Two Novel Packet Structures Based on FRFT Underwater Acoustic Communication System

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***Abstract*—Two novel packet structures are proposed based on the FRFT (Fractional Fourier Transform) communication system for different channel. The first packet is designed for the channel of fast change, and it consists of Chirp signal, sine signal and BPSK, which immensely improve the reliability of underwater communication; the second one is designed for the channel of slow change, and it consists of Chirp signal and BPSK, which greatly promote the efficiency of underwater communication. The simulation results show the effectiveness of two packet structures.**

Keywords- Underwater acoustic communication, Underwater acoustic channel, FRFT, The packet structure

I. INTRODUCTION

With global increased interest in the exploration of the ocean, underwater acoustic communication will be widely applied in oceanographic data collection, tactical surveillance, assisted navigation, etc. However, the underwater acoustic channel is characterized by time-variant, space-variant, time-delay and Doppler-shift. Besides, underwater acoustic communication is also influenced by the path loss, noise and other factors [1-5]. Therefore, two novel packet structures are proposed in order to reliable and efficient underwater communication.

- The first packet. It is effective to make the parameter estimation per packet possible in channel of fast change, which greatly increase the reliability of data transmission. However, it reduces transmission efficiency.
- The second packet. It is effective to estimate the parameters in channel of slow change. Although transmission efficiency is increased, the reliability of data transmission is reduced.

II. UNDERWATER ACOUSTIC CHANNEL AND FRFT

Assume that $x(t)$ is the sending signal, N is the eigen-ray number, and $n(t)$ is the white Gaussian noise. And assume A_i ($i=0,...,N-1$) is the amplitude, ε_i ($i=0,...,N-1$) is the Doppler shift, and τ_i ($i=0,...,N-1$) is the delay. Then the received signal will be [7-8]

$$r(t)=A_0x(t-\tau_0)e^{j2\pi\varepsilon_0(t-\tau_0)}+\sum_{i=1}^{N-1}A_ix(t-\tau_i)e^{j2\pi\varepsilon_i(t-\tau_i)}+n(t) \tag{1}$$

Employing FRFT upon (1), we get [6]

$$\begin{aligned}R_p(u)&=A_0X_p(u-\varepsilon_0\sin\alpha-\tau_0\cos\alpha)\\&\times\exp(j\pi\tau_0^2\sin\alpha\cos\alpha-j2\pi(u-\varepsilon_0\sin\alpha)\tau_0\sin\alpha)\\&\times\exp(-j\pi\varepsilon_0^2\sin\alpha\cos\alpha-j2\pi u\varepsilon_0\cos\alpha)\\&+\sum_{i=1}^{N-1}A_iX_p(u-\varepsilon_i\sin\alpha-\tau_i\cos\alpha)\\&\times\exp(j\pi\tau_i^2\sin\alpha\cos\alpha-j2\pi(u-\varepsilon_i\sin\alpha)\tau_i\sin\alpha)\\&\times\exp(-j\pi\varepsilon_i^2\sin\alpha\cos\alpha-j2\pi u\varepsilon_i\cos\alpha)+N_p(u)\end{aligned} \tag{2}$$

The $X_p(u)$ of FRFT of Chirp signal can be interpreted to the expansion of the function space based on the inverse transformation nuclear $K_{-p}(t,u)$ of $x(t)$ according to the inverse transformation of FRFT $x(t)=\int_{-\infty}^{+\infty}X_p(u)K_{-p}(t,u)du$. And the nuclear is a group of orthogonal Chirp-based in the u domain. it is analogous to the principle of Fourier, and they only have different basement. The basement of FRFT is a group of orthogonal Chirp-based in the u domain, that is, the Chirp-based decomposition characteristic of FRFT [5] [9]. Thus, a peak will be manifested when a Chirp signal is at the appropriate u domain. That is, the energy of Chirp signal will gather at a certain order for a given Chirp signal (the chirp rate is certain), so it is called the "best" order for the chirp rate.

Theoretically, the corresponding relation of the k and the p is [9]

$$k=-\cot\left(\frac{p\pi}{2}\right) \tag{3}$$

There is a corresponding order p for any chirp rate k, conversely, there is a corresponding chirp rate for any order p. That is to say, FRFT contains Chirp signal of any chirp rate.

The reason why using a Chirp signal estimate delay instead of a sine signal is that the chirp rates of sine signal with any Doppler shift are constant, but the chirp rates of Chirp signal with any Doppler shift are variable. Therefore, the different variation characteristic is adopted between the

Published by Atlantis Press, Paris, France.

chirp rate of sine signal and that of Chirp signal to estimate the delays of multi-path signals [10].

III. PACKET STRUCTURES AND THE PROCESSING OF FIRST PACKET

Two packet structures based on the FRFT communication system are proposed for different channels, as shown in Figure 1.

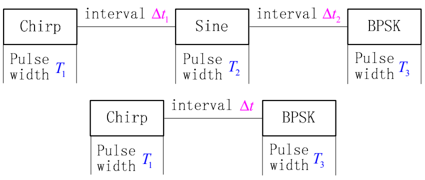

Figure 1. Two packet structures

The first packet was designed for the channel of fast change, which consists of Chirp, sine and BPSK. The pulse width of Chirp is T_1, and it is used as the head of first packet. The pulse width of sine is T_2, which is used to estimate the Doppler shifts and the multi-path number. BPSK are adopted with pulse width T_3. Let the interval between Chirp and sine be Δt_1, and the interval between sine and BPSK be Δt_2 in order to prevent the interference between signals.

The second packet, which is designed for the channel of slow change, is similar to the previous packet. The pulse width of Chirp is T_1, and it is used as the head of second packet. BPSK are adopted with pulse width T_3. The sine with pulse width T_2 is launched every certain time interval. And in order to prevent the interference between signals, the interval between Chirp and BPSK is Δt.

The FFT of high resolution is carried out on the sine part of received signal, then the multi-path number is determined, at the same time the Doppler shifts are accurately and quickly estimated. According to the estimated Doppler shifts and prior signal knowledge, the reconstructed Chirp signals are decorrelated with the received signal according to the arrival order of multi-path signals. By taking advantage of the chirp-based characteristic of FRFT, the channel parameters are accurately and quickly estimated through the differences of the decorrelated peak coordinates and different chirp rate [10]. Finally, the BPSK are demodulated according to the estimated channel parameters. The flow of signal processing algorithm of the first packet structure is shown in Figure 2.

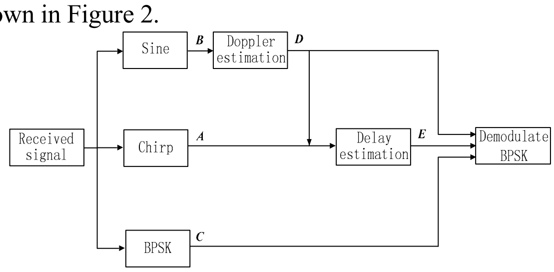

Figure 2. The processing flow of the first packet

Remark: D is estimating the Doppler shifts of multi-path signals; E is getting the delays through the decorrelation between A and the reconstructed signals for D. Finally, the BPSK are extracted.

The proposed first packet processing algorithm includes the following steps:

- The multi-path number and Doppler shifts are estimated.
- The delays are estimated.
- The BPSK are demodulated.
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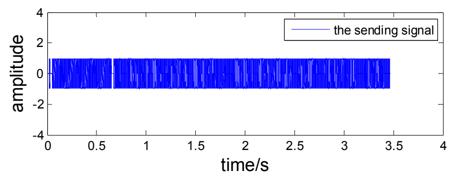
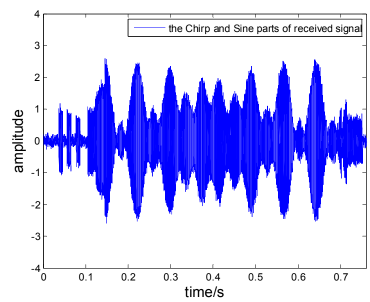
IV. SIMULATION

Example 1. A Chirp signal and a sine signal are sent with a fixed time interval 0.07s, and let the interval between sine signal and BPSK be 0.67s. Let the pulse width of Chirp signal be 0.01s, the bandwidth be 800Hz, the center frequency be 1kHz. Let the carrier frequency of sine signal be 1kHz, and let the pulse width be 0.6s. Let the carrier frequency of BPSK be 1kHz, and let the pulse width be 2.83s. Let all sample rates be 12kHz (12000points per second).

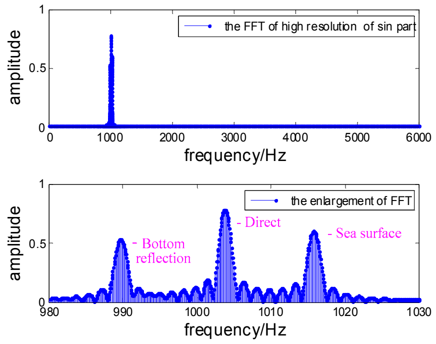
Let channel parameters be as follows: there are three paths. The delay of direct path is 200points, and the amplitude is 1. The delay of sea surface - direct path is 230points, and the amplitude is 0.8. The delay of sea surface - bottom reflection is 260points, and the amplitude is 0.7. SNR is 20dB. The Doppler shift of direct path, sea surface and bottom reflection respectively is 3.777Hz, 15.777Hz, -10.333Hz. The processing of first packet are shown in Figure 3.



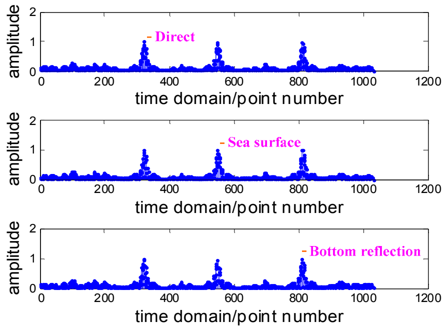
a. The sending and received signal



b. The enlargement and received signal



c. The FFT and received signal



d. The decorrelation

Figure 3. The sending signal structure and processing flow of first packet

The FFT of high resolution is carried out on the sine part of received signal, and the multi-path number is 3, at the same time the Doppler shifts are determined from Figure 3 (c) and listed in Table I.

TABLE I. THE DOPPLER SHIFT ESTIMATION

Doppler/Hz	direct path	sea surface	bottom reflection
Real channel	3.777	15.777	-10.333
Estimation	3.796	15.735	-10.266

According to the estimated Doppler shifts and prior signal knowledge, the reconstructed Chirp signals are decorrelated with the received signal according to the arrival order of multi-path signals, and the delays is estimated from Figure 3 (d) and listed in Table II. Finally, the BPSK are demodulated according to the estimated parameters.

TABLE II. THE DELAY ESTIMATION

Delay/points	Direct	Direct - surface	Surface - bottom
Real channel	200	230	260
Estimation	200	230	260

The simulation of second packet is similar to the one of first packet, therefore, it is not detailed here. However, the sine signal is launched to estimate the Doppler shifts and the multi-path number every certain time interval with pulse width T_2.

V. CONCLUSION

This paper proposes two packet structure designs based on FRFT communication system for different channel. The first packet structure for the channel of fast change is designed, and the strongpoint of this packet is that the parameters of underwater acoustic channel can be estimated per packet, which greatly increase the reliability of data transmission, however, it reduces transmission efficiency. The second packet structure for the channel of slow change are designed, and the strength of this packet is that transmission efficiency can greatly be increased, however, the Doppler shifts of underwater acoustic channel can't be estimated per packet, which enormously reduce the reliability of data transmission. In conclusion, the chirp-based characteristic of FRFT is applied to analyzing and processing the Chirp signal part of the mixed signal for both two packets, which avoids the using of the fast algorithm of FRFT and greatly improve the algorithm efficient. Besides, both two packets can be realized for real-time processing under the accurate parameter estimation.

ACKNOWLEDGMENT

The first author wishes to thank Zheng yi and Li Ming for their valuable comments that improved the quality of this paper. And this paper was supported by the National Natural Science Foundation of China under Grant 60704023 , 40806044, and supported by the Qingdao Science and Technology Planning Project Fund of China under Grant 10-3-4-9-2-jch.

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