Maximal Ratio Combining for Long-Range Underwater Acoustic Communication in East Sea

Hyeonsu Kim, Sunhyo Kim, Kang-Hoon Choi, and Jee Woong Choi
Dept. of Marine Science and Convergence Engineering
Hanyang University
Ansan, Republic of Korea
hskim00@hanyang.ac.kr, sunhyo4485@hanyang.ac.kr, choikh0210@hanyang.ac.kr, and choijw@hanyang.ac.kr

Ho seuk Bae
The 6th R&D Institute
Agency for Defense Development
Changwon, Republic of Korea
belfre@add.re.kr

***Abstract*— In October 1999 a long-range underwater acoustic communication experiment was conducted in East Sea of Korea. In this experiment, horizontal distance between a transmitter and receiving array was 559.25 km. The transmitted signals were 511-digit m sequence with a center frequency of 366 Hz and a bandwidth of 45.75 Hz, and the modulation type was binary phase shift keying. In order to compensate inter-symbol interference, maximal ratio combining and equalization are adopted sequentially. As a result, 0.01 of uncoded bit error rate is obtained at a data rate of 37.2 bit per second.**

Keywords— underwater acoustic communication; long-range communication; maximal ratio combining; channel equalization; phase lock loop

I. Introduction

Underwater acoustic (UWA) communication techniques have been researched for a variety of commercial and military applications, such as underwater navigation, oceanographic data collection, ocean surveillance, and unmanned underwater vehicle control [1], [2]. Especially, long-range UWA communications has attracted attention in order to command and control unmanned underwater vehicles remotely with the capability of communicating at ranges of several hundred kilometers [3], [4]. For the reason, various long-range UWA communication experiments using sound channel have been carried out in deep water [4], [5]. Acoustic waves passing through sound channel can propagate long distance. However, sound channel occurs when there is a minimum sound velocity layer between the thermocline and deep water and cannot be artificially created [6]. Thus, it is necessary to carry out the experiment in the sea where the sound channel is formed naturally. Although the long-range communication experiment in the site with the sound channel was conducted, the strength of signals propagating a long distance is very weak. Moreover, multipath propagation of UWA channel causes inter-symbol interference(ISI) and makes signal detection difficult. Therefore, amplifying the strength of the weakened signal and compensating ISI are required essentially.

In this paper, long-range UWA communication experiment using maximal ratio combining(MRC) and equalization is presented. Since MRC can achieve spatial and temporal diversity gain and reduce ISI, it is suitable for restoring the long-range communication signal. Although complete ISI cancellation cannot be implemented by MRC, residual ISI can be eliminated by additional channel equalization since MRC is coherent processing.

The rest of this paper consists of the following sections. Section II contains explanation about MRC and multipath channel equalization. In section III, long-range UWA communication experiment in the East Sea of Korea is presented.

II. Channel Compensation

A. Maximal Ratio Combining

MRC is an effective combining method to combat fading channel by achieving spatial and temporal diversity, and also the optimal combiner in Gaussian noise and flat fading channel [7]. The weighting of MRC in the complex baseband is equal to the complex conjugate of each channel response. Thus, the signal combined by MRC can be considered as spatial and temporal matched filtered signal, thus its signal-to-noise ratio is maximized. Therefore, MRC is utilized for compensating channel effects on the long-range communication signal in this paper.

B. Transversal Equalizer

Although MRC is a simple and effective processing in multipath fading channel, it cannot completely compensate channel. As mentioned above, MRC is operated as matched filtered signal combiner. The matched filtered response of multipath channel response has temporal sidelobe which causes residual ISI. That is, MRC can reduce ISI, but not remove. Therefore, additional scheme is required to eliminate residual ISI. In this paper, we adopt transversal equalizer composed of feedforward taps and/or feedback taps. Transversal equalizer is easy to implement and can compensate channel effectively. Two types of equalizer are applied for compensation. One is a linear equalizer with feedforward only. Another is a decision-feedback equalizer with feedforward and feedback. Initial tap coefficients will be calculated based on known signal (i.e.

training sequence). Subsequent tap coefficients will be updated by adaptive algorithm.

III. Long-Range Communication Experiment

In October 1999 a long-range UWA communication experiment was carried out in the East Sea of Korea as illustrated in Fig. 1. An acoustic source as a transmitter was installed on the shallow-water shelf near Vladivostok harbor and vertical line array equipped with ten hydrophones spaced 10 meters apart as a receiver was deployed near Ulleung-do. Horizontal distance between the transmitter located at a depth of 23 meters and the receiver at 355 meters was 559.25 kilometers. The sound velocity was measured at 11 points (0, 14, 75, 139, 249, 305, 361, 417, 466, 529, 559 kilometers away from the transmitter) on the straight line between the transmitter and the receiver.

Communications signals were 511-digit *m* sequence with a center frequency of 366 Hz and a bandwidth of 45.75 Hz, and the modulation type was binary phase shift keying. Unfortunately, instead of root raised cosine, rectangular pulse was used as baseband pulse. Because the main purpose of this experiment was not to implement UWA communication link. Fig. 2 describes the frame structure of the communication signal. Initial 96 symbols were used as training sequence for synchronization and channel estimation, and the remaining 415 symbols were used as information sequence. Thus, effective data rate is 37.5 bit per second.

Fig. 3 shows an example of estimated channel responses from received signal on Oct. 21. Least squares method was applied as an estimation method. In empirical sense, visible dominant components on the estimated channel response mean that synchronization and channel estimation are successful. Delay spread spans to about 300 milliseconds and 14 in symbol interval.

Fig. 4 shows a constellation of received information symbols which are detected without any channel compensation, i.e. the signal is synchronized only. The form of constellation spreads widely and uncoded bit error rate(BER) is 0.2186. On the other hand, the constellation of samples after MRC converges as shown in Fig. 5. Note that scale of plotting in Fig. 5 differs from that in Fig. 4. BER after MRC is greatly reduced to 0.0195. This means that MRC compensates the distortion from channel effectively.

In order to eliminate residual channel effects after MRC, two types of equalization are applied. One is a linear equalizer composed of feedforward filter with 20 taps. Another one is a decision-feedback equalizer composed of feedforward filter with 20 taps and feedback filter with 10 taps. Both of them update tap coefficients with adaptive algorithm which is recursive least squares with 0.99 of forgetting factor. Fig. 6 is a constellation after linear equalization. BER is 0.0109. This means that linear equalization eliminates distortion from channel additionally. Fig. 7. Shows a constellation of information symbols which are equalized with decision-feedback. the distribution in constellation is similar to that of linear equalization. However, BER after decision-feedback equalization is 0.0176. These results indicate that error propagation in decision-feedback equalization exists and linear equalization is more effective in this case.

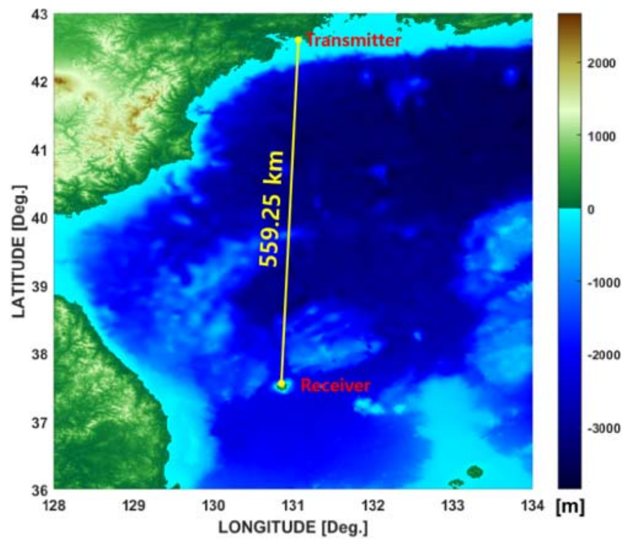

Fig. 1. Experiment site

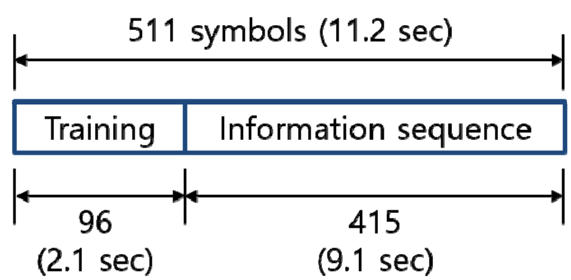

Fig. 2. Frame structure

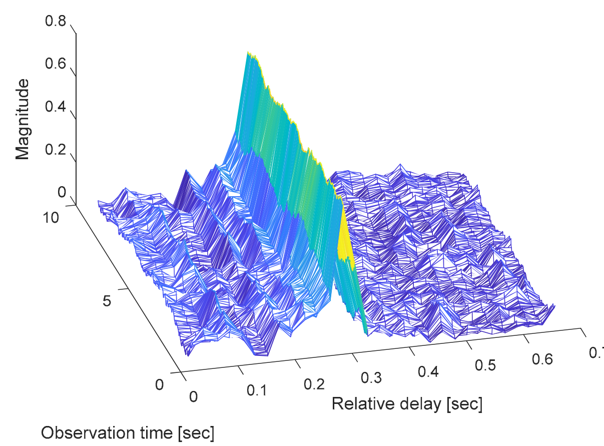

Fig. 3. Example of estimated channel responses

IV. Conclusion

A long-range underwater acoustic communication experiment was conducted in East Sea of Korea. For compensating multipath channel effects, MRC and transversal equalizer are adopt. As a result, 0.01 of uncoded BER is obtained at a data rate of 37.2 bit per second.

Acknowledgment

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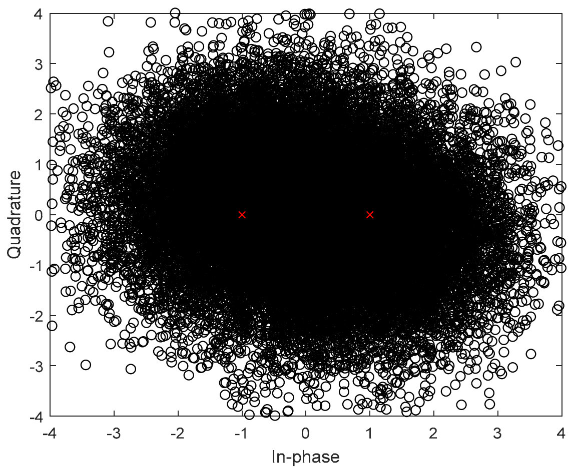

Fig. 4. Constellation of symbols detected without compensation

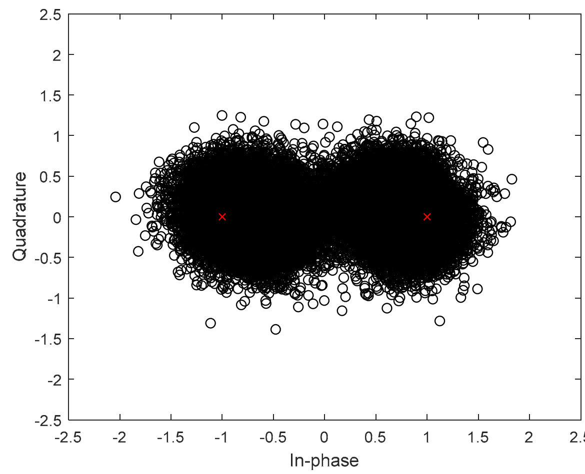

Fig. 6. Constellation of symbols after MRC and linear equalization

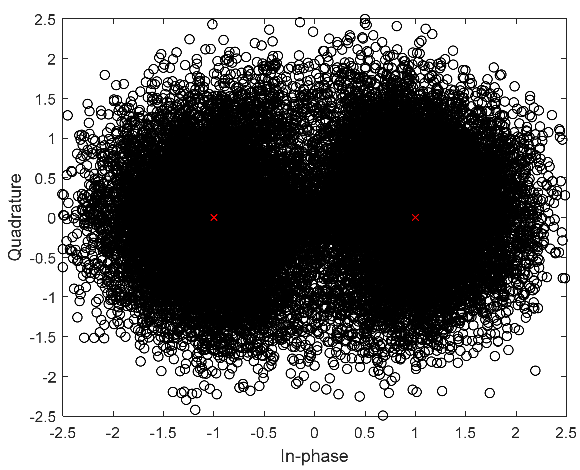

Fig. 5. Constellation of symbols after MRC

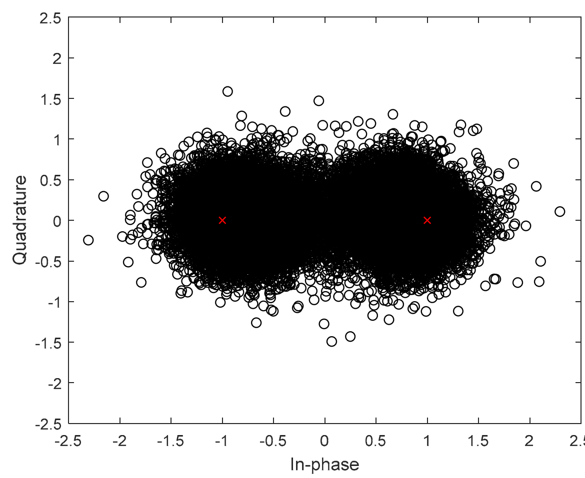

Fig. 7. Constellation of symbols after MRC and decision-feedback equalization