Multiband FSK with Direct Sequence Spread Spectrum for Underwater Acoustic Communications

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***Abstract*—** This paper presented an efficient multiband FSK signals with direct sequence spread spectrum for maintaining covertness and performance. In aspect to covertness, direct sequence spread spectrum method, which multiplying by PN codes whose rate is much higher than that of data sequence, is employed. In aspect to performance, we applied multiband, turbo equalization, and weighting algorithm. Underwater acoustic communication experiments were conducted in the lake. In the lake experimental results, we confirmed that the performance was improved as the number of bands and chips are increased. Furthermore, the performance of multiband was improved when the proposed weighting algorithm was applied.

Keywords—multiband; underwater acoustic communications; direct sequence spread spectrum; turbo equalizer; weighting algorithm;

I. Introduction

This paper focused on covertness and performance in underwater communication. For the purpose of personal or military security, underwater acoustic communications with low-probability-of-interception (LPI) covert characteristics were received much attention recently [1, 2]. Covert underwater acoustic communication system designed for the purpose of transmission signal is not being intercepted by the unintended other receivers. Therefore, typical covert communication systems use spread spectrum communication technology. It used to hide the transmitted signal by transmitting it at low power and, thus, making it difficult for an unintended listener to detect the signal in the presence of background noise. Direct sequence spread spectrum method used in underwater acoustic channels to a limited extent and for different purposes. The problem for spread spectrum communications in an underwater acoustic channel is the multi-path arrivals, which create severe inter-chip and inter-symbol interferences. Furthermore, the performance of underwater wireless communication depends on the factors such as propagation loss according to the distance of acoustic signals, interference signal caused by multi-path propagation, background noise, and Doppler effects. In order to improve performance in multi-path underwater channel with low SNR, this paper presented multiband technology, which allocates the same data to different frequency bands, and it overcomes the frequency-selective fading due to underwater multi-path and Doppler spread [3]. In other words, the multiband communication technology overcomes various underwater channel environments and extends propagation distances, thereby improving both performance and propagation efficiency. This paper presented an efficient transceiver structure in aspect to covertness and performance in underwater acoustic communication environment. Therefore, this paper presented multiband frequency shift keying (FSK) with direct sequence spread spectrum for maintaining covertness and performance.

II. System Model

Figure 1 shows structure of multiband FSK transceiver model with direct sequence spread spectrum. In transmitter side, turbo codes with 1/3 coding rates are employed. After k bits pass through channel coding at the transmitter, N coded bits generated, and it input to interleaving block, which change burst errors to random errors [4]. After an interleaving, the bit columns of one packet data of $N_P = (N + n)$, consisting of n preamble bits $\{p_0, p_1, \cdots p_{n-1}\}$ for synchronous acquisition and N coded bits $\{c_0, c_1, \cdots c_{N-1}\}$. After spread using N_c chip bits, the spread bits Q with $N_T = (N_p \times N_c)$ bits, can be expressed $\{q_0, q_1, \cdots q_{N_T-1}\}$. In the Tx sub-band processing block in Figure 1, we divided the bit column of the packet data into a group of m bit columns, frequencies are allocated according to group.

In receiver side, Rx sub-band processing block separate frequency band, and demodulates the data for each band with the maximum value by energy detector. A RAKE receiver is a matched filter. If we represent the channel as a tap delay line, the RAKE taps are chosen as the conjugates of the channel taps and an optimum receiver is built. The same structure can be also realized with correlators. At each tap the time delayed replica of the received signal is correlated with the replica of the pseudo noise (PN) signal used to spread the data symbols. Because PN codes ideally have maximum correlation at zero delay and zero correlation at non-zero delays, we will get signal from taps that correspond to the multiple propagation paths [5]. Also, turbo equalization model proposed in the Figure 1, which configures the turbo decoder with outer codes was employed and decision feedback equalizer (DFE) equalizer employed as inner decoder. Inner decoder and outer decoder are connected through interleaving and de-interleaving that updates each other's information repeatedly [6].

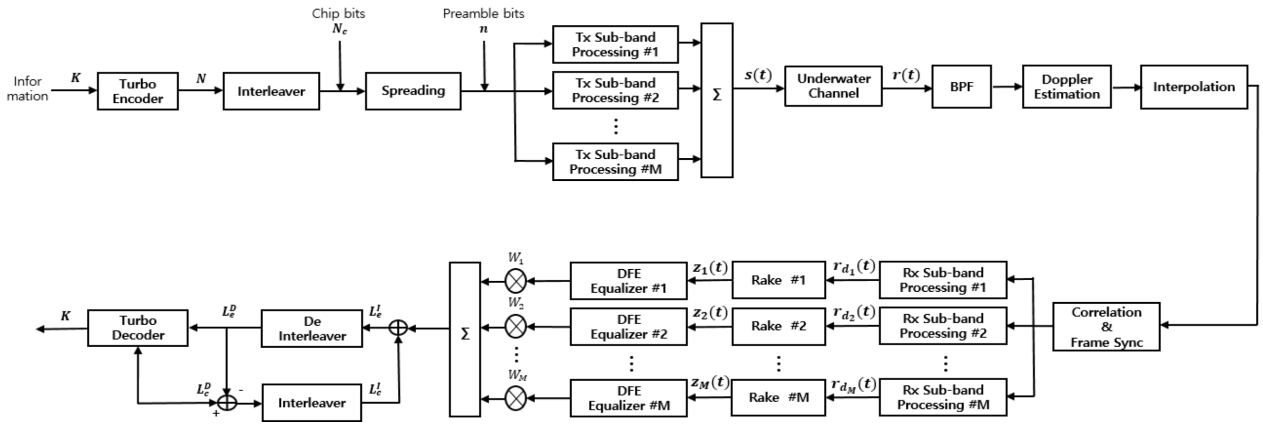


Fig. 1. The structure of multiband FSK transceiver model with direct sequence spread spectrum

III. Experiment Result

We evaluate the performance of the proposed method in real underwater environments. The experiment was conducted on a lake of Munkyeong city, Korea, in March 2021.

TABLE I. Experimental Parameters

Source (*K*)	112
Preamble bit (*n*)	8160
Number of chips (N_c)	8, 32
Number of multibands (N_b)	4
Modulation	4-ary FSK
Channel coding	Turbo code with rate of 1/3
Center frequency	16 kHz
Sampling frequency	192 kHz
Data rate	20 bps
Distance	300 ~ 500 m
Depth	Transmitter : 5 m Receiver : 20 m

Table 1 shows the lake experimental results, and five trial of same packet with preamble size of 8160 bits and spreading coded size of 10,752 bits, were iteratively conducted. by applying four bands and number of chips are 8 and 32. 4-ary FSK modulation was applied, and turbo codes with 1/3 coding rates are employed.

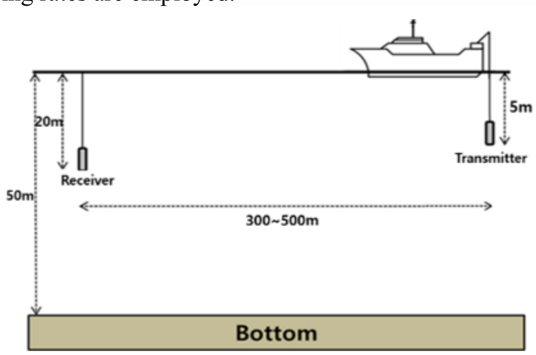
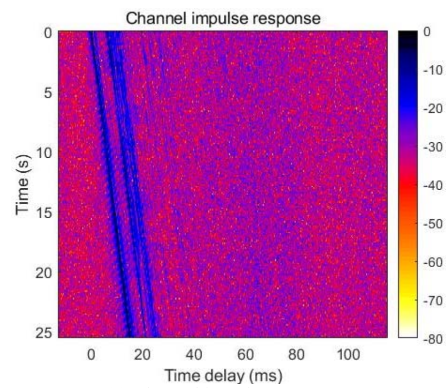
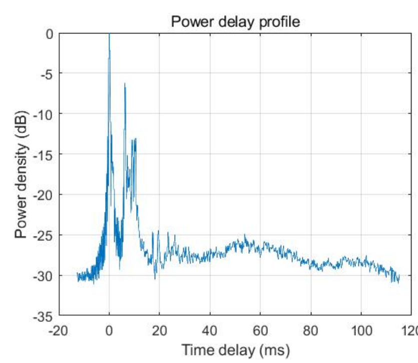


Fig. 2. Illustration of the lake trial.

Figure 2 shows Illustration of the lake trial. The water depth was approximately 50 m and the source signal has 16 kHz center frequency and 20 bps data rate. The hydrophone was equipped at 50 m lake bottom and the horizontal range from transducer was 300~500 m. The received signal was sampled at 192 kHz sampling frequency.



(a) Channel impulse response.



(b) Delay profile.

Fig. 3. Underwater channel characteristic.

In Figure 3(a) and 3(b) show the underwater channel characteristics, and show this channel is affected by the multi-path propagation which caused by the reflection from the surface and bottom.

TABLE II. EXPERIMENT RESULT

Trial / Method	1	2	3	4	5
$N_c = 8$ $N_b = 4$	Success	Fail	Success	Fail	Fail
$N_c = 32$ $N_b = 4$	Success	Success	Success	Success	Success

N_b denotes the number of bands. Success and Fail shown in Table 2 means error occurrence or not after turbo decoding. Only two of the five packets are successfully decoded for $N_c = 8,\ N_b = 4$, and all the packet are error free for $N_c = 32,\ N_b = 4$. It means that the more spreading, performance is the better.

TABLE III. PERFORMANCE ANALYSIS ACCORDING TO THE NUMBER OF ITERATIONS ($N_c = 8,\ N_b = 4$)

	Data BER according number of turbo equalization iterations		
packet number	**1**	**3**	**5**
1	$10^{-0.60}$	$10^{-2.05}$	0
2	$10^{-0.51}$	$10^{-0.52}$	$10^{-0.54}$
3	$10^{-0.97}$	0	0
4	$10^{-0.37}$	$10^{-0.37}$	$10^{-0.37}$
5	$10^{-0.37}$	$10^{-0.37}$	$10^{-0.37}$

TABLE IV. PERFORMANCE ANALYSIS ACCORDING TO THE NUMBER OF ITERATIONS ($N_c = 32,\ N_b = 4$)

	Data BER according number of turbo equalization iterations		
packet number	**1**	**3**	**5**
1	$10^{-0.94}$	$10^{-1.09}$	0
2	$10^{-0.82}$	0	0
3	$10^{-1.35}$	0	0
4	0	0	0
5	$10^{-2.05}$	0	0

In turbo equalization structures with $N_c = 8$ and $N_c = 32$, the error rate according to the number of iterations is shown in Table 3 and Table 4. In both cases, we confirmed that BER performance improves as the number of turbo equalization iterations increases. However, the multiband configuration may have worse performance than the single-band one because performance degradation in a particular band affects the output from the entire bands. This problem can be solved through a receiving end that analyzes error rates of each band, sets threshold values and allocates lower weights to inferior bands [7]. In order to set the weighting to each band, we utilize preamble data that are already known to both transmitter and receiver. Weighting algorithm sets a threshold value by measuring the error rate of preamble data and predicting the data performance at the payload section. The conventional underwater communication methods use preamble data as the training symbol of an equalizer to remove the effects of multi-path and synchronous acquisition of frequency and phase of payload. However, since the performance of payload data can also be predicted based on the error rate of preamble data, information can be provided to the decoding unit of payload data. In a poor channel environment like multi-path, numerous preamble data are allocated and the error rate of these data is also related to that of payload. Accordingly, the error rate of un-coded preamble is used to predict the error rate of payload and set a threshold value that can satisfy the Quasi Error Free (QEF) condition after decoding payload. Therefore, we analyzed the performance of preamble bits of each band, in order to assign weighting value to each band in the case of $N_c = 32,\ N_b = 4$. Table 5 shows error rate according to the weighting value. In the case of fifth packet, even though the number of turbo equalization iterations was five, decoding failed. Based on the result of error rates of preamble, we assigned high weighting value to f_3 and f_4 bands with low preamble error rates and low weighting value to f_1 and f_2 band with high preamble error rates. Therefore, we successfully decoded by weighting to each band adaptively based on preamble error rates. We confirmed that weighting algorithms are well operated in real lake experiment.

TABLE V. PERFORMANCE ANALYSIS ACCORDING TO THE WEIGHTING ($N_c = 32,\ N_b = 4$)

Packet number	f_c	**Preamble BER**	**Weighting**	**Data BER according number of turbo equalization iterations**		
				1	**3**	**5**
5	f_1	$10^{-0.60}$	1.0	$10^{-0.69}$	$10^{-0.77}$	$10^{-0.82}$
	f_2	$10^{-0.63}$	1.0			
	f_3	$10^{-1.22}$	1.0			
	f_4	$10^{-1.32}$	1.0			
5	f_1	$10^{-0.60}$	0.1	$10^{-2.05}$	0	0
	f_2	$10^{-0.63}$	0.1			
	f_3	$10^{-1.22}$	1.0			
	f_4	$10^{-1.32}$	1.0			

IV. CONCLUSION

In this paper, we presented an efficient multiband FSK signals with direct sequence spread spectrum for maintaining covertness and performance. In aspect to covertness, direct sequence spread spectrum method, which multiplying by PN codes whose rate is much higher than that of data sequence, is employed. In aspect to performance, in order to overcome performance degradation caused by multipath and Doppler spreading, we applied multiband and turbo equalization. Underwater acoustic communication experiments were conducted in the lake with a distance of moving from 300m to 500m between the transceivers. by applying four bands and number of chips are 8 and 32, We confirmed the performance was improved as increasing the number of bands, iteration number, and number of chips. Furthermore, based on the result of error rates of preamble, which known transmitter and receiver side, the performance of multiband was improved when the proposed weighting algorithm was applied.

ACKNOWLEDGMENT

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