Multiuser Underwater Acoustic Communication based on Multicarrier-Multiple Chirp Rate Shift Keying

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***Abstract*—Multiuser underwater acoustic communication is one of the enabling technologies for the autonomous oceans sampling network (AOSN). Based on explicit relationship between fractional Fourier transform properties of chirp signal and its parameters, we proposed a new modulation and demodulation scheme named multicarrier-multiple chirp rate shift keying (MC-MCrSK). The scheme can support four users communication via underwater acoustic channel with 10 KHz bandwidth. Receiver can increase robustness by virtual time reversal mirror technology (VTRM). The validity of the simulation comparison is verified in experiment. 425 bps data rate per user of the proposed communication scheme is realized in 10 KHz bandwidth.**

Keywords*—*underwater acoustic communication; fractional Fourier transform; multi-user.

I. Introduction

Underwater acoustic communication technology is very important for military application and it has been used in military domain for a long time. Thus, underwater acoustic channel is a highly space, time and frequency dependent channel [1]. Due to the complexity of channel, the underwater acoustic signals exhibit random temporal and spatial frequency fluctuations in both amplitude and phase [2]. LFM signal is one of the normal time and frequency compressed signals, and it has a better Doppler tolerance and anti-multipath capability. Due to this feature, LFM signal is widely used in sonar, underwater acoustic communication and radio filed.

Based on LFM spectrum bandwidth scheme had been a standard of IEEE 802.15.4a which specifies the physical layer and media access control for low-rate wireless personal area network (LR-WPANs) [3]. In sonar and underwater communication field, LFM is also widely used [4]. As LFM signal has good autocorrelation characteristics and noise immunity, it is used to extract the sync signal and channel estimation [5]. University of Genoa combine chirp spread spectrum (CSS) with direct-sequence spread spectrum (DSSS) to underwater acoustic communication scheme, and the results of the experiments conducted in sea environment show the transmission data rates reach 27 bps in range of 25 km and SNR -9dB with the bit error rate less than 10^{-3} [6]. Xiamen University utilizes Chirp-BOK Ultra-Wideband technology to implement a high reliable chirp underwater acoustic modem and the modem can achieve 300 bps in range of 212 m with error-free transmission while transmit power less than 0.97 w [7]. Northwestern Polytechnical University propose M order CSS scheme and it can reach 300 bps in range of 25km with bit error rate less than 10^{-4}. Matched filters are used in these scheme. In signal processing, a match filter is obtained by correlating a known signal, or template, with an unknown signal to detect the presence of the template in the unknown signal. As orthogonal chirp signals are used as the carrier, match filters cannot make full use of limited bandwidth of underwater acoustic channel. Based on the explicit relationship between the fractional Fourier transform properties of chirp signals and their parameters such as chirp-rate and central-frequency, Harbin Institute of Technology proposed modulation called multiple chirp-rate shift keying which could be demodulated with a method based on fractional Fourier transform [8]. Compared with chirp-BOK modulation, MCrSK can improve data rate as chirp carrier overlap in the frequency domain, but receiver would compute several times FRFT. Although it holds a constant envelope, the MCrSK system could not further improve data rate compared with multicarrier.

Based on fractional Fourier transform properties of chirp signal, this paper proposed a modulation named multicarrier-multiple chirp-rate shift keying (MC-MCrSK), each symbol time include two carriers (up-chirp and down-chirp), so it can get a higher data rate than signal carrier system. The scheme can support multiuser to communication based on chirp-rate combination order. Multipath effect of underwater acoustic would lead receiver to produce erroneous judgment.

In order to establish a stable communication system, channel estimation and compensation is required. And virtual time reversal mirror technology (VTRM) [9] can reduce the impact of multipath effects on the system. The validity of simulation comparison is verified in experiment. 425 bps data rate per user of the proposed communication scheme is realized in 10 KHz bandwidth.

The first section of this article we will introduce the fractional Fourier transform properties of chirp signals and their parameter. Section II will be focused on how to design the MC-MCrSK system and analysis of system parameters. Section III verifies the validity of the scheme in underwater acoustic environment. And analysis and Summary of this scheme will be discussed in conclusion section.

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II. Fractional Fourier Transform of Chirp Signal and Channel Estimation

A. Fractional Fourier transform

Fractional Fourier transform is widely used in signal processing applications as it can be viewed as the chirp-basis expansion directly from its definition, but essentially it can be interpreted as a rotation in the time-frequency plane, i.e. the unified time-frequency transform. A certain order of fractional Fourier transform of chirp is a δ function, so the fractional Fourier transform has a good focus for chirp signal. In addition, fractional Fourier transform is a one-dimensional linear transformation, so it can avoid cross-term than Wigner-Ville transform when dealing with multi-component signals. Fractional Fourier transform can expressed as

$$f_p(u) \equiv \{F^p[f(u')]\}(u) = \int_{-\infty}^{+\infty} K_p(u,u') f(u') du'$$
$$= \begin{cases} \sqrt{\dfrac{1-j\cot\alpha}{2\pi}} \displaystyle\int_{-\infty}^{+\infty} \exp\left(j\frac{u'^2+u^2}{2}\cot\alpha - \frac{ju'u}{\sin\alpha}\right) f(u') du' & \alpha \neq n\pi \\ f(u') & \alpha = 2n\pi \\ f(-u') & \alpha = (2n\pm1)\pi \end{cases} \tag{1}$$

Equation (1) show that FRFT has the following properties:

$$\begin{cases} f_0(u) = f(u) \\ f_1(u) = F(\omega) \\ f_2(u) = f(-u) \\ f_3(u) = F(-\omega) \end{cases} \tag{2}$$

Chirp signal time domain expression for the plural form of writing:

$$x(t) = \exp\left[j\left(2\pi f_0 t + \pi k t^2\right)\right] \tag{3}$$

Where f_0 is the center frequency of chirp signal, k is the chirp-rate and $-T/2 \leqslant t \leqslant T/2$. FRFT of chirp is shown as follows:

We assume that $p \in [-1,1]$

$$x_a(u) = A\sqrt{1-j\cot\alpha} \cdot \int_{-T/2}^{T/2} \exp\left\{j\pi\left[(k+\cot\alpha)t^2 + 2(f_0 - u\csc\alpha)t + u^2\cot\alpha\right]\right\} dt \tag{4}$$

While $p = 2\cot^{-1}(-k)/\pi$, so equation (4) can be rewritten:

$$\left|x_a(u)\right| = AT\sqrt{1-j\cot\alpha}\, Sa\left[\pi(u\csc\alpha - f_0)T\right] \tag{5}$$

Parameters of chirp (p, f_0) carry information of user and symbol, and signal after underwater acoustic channel transmission can be demodulation by p-order FRFT and subscript of peak, so receiver can restore the original message of sender.

In digital signal process field, FRFT must be taken as discrete fractional Fourier transform (DFRFT). Document elaborated DFRFT algorithm, but the most striking is that H.M. Ozaktas [10] gives an algorithm for efficient and accurate computation of the fractional Fourier transform. For signals with time-bandwidth N, the presented algorithm computes the fractional transform in time. And (5) can be rewritten as follows:

$$x_p\left(\frac{m}{2\Delta x}\right) = \frac{A}{2\Delta x}\exp\left\{\frac{j\pi[\cot\alpha]m^2}{(2\Delta x)^2}\right\} \sum_{n=-N}^{N} \exp\left[\frac{j\pi[\cot\alpha](m-n)^2}{(2\Delta x)^2}\right] \exp\left\{\frac{j\pi[\cot\alpha - \csc\alpha]n^2}{(2\Delta x)^2}\right\} x\left(\frac{n}{2\Delta x}\right) \tag{6}$$

Where $\Delta x = \sqrt{\Delta t \Delta f}$

B. Chirp channel estimation

Assuming that transmit signal is $x(t)$, and Gaussian noise of channel is $n(t)$, so channel impulse response can be written as follow:

$$h(t) = A_0\delta(t) + \sum_{i=1}^{N-1} A_i \delta(t-\tau_i) + n(t) \tag{7}$$

After the FRFT operation, receiving signal can be expressed as:

$$R_p(u) = A_0 x_p(u) + \sum_{i=1}^{N} A_i x_p(u - \tau_i\cos\alpha) \cdot \exp\left(j\pi\tau_i^2 \sin\alpha\cos\alpha - j2\pi u\tau_i \sin\alpha\right) + N_p(u) \tag{8}$$

From equation (8), we can see that different delay will produce a series of pulse in the FRFT domain. According to the time-shifting property of FRFT, it's easy to get the relationship between delay and pulse spacing in FRFT domain:

$$\tau_N = \frac{\Delta f_u}{\cos\alpha} \tag{9}$$

τ_N is the delay of two paths, Δf_u is the pulse spacing.

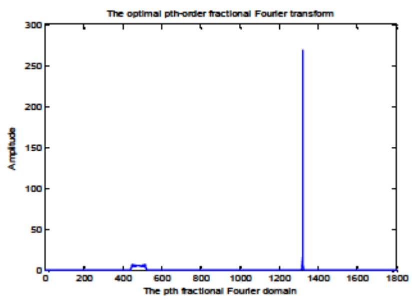


Fig. 1. The p-order FRFT domain of chirp signal

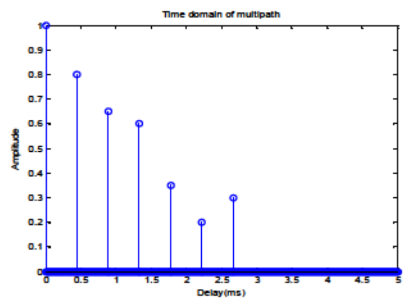


Fig. 2. Channel impulse response in time domain

The Fig. 7 shown the relationship between chirp-rate and the signal bandwidth. Each symbol time contains two carriers-up chirp and down chirp.

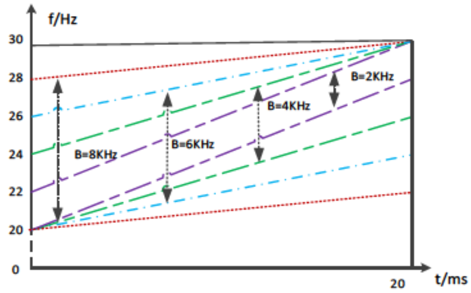


Fig. 7. Relationship between chirp-rate and signal bandwidth

TABLE 2 RALATIONSHIP BETWEEN SWEEP RANGE AND CARRIERD BITS

Range of sweep(KHz)	2	4	6	8
Numbers of bits	5*2	5*2	4*2	3*2

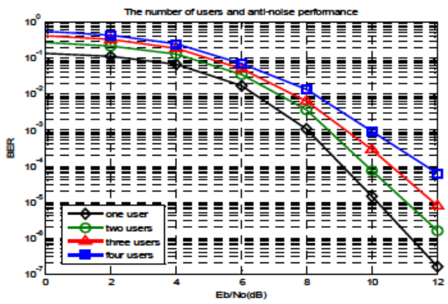


Fig. 8. BER and numbers of users

Form the discussing above, 425bps per user communication rate will be gotten.

C. *Water-tank experiment*

The environment of experiment is the No.2 water-tank of Xiamen University, shown as Fig. 9. It's a non-anechoic tank with the size 22.89m*5.18m and the multipath phenomenon is quite significant.

As shown in Fig. 10, (a) is the original photo, (b) and (c) are respective the receiving photos using VTRM and without VTRM. From the photos received, we can see that VTRM technology can increase the robust for the system.

As shown in Fig. 12, from (b) we can see that original data with up-chirp and down-chirp will be get two pulses after do FRFT processing. As the multipath phenomenon of the water-tank is quite serious, the FRFT domain will get a series of pulses, and it will lead to false judgment (d). And (f) shows the VTRM technology can increase the SNR and decrease the impact of multipath phenomenon.

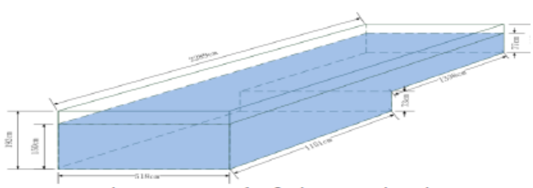
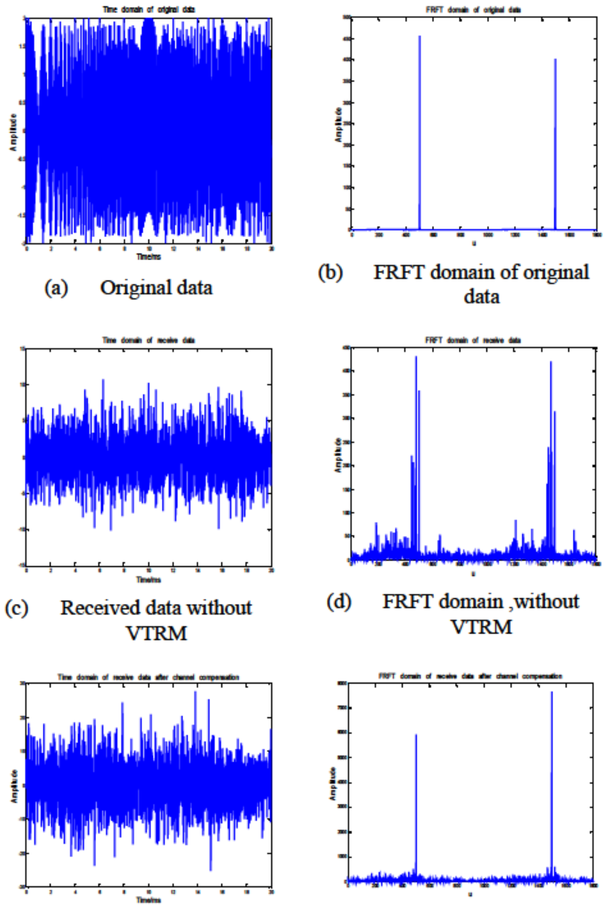


Fig. 9. Water-tank of Xiamen University

(a) Original (b) 0.53% (c) 0.16%

Fig. 10. Sender photo and received photos



(a) Original data (b) FRFT domain of original data

(c) Received data without VTRM (d) FRFT domain ,without VTRM

(e) Received data with VTRM (f) FRFT domain, with VTRM

Fig. 11. Time and FRFT domain of data

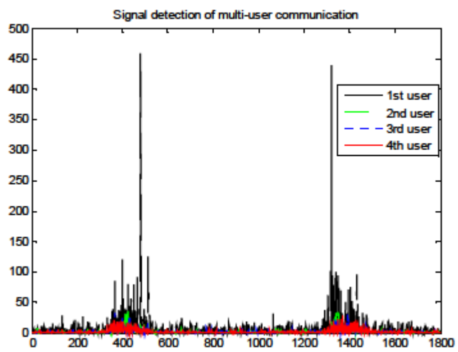


Fig. 12. Interference of multi-user communication