Experimental results of long range underwater communication based on chirp-FH signals

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***Abstract*—** It is sometimes required that acoustic communication be covert while at the same time maintaining reliability. We proposed a covert underwater acoustic communication method which was robust against channel fading and Doppler shift in our previous paper. In this paper we verify the previously proposed method through the sea experimental results at range of 60 km.

Keywords—Underwater acoustic communication, Covert communication, Sea trial, Frequency hopping spread spectrum

I. Introduction

In the past, many studies have been carried out regarding communicating in underwater conditions. Because of the characteristics of underwater channels, acoustic signals are commonly used [1,2]. It is sometimes required for military or other special reasons that underwater acoustic communications should be covert. Covert communication should be protected against unauthorized eavesdropping. Spread spectrum techniques are widely used in covert underwater acoustic communication, and typically there are two methods. One is a direct sequence spread spectrum (DS-SS) method in which a spread factor is directly multiplied by data. The other is a frequency-hopping spread spectrum (FH-SS) method in which a frequency band is shifted by a spread code [3,4]. The FH-SS scheme randomly hops according to the hopping pattern. Therefore, an interceptor who does not know the pattern cannot recover the signal. In addition, anti-jamming performance is good because the band continuously changes even if jamming is executed with malicious intention. However, the basic FH-SS scheme uses the form in which a single frequency continuously hops. Problems can occur in that it is not robust with regard to Doppler shift and it is not resilient to intersymbol interference (ISI). On the other hand, a linear chirp signal is robust with regard to Doppler shift and is resilient to ISI. Moreover the chirp signal reduces or impedes channel fading [5]. Thus, combining the chirp signal with the FH-SS scheme, existing problems can be solved. A chirp-FH method utilizes a data modulated signal, which has its energy spread over a bandwidth that is greater than the rate of information being sent, as do all spread spectrum systems. The chirp modulation method is one in which the binary information modulates the slope of a linear chirp, with chirps representing zeros or ones [6]. This method alone can be considered covert underwater acoustic communication technology.

Fractional Fourier transform (FrFT), as a generalized analysis method of the existing Fourier transform concept, was introduced many years ago in mathematical literature. The original purpose of FrFT was to solve differential equations, but these days, it is used in signal processing such as fractional filter or noise removal [7,8]. Especially in our previous method, robust detection was possible in a noisy or reverberant environment as the FrFT can obtain a concentrated energy spectrum in the fractional domain.

In this paper, we verify the proposed method which was performed in simulations and lake trials in our previous paper [9] over a 60 km long transmission range.

II. Chirp-FH Scheme and Receiver

Chirp modulation is a digital modulation in which the frequency increases or decreases (up-slope/down-slope) for a binary value "1"/"0". A chirp signal can be expressed as:

$$x(t) = \exp[j(2\pi f_0 t + k\pi t^2)] \quad (1)$$

where f_0 is the starting frequency and k is the chirp rate. Equation (1) can be modified to express the frequency hopping as follows:

$$x_H(t) = \exp\{j[2\pi(f_0 + f_H)t + k\pi t^2]\} \quad (2)$$

Equation (2) expresses the chirp-FH signal where f_H is the hopping frequency. The starting frequency of the chirp signal is continuously changed according to the preset pattern.

Fig. 1 shows a block diagram of the chirp-FH method. A hopping frequency is set by pattern generator and multiplied by the modulated transmission signal to perform frequency hopping, and the receiver utilizes a bandpass filter with the preset pattern.

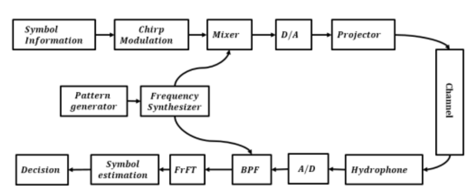

Fig. 1. Block diagram of chirp-FH transmission.

In the time-frequency domain, a chirp signal which has linear variation is combined with frequency hopping, and it can be said that this signal has a constant frequency rate, whether up-chirp or down-chirp. This points correspond to a transform order in the fractional domain. In the fractional domain, a linear chip signal is concentrated in one point. And depending on whether the chirp is up-slope or down-slope, the concentrated location also changes. Therefore up-chirp and down-chirp can be distinguished by using the FrFT spectrum. The above method can be called FrFT receiver. Details are given in reference [9].

III. Sea Trial and Results

Sea trials were carried out to analyze the performance of chirp-FH underwater acoustic underwater acoustic communication in October 2018. Fig. 2 shows the experimental structure. The water depth of the experimented area was about 900 m ~ 1,500 m and the range between source and receivers was 60 km. The receiver array which consists of the 16-channel of vertical line array (VLA) was fixed by buoy and located between depths of 179 m and 221 m. A Neptune T161 model was used as the projector and located at a depth of 200 m. We used 114-bit data per frame, a center frequency of 1.9 kHz, a data rate of 4 bps and the hopping of the two bands. Each chirp symbol band was 48 Hz and the hopping interval was 100 Hz. The LFM (linear frequency modulation) train signal which consists of 20-pings is used to distinguish the packets. Sea trials were carried out in the Korean East Sea near Pohang city.

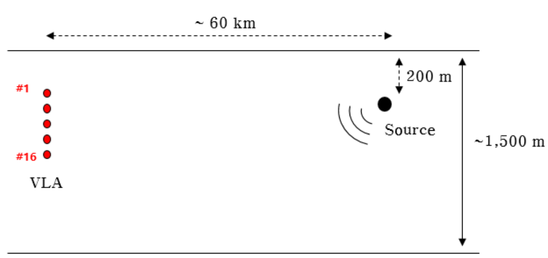

Fig. 2. The experimental structure.

Fig. 3. CTD (conductivity, temperature, depth) equipment

Fig.3 shows the CTD (conductivity, temperature, depth) equipment. The sound speed profile that was measured by CTD at the transmitter location is shown in Fig.4. The CTD was taken as often as possible on the ship during the experiment. Fig.5 and Fig.6 shows the acoustic source and VLA used in the experiments.

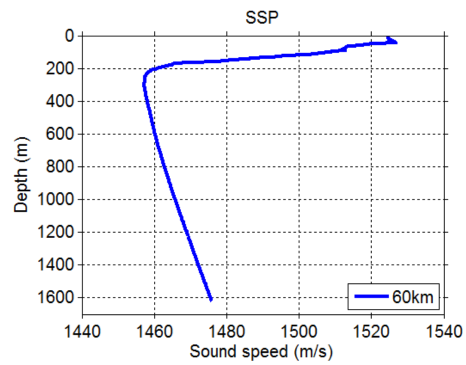

Fig. 4. Sound speed profile

Fig. 5. Body of the acoustic source.

Fig. 6. Vertical line array.

Fig. 7 and Fig. 8 show the channel impulse response (CIR) and CIR was calculated from the LFM train signals. In Fig. 7, it was received at the 1st-channel of the VLA and the second path wave appears after the direct path from 0.05 seconds. But, Fig. 8 shows a different delay profile that was received at the 16th-channel of the VLA - unlike Fig. 7. In this case, the delay time between first path and second path was 0.02 seconds. And the third path appeared for a moment. Fig. 7 and Fig. 8 show that the time of the CIR was same but occurred in different spaces. This difference makes the two-path delay results different and determines the occurrence of interference. This means that the underwater channel has a complex channel whose state continuously changes with time and space and so it is hard to predict the results.

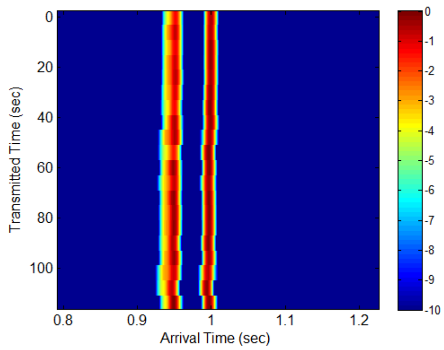

Fig. 7. Channel impulse response at channel #1.

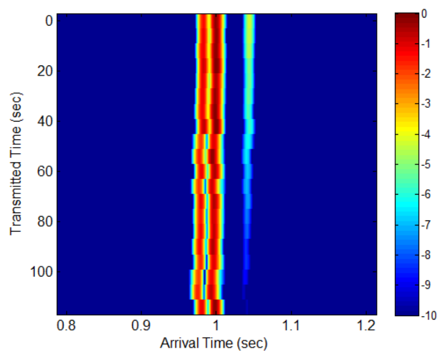

Fig. 8. Channel impulse response at channel #16.

Fig. 9 shows a spectrogram of the received chirp-FH signal. It was received at the 1st-channel of the VLA and the received signal was demodulated by the FrFT receiver. In this case, the effects of delay are not visible, SNR (signal-to-noise ratio) is high compared with the environment and marine life noises are not in these times. As a result, the bit error rate was zero in all of the channels.

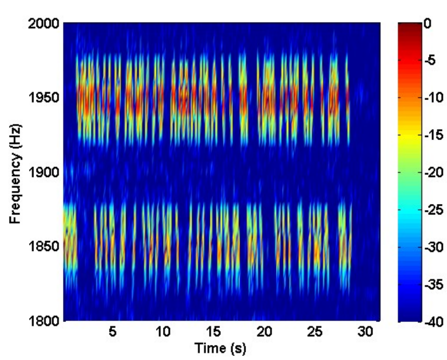

Fig. 9. Spectrogram of the received signal.

IV. Conclusion

The underwater acoustic channel is one of the complex channels whose state changes with time. And background noise such as marine life communication also has a significant impact on communication performance. However, the arrangements or configurations we can deploy in underwater communications (such as propagation rate, bandwidth, etc.) are limited by physical conditions. Many studies have been conducted in an effort to address these issues, and we believe that this paper makes a contribution with respect to such problems.

In this paper, we carried out the sea trials to verify the performance of the previously proposed method. The source-receiver range was 60 km. The received signal was demodulated using the FrFT, and as a result, the bit error rate was free in all cases. The results obtained in our trials were due to the fact that the SNR was high, the channel was clear and because of the characteristics of the chirp signal. In the future, experiments with low SNR should be performed to evaluate covertness and make comparisons with interceptors.

Acknowledgment

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