Evaluation of Image Transmission for Underwater Acoustic Communication

Seung-Woo Lee, Byung-Woong Choi, Chang-Hong Shin, Jeong-Soo Kim, and Kyun-Kyung Lee
School of Electrical Engineering and Computer Science, Kyungpook National University, Daegu, Korea
Tel : +82-53-940-8846 Fax : +82-53-950-5505 E-mail : kklee@ee.knu.ac.kr

Abstract: Underwater acoustic(UWA) communication is one of the most difficult field because of several factors such as multipath propagation, high temporal and spatial variability of channel conditions. Therefore, it is important to model and analyze the characteristics of underwater acoustic channel such as multipath propagation, transmission loss, reverberation, and ambient noise. In this paper, UWA communication channel is modeled with a ray tracing method and applied to image transmission. Quadrature phase shift keying(QPSK) and multichannel decision feedback equalizer(DFE) are utilized as phase-coherent modulation method and equalization technique, respectively. The objective is to improve the performance of vertical sensor array than that of single sensor in the viewpoint of bit error rate(BER), constellation output, and received image quality.

About Underwater acoustic communication, QPSK, Adaptive beamformer, Adaptive equalizer

1. INTRODUCTION

Underwater acoustic(UWA) communication is a rapidly growing field of research and engineering, driven by the expansion of various application areas such as telemetry and telephony, remote control, speech, or image transmission which require underwater data transmission without wired connections. Wireless underwater communications can be established by transmission of acoustic waves. Radio waves are of little use because they are severely attenuated, while optical waves suffer from scattering and need high precision in pointing the laser beams [2].

UWA communication is one of the most difficult field because of several factors such as multipath propagration, very limited bandwidth, high temporal and spatial variability of channel conditions. Through the UWA channel, the transmitted signals can be reflected and scattered from the surface and bottom, and refracted by variations in the sound velocity profile(SVP). Therefore, considering multipath propagation is important. Multipath propagation in UWA channels causes intersymbol interference(ISI) in the transmission of digital communication signals. An increase of the transmission rate in a multipath channel results in longer ISI, which ultimately limits the performance of a phase-coherent digital communication system. As a result, it is important to model and analyze the characteristics of UWA channel such as multipath propagation, transmission loss, reverberation and ambient noise.

High-speed UWA communication using sensor array requires computationally intensive receiver algorithm. The size of adaptive filters, determined by the extent of ocean multipath, increases with signaling rate and limits system performance through large noise enhancement and increases the sensitivity of computationally efficient algorithms to numerical errors. To overcome these limitations, reduction in receiver complexity is achieved by beamforming. The beamfoming approach leads to a receiver of lower complexity and reduces multipath effect.

In this paper, UWA communication channel is modeled with a ray tracing method and applied to image transmission using vertical sensor array. Quadrature phase shift keying(QPSK) and decision feedback equalizer(DFE) are utilized as phase-coherent modulation method and equalization technique, respectively. Also beamfoming approach is applied to array signal processing. This paper demonstrate the improved performance of transmission using vertical sensor array in the viewpoint of BER, constellation, and received image quality.

2. UNDERWATER ACOUSTIC CHANNEL

For UWA communication, transfer characteristic of underwater channel is represented in the impulse response function as

$$h(\tau,t)=\sum_{k=1}^{K}a_k\delta(t-\tau_k)e^{j\theta_k}, \quad k=1,\cdots,K. \qquad (1)$$

In this function, K is the number of multipath, and a_k, τ_k, θ_k are the magnitude of each path, time delay, and phase, respectively [2].

To obtain each parameter of channel transfer function it needs to know transmission path of sound and its loss. In this paper, analysis of transmission path is done with ray tracing that uses range independent SVP [5].

Plus, transmission loss along the propagation path is computed taking account of spreading loss, surface reflection, bottom reflection, and absorption loss.

Spreading loss of sound propagation from r_0 to r_1 is obtained by

$$\frac{I_1}{I_0}=\frac{2\pi r_0 l_0}{2\pi r_1 l_1}=\frac{r_0(|z_{0,i-1}-z_{0,i}|+|z_{0,i}-z_{0,i+1}|)\cos\theta_0}{r_1(|z_{1,i-1}-z_{1,i}|+|z_{1,i}-z_{1,i+1}|)\cos\theta_1}. \qquad (2)$$

Bottom reflection uses a loss coefficient that classified by bottom state, frequency, and incident angle by Weinberg. Surface reflection loss uses the equation parameterized with reflection loss of sea state that is obtained experimentally from sea data by Marsh [6]. It is given by

$$\alpha_s=-10\log[1-0.0234(fH)^{\frac{3}{2}}], \qquad (3)$$

where f is the frequency(kHz), and H is the average wave height(ft).

Absorption loss caused by medium uses the equation proposed by Thorp that is widely used sound analysis in underwater [5]. That is represented by

$$\alpha=\frac{0.1f^2}{1+f^2}+\frac{40f^2}{4100+f^2}+2.75\times10^{-4}f^2+0.003, \qquad (4)$$

where α is the attenuation coefficient(dB/kyd), and f is the frequency(kHz). The constant 0.003 has been added to take care of the attenuation at very low frequencies.

Considering these whole causes of propagation loss, sound pressure varying with tracking ray is given by

$$I_{r_1,z_1}=\eta_{sp}(\eta_{surf})^{n_{surf}}(\eta_{bot})^{n_{bot}}10^{-\alpha S/10}I_{r_0,z_0}, \qquad (5)$$

where n_{surf}, n_{bot} are the number of the surface reflection and bottom reflection, respectively, and η_{sp}, η_{surf}, η_{bot} are the spreading loss, surface reflection loss, and bottom reflection loss, respectively. α is the absorption loss(dB/kyd), S is the length of transmission path(kyd).

Also, ambient noise due to wind is modeled by equation (6) that is obtained experimentally by Kundsen [7] as follows

$$NL=-17.13\log f+40+20\log v, \qquad (6)$$

where f is the frequency(Hz), and v is the wind speed(knots).

3. MODULATION OF DIGITAL SIGNAL

Modulation methods of digital signals are categorized broadly in two groups. The one is noncoherent modulation such as frequency shift keying(FSK), the other is coherent modulation such as phase shift keying(PSK), quadrature amplitude modulation(QAM).

Noncoherent modulation is used widely because it is easy to design transmitter(TX) and receiver(RX). But it is not suitable for complex channel characteristic and severely bandlimited underwater channel. Thus for underwater communication coherent modulation, which uses phase difference with single frequency, is mostly used. Coherent modulations are grouped by PSK that use phase only and QAM that use both phase and amplitude.

PSK modulation sends the information with carrier phase through the communication channel. Since phase variation of carrier is $0\le\theta\le2\pi$, carrier phase is $\theta_m=2\pi m/M$, $m=0,1,\ldots,M-1$, where M is the number of carrier phase for transmission of digital information using phase modulation. Representation of M carrier phase modulation signals are given by

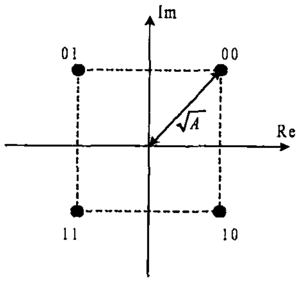


Fig. 1. Constellation of QPSK signal.

$$u_m(t)=Ag_T(t)\cos(2\pi f_c t+\frac{2\pi m}{M}), \qquad (7)$$

where $g_T(t)$ represents the pulse of transmission filter, and decides spectrum characteristic of transmitted signal. Also A is an amplitude of signal. All PSK modulation signals have same energy.

QPSK, one of the PSK modulation, has four carrier phases, $\theta_0=0$, $\theta_1=\pi/2$, $\theta_2=\pi$, and $\theta_3=3\pi/2$. Fig. 1 shows the constellation of QPSK signal [4].

4. TRANSMITTER AND RECEIVER

4.1. Transmitter

Fig. 2 is a block diagram of whole TX and RX. TX is composed of basic structure generally used in digital communication. In the encoder, source data(image) is transformed into binary code. And then these binary information is mapped into complex symbol composed of I(Inphase) and Q(Quadrature) channels in mapper. These complex symbols are filtered by pulse shaping filter(PSF). PSF uses square root raised cosine filter that is used widely. In the simulation the roll-off factor of PSF is set to 0.2. And filtered symbols are modulated by carrier frequency f_c.

UWA channel experiences transmission loss due to range and carrier frequency. Accordingly power amp is needed to compensate the loss and is used to transmit high power output.

4.2. Receiver

In the RX a vertical line sensor array is used to utilize the adaptive beamfoming for the better performance of RX than single sensor setup. The system which has been developed to alleviate the multipath problem by spatially filtering the signal arrivals to remove all but one of the received signals. This is accomplished by using an adaptive receiving beamformer as shown in Fig. 3. This system attempts to minimize the mean square error between a reference signal and the array output by using weight adjustment algorithm [8].

Received signals through the UWA channel are multiplied by $\cos(2\pi f_c t)$ and $\sin(2\pi f_c t)$ to each sensor. And these are demodulated to I channel and Q channel signals. In this phase, each sensor output is low-pass filtered. Matched filter block is processed as a inverse processing of PSF. Next beamfoming and adaptive

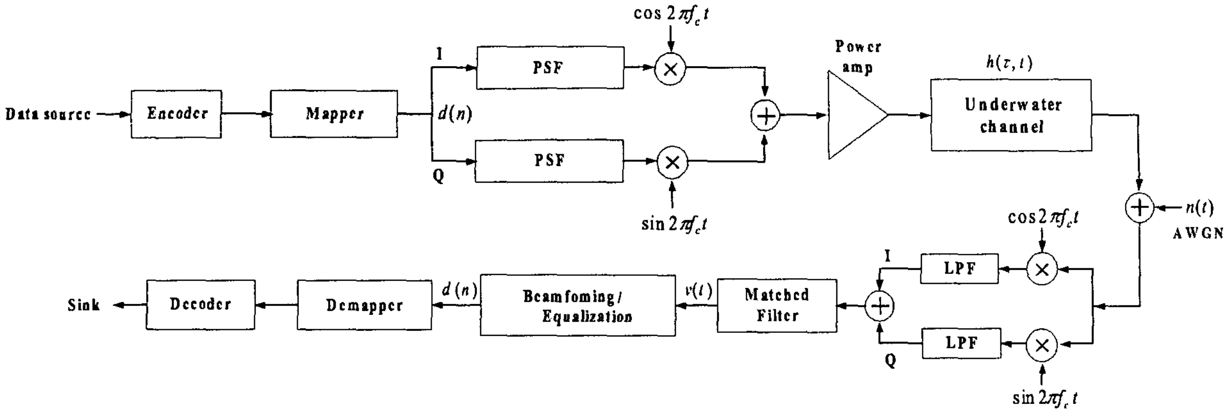


Fig. 2. Block diagram of transmitter and receiver.

equalization estimate UWA channels and reconstruct original signal from multipath. A reconstructed signal $d(n)$ is a transformed signal in mapper block of TX. Thus demapper maps complex symbol to binary data. And decoder reconstruct original data source.

4.2.1. Adaptive beamformer and equalizer

In the UWA channel an indirect path signal may arrives earlier than the direct path owing to SVP. Therefore we need to separate indirect and direct paths to follow up the variance of UWA channel. In this paper we use adaptive DFE composed of feedforward filter and feedback filter. Feedforward Filter compensates ISI for each symbol utilizing beamformer output and feedback filter minimizes the error between previous decision and present decision.

Fig. 3 shows the adaptive beamformer and DFE block diagram. Updating algorithms of each filter and beamformer use least mean square(LMS) algorithm and recursive least square(RLS) algorithm. RLS algorithm is applied to achieve fast convergence in following up rapidly changing UWA channel. But RLS algorithm requires many computation processes. Accordingly, we compromised RLS and LMS algorithm in training mode and decision feedback mode.

5. SIMULATION AND RESULTS

In overall simulations, we obtained parameters of equation (1) from SVP of East Sea, Korea, including absorption loss, spreading loss, and reflecting loss. And ambient noise is set to $55\,\mathrm{dB\ re}\ \mu\mathrm{Pa}$. With this configuration, we assume that the depth of water is deep and the distance between TX and RX is relatively long as stated in Table 1. From the above, channel impulse response is given in Fig. 4.

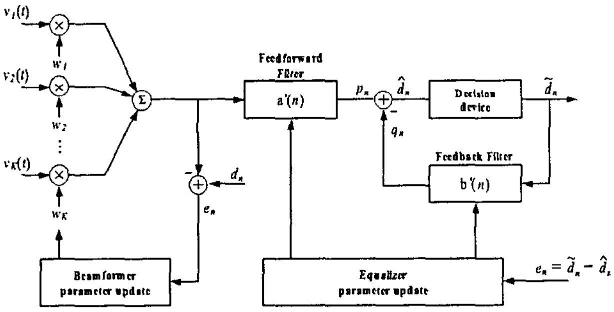


Fig. 3. Adaptive beamformer and DFE.

The RX has a vertical line array of 7 sensors. Simulations are conducted for two cases. One is single sensor and the other is vertical sensor array. In both cases we set up the TX power, carrier frequency, symbol rate, and modulation method to $220\,\mathrm{dB\ re}\ \mu\mathrm{Pa}$, 10kHz, 5000sps, and QPSK, respectively. A signaling frame is shown in Fig. 5. It consists of training sequence and data block.

We run 100 Monte-Carlo simulations and the result of BER for two cases are shown in table 2.

Table 1. Configuration of simulations.

Distance between TX and RX	10 km
Depth of water	1494 m
Depth of TX	650 m
Depth of RX	650 m
Wind speed	14 knots

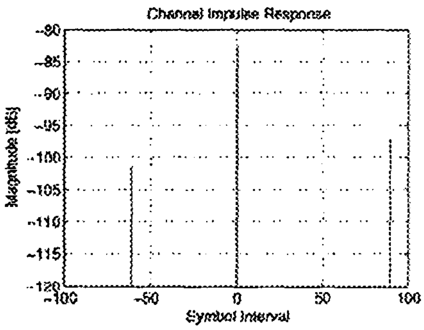
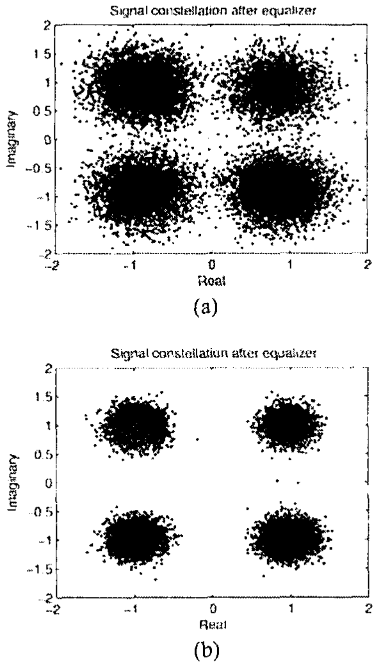


Fig. 4. Channel impulse response.

Fig. 5. Signaling frame.

Table 2. BER of two simulations.

	Single sensor	Vertical sensor array
BER	0.00259	0.00004



(a)

(b)

Fig. 6. Signal constellations after equalizer : (a) single sensor. (b) vertical sensor array.

Constellations of post-equalization are shown in Fig. 6. Fig.6(b) shows better constellation than Fig. 6(a). Fig. 7 is the transmitted image and received images. Transmitted image is 256×256, 4bit gray bitmap image. Received image of single sensor has more spots than vertical sensor array and the vertical sensor array has lower BER.

6. CONCLUSION

In this paper we compared vertical sensor array to single sensor in image transmission in UWA channel. UWA channel is modeled from SVP of East Sea, Korea, including absorption loss, spreading loss, and reflecting loss. We utilized the adaptive beamfoming with vertical sensor array and equalizer with DFE. Vertical sensor array shows better performance than the single sensor.

Acknowledgment

This work was supported in part by the Underwater Acoustic Research Center, SNU, Korea and in part by the BK21 project.

(a)

(b)

(c)

Fig. 7. (a) Transmitted image. (b) received image(single sensor). (c) received image(vertical sensor array).

References

[1] M. Stojanovic, J. Catipovic, and J. Proakis, "Phase coherent digital communications for underwater acoustic channels," *IEEE J. of Oceanic Eng.*, Vol. 19, pp. 100-111, Jan, 1994.

[2] R. S. H. Istepanian, and M. Stojanovic, *Underwater Acoustic Digital Signal Processing and Communication Systems*, Kluwer Academic Publishers, Boston, 2002.

[3] J. G. Proakis, "Adaptive equalization techniques for acoustic telemetry channels," *IEEE J. of Oceanic Eng.*, Vol. 16, pp. 21-31, Jan, 1991.

[4] J. G. Proakis, *Digital Communications*, McGraw Hill, 2001.

[5] R. J. Urick, *Principles of underwater sound, 3rd-Ed.*, Mcgraw-Hill Book Company, 1983.

[6] P. C. Ettr, Underwater Acoustic Modeling Principles, Techniques and Applications, 2nd-Ed., Chapman and Hall, London, 1996.

[7] V. O. Knudsen, R. S. Alford, and J. W. Emling, "Underwater ambient noise," *J. Marine Res.*, Vol. 7, pp. 410-429, June, 1997.

[8] G. S. Howe et al., "Sub-sea remote communications utilising an adaptive receiving beamformer for multipath suppression," in Proc. *OCEANS'94*, pp. I.313-I.316, Brest, France, Sept. 1994.