UWAC. The results show that the Doppler shifts of multipath signals highly depend on the configuration, and that demodulation methods appropriate for situations, including the Doppler shifts, are required.

Table 1 relationship of output SNRs and position

R	0 m		1000 m	
z_{tx}	10 m	90 m	10 m	90 m
DFE	1.0 dB	19.9 dB	31.0 dB	17.6 dB
ADDC-DFE	1.2 dB	20.9 dB	32.2 dB	17.8 dB
FBDPLL-DFE	19.2 dB	19.5 dB	36.9 dB	17.3 dB
ADDC-FBDPLL-DFE	23.8 dB	20.8 dB	39.7 dB	17.5 dB

Table 2 relationship of delays and position

R	0 m		1000 m	
z_{tx}	10 m	90 m	10 m	90 m
s-reflected	2.1 to 2.3 ms	2.4 ms	0.02 ms	0.2 ms
b-reflected	119 to 120 ms	13.3 ms	11.7 ms	1.3 ms
sb-reflected	132 to 133 ms	133 ms	14.3 ms	24.5 to 24.7 ms
bs-reflected	122 ms	15.7 ms	12.1 to 12.2 ms	1.6 ms

Table 3 Averages of relative amplitudes A_m / A_0

R	0 m		1000 m	
z_{tx}	10 m	90 m	10 m	90 m
s-reflected	-0.51	-0.68	-0.71	-0.71
b-reflected	0.01	0.18	-0.25	-0.47
sb-reflected	-0.01	-0.05	0.15	0.06
bs-reflected	-0.01	-0.13	0.17	0.33

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