A Precise Synchronization Scheme Using in the Underwater Acoustic Communication System Based on FRFT-OFDM

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***Abstract*—Synchronization is very important in underwater acoustic OFDM communication system based on the fractional Fourier transform (FRFT-OFDM). To improve the synchronization performance, a new way is proposed in this paper, which use symmetrical triangular linear frequency modulation (STLFM) signal as the preamble for the system. A scheme of the communication system based on FRFT-OFDM is given in this paper. The synchronization algorithm using STLFM signal as the preamble is discussed in detail. Theoretical analysis and simulation results show that the proposed synchronization method in optimal fractional Fourier domain can significantly improve the synchronization performance of system as compared to the traditional method.**

***Index Terms*—underwater acoustic communication, FRFT-OFDM, symmetrical triangular linear frequency modulation signal, joint synchronization**

I. Introduction

Underwater Acoustic Communication (UWA Communication) is the primary means of achieving the underwater integrated information perception and interaction. Water acoustic channel is the only physical medium to remotely transport information under the water. The water acoustic channel is the time diffuse and the slowly fading channel. Not only with the distance and with increasing frequency, the loss of energy will becomes larger. So the available bandwidth is only a few thousand hertz. The information capacity of underwater acoustic channel is small, and the time-varying, spatially variable and multipath severely effect in the propagation process, which are seriously restricting the development of underwater acoustic communication technology. Orthogonal Frequency Division Multiplexing (OFDM) has become the most commonly means of high-speed underwater acoustic communication technology for the cause of its characteristics of the simplicity in structure, high spectral efficiency and resistance to the frequency selective fading. However, OFDM is very sensitive to frequency offset and phase noise. Only 1% of frequency offset can make the signal to noise ratio (SNR) decreased 30dB. It is important to achieve precise synchronization at the receiver.

The symbol synchronization methods are Takahashi [1] and Ramasubramanian [2]. But both methods are sensitive to the carrier frequency offset and the accuracy is low. The methods described in [3], [4] require the information of the channel is less, but the operation is too large. The methods described in [5], [6] can overcome the computational complexity, but the estimation accuracy need to be improved.

To achieve synchronization, there are many methods, such as timing synchronization scheme based on time-domain correlation [7] and the LFM signals inserted into the OFDM symbols as a synchronization code [8]. However, synchronization error rate of these methods is higher. In recent years, STLFM signal is used in the LPI radar [9]. In this paper, we use the STLFM signal as a synchronization code inserted into the OFDM symbol. We can search the peak position in the fractional Fourier domain to achieving synchronization. Simulation analysis and verified the validity and reliability by using BER and MSE as an evaluation index. It can achieve precise synchronization scheme using in the underwater acoustic communication system based on FRFT-OFDM.

The paper is organized as follows. Section II describe the system scheme and derives the synchronization algorithm. Simulation results and analysis are presented in Section III. The conclusions are presented in section IV.

II. Precise Synchronization Scheme

A. The Fractional Fourier Transform

The fractional Fourier transform (FRFT) was introduced in [10]. FRFT as a generalization of the Fourier transform attracts increasing attention in signal processing society in recent years. In the signal processing community, the interpretation of the FRFT

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can be seen as a ‘‘rotational” operator in the time-frequency plane.

The p -order FRFT of $x(t)$ is defined as:

$$X_p(u)=\{F_p[x(t)]\}(u)=\int_{-\infty}^{+\infty}K_p(t,u)x(t)dt \quad (1)$$

where p is the order of FRFT, and $\alpha = p\pi/2$. The domains of the signal for $0 \le |\alpha| \le \pi$ are defined fractional Fourier domains and $\alpha = \pi/2$ gives the traditional Fourier transform (FT). $F^p[\cdot]$ denotes the FRFT operator, and $K_p(t,u)$ is the kernel of FRFT:

$$K_p(u,t)=\begin{cases}\sqrt{\dfrac{1-j\cot\alpha}{2\pi}}\exp\left(j\dfrac{t^2+u^2}{2}\cot\alpha - jut\csc\alpha\right), \alpha \ne n\pi\\ \delta(t-u), \alpha = 2n\pi\\ \delta(t+u), \alpha=(2n\pm1)\pi\end{cases} \quad (2)$$

The inverse FRFT (IFRFT) can be expressed as:

$$x(t)=\int_{-\infty}^{+\infty}X_p(u)K_{-p}(t,u)du \quad (3)$$

Equation (3) indicates that signal $x(t)$ can be interpreted as decomposition to a basis formed by the orthonormal LFM functions in the u domain. The u domain is usually called the fractional Fourier domain (FRFD), while the time and frequency domain can be considered as its special cases when p=1.

For practical applications, we need to know the characteristics of FRFT. We use these characteristics, which proposed in the literature [11]. The characteristics are defined as:

(1) Linear characteristic

$$F^p\left[\sum_n c_n x_n(u)\right]=\sum_n c_n\left[F^p x_n(u)\right] \quad (4)$$

(2) Time shift characteristic

$$x(t-\rho)\leftrightarrow \exp\left(j\pi\rho^2\sin\alpha\cos\alpha\right)$$
$$\exp(-j2\pi u\rho\sin\alpha)X_p(u-\rho\cos\alpha) \quad (5)$$

(3) Phase shift characteristic

$$\exp(j2\pi t\rho)x(t)\leftrightarrow \exp\left(-j\pi\rho^2\sin\alpha\cos\alpha\right)$$
$$\exp(-j2\pi u\cos\alpha)X_p(u-\rho\sin\alpha) \quad (6)$$

(4) Fractional convolution characteristic

$$f(t)\otimes g(t)=\frac{B_\alpha}{\sqrt{2\pi}}\exp\left(-j\frac{\cot\alpha}{2}t^2\right)$$
$$\left\{\left[f(t)\exp\left(-j\frac{\cot\alpha}{2}t^2\right)\right]*\left[g(t)\exp\left(j\frac{\cot\alpha}{2}t^2\right)\right]\right\} \quad (7)$$

where $B_\alpha=\sqrt{1-j\cot\alpha}$, $\alpha = p\pi/2$.

(5) Convolution theorem [11]

$$F^p\left[f(t)g(t)\exp\left(jD_\alpha t^2\right)\right]=C_\alpha[F(u)\otimes G(u)] \quad (8)$$

where $C_\alpha=\cot\alpha/2$,

$D_\alpha=\exp\left[-j\pi\,\mathrm{sgn}(\sin\alpha)/4+j\alpha/2\right]/\sqrt{|\sin\alpha|}$

B. The Signal of STLFM Based on FRFT

In each cycle of STLFM signal, there are positive and negative parts of chirp constant and echo part takes the half cycle of a LFM signal. The frequency of signal will increase into a point and then decrease to the beginning point in a signal cycle, performing in each cycle. The STLFM signal model is defined:

$$L(t)=\begin{cases}A\exp\left\{j2\pi\left[\left(f_c-\dfrac{\Delta F}{2}\right)t+\dfrac{\Delta F}{2t_m}t^2\right]\right\}\\ A\exp\left\{j2\pi\left[\left(f_c+\dfrac{\Delta F}{2}\right)t+\dfrac{\Delta F}{2t_m}t^2\right]\right\}\end{cases} \quad (9)$$

where A is amplitude, f_c is carrier frequency, ΔF is modulation bandwidth, t_m is modulation cycle of one LFM. From formula (9), we can obtain the positive and negative modulation frequency of signals were $u_1=\Delta F/t_m$ and $u_2=-(\Delta F/t_m)=-u_1$.

From the literature [12], we can know the signal contains plus chirp constant and negative chirp constant and the fuzzy function of the STLFM signal is quite different to the traditional LFM signal. Thus we can use STLFM as a synchronous signal for increasing the ability of distinguishing.

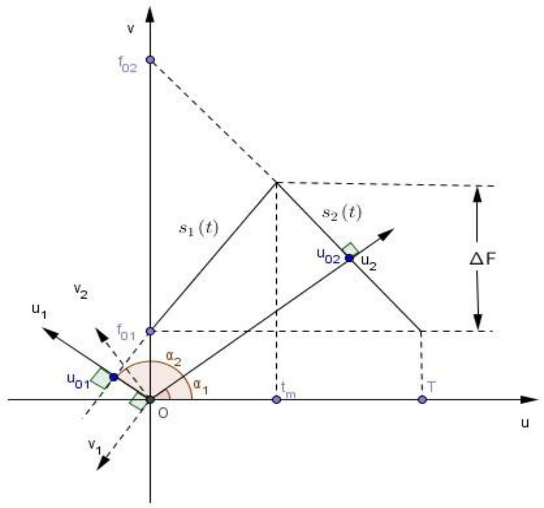

Figure 1. Time-Frequency distribution of a cycle STLFM signal projected on FRFT domain

As the FRFT can be understood the rotation angle of time-frequency, we can analyze the spectrum distribution characteristics of STLFM signal in FRFT domain. Fig. 1 shows a modulation period STLFM signal time-frequency distribution and projection in FRFT domain. α_1 and α_2 were “best” Fractional rotation angle of two LFM signals in a signal cycle. In the corresponding FRFT region, STLFM signal exhibits energy spikes, u_{01} and u_{02} were the coordinate values of the two spikes about LFM signals. If we know the modulation frequency u_1 and u_2, in accordance with characteristic of FRFT, we can obtain the rotation angle, $\alpha_1 = -arc\cot u_1$, $\alpha_2 = -arc\cot u_2 = -\alpha_1$. And $\alpha = \pi p/2$, the Fractional of FRFT were $p_1 = -2arc\cot u_1/\pi$, $p_2 = -2arc\cot u_2/\pi$, then calculated fractional Fourier transform. Respectively, in the corresponding Fractional field search coordinates of the maximum point u_1, u_2. The initial frequency of signal was respectively estimated. $f_{01} = u_1 \csc(p_1\pi/2)$, $f_{02} = u_2 \csc(p_2\pi/2)$. And $f_0 = u_0 \csc(\alpha)$, we can obtain $u_0 = f_0 \sin(\alpha)$. Therefore, we have estimated that the initial frequency of the signal is the point of intersection between the signal's straight line of time-frequency distribution and frequency axis on the original time-frequency plane.

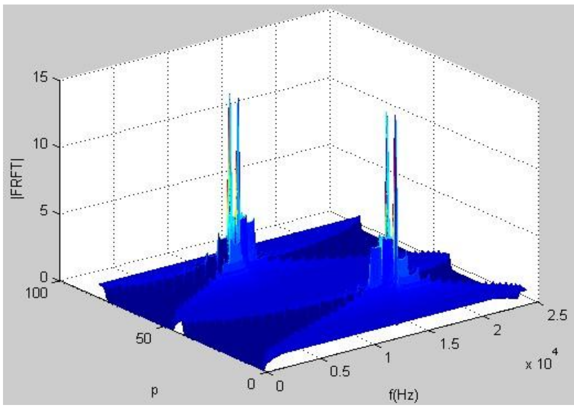

Figure 2. Three-Dimensional of STLFM on FRFT

As shown in Fig. 2, it describes the distribution characteristics of the amplitude spectrum about a period of the modulation period STLFM signal in FRFT domain. The parameters of STLFM signal is defined as f_c =5kHz, ΔF=4kHz, f_s=48kHz, t_m=0.25s. Fig. 2 presents STLFM signal forming four highly similar energy spikes in the plane (u, α). Thus, we can use STLFM signal as synchronization code to detect at the receiving end, the synchronization performance is greatly improved.

C. Signal Model of FRFT-OFDM

According to sampling theory of FRFT-OFDM signal, the transmission signal can be expressed as:

$$y(k) = \sum_{i=0}^{N-1} d_i A_{-\alpha} \exp\left\{-j\pi\left\{\left[\left(\frac{kT_r}{N}\right)^2 + \left(\frac{i}{T_s}\right)^2\right]\cot\alpha - 2\frac{ki}{N}\cdot\frac{T_r}{T_s}\csc\alpha\right\}\right\} \tag{10}$$

where T_s is sampling period of transmitter, N is the number of sub-carriers, $A_{-\alpha} = \exp[-j\pi\,\mathrm{sgn}(\sin\alpha)/4 + j\alpha/2]/\sqrt{|\sin\alpha|}$, d_i is the data of sub-carrier transmission. The received signal can be indicate as:

$$r(k) = \exp(j2\pi\Delta f_c kT_r)[y(k) * h(k)] + \eta(k) \tag{11}$$

where Δf_c is the carrier frequency offset of receiving end, Δf_s is sampling frequency offset of receiving end, $T_r = N/(N/T_s - \Delta f_s)$ is sampling period of receiving end, $h(k)$ is channel impulse response, $\eta(k)$ is noise vector.

D. Synchronization Algorithm

In the sending side, adding a length of N_L STLFM signal as a preamble before each cyclic prefix and an independent sub-carrier to transmit it. The structure of sent OFDM symbol is shown in Fig. 3.

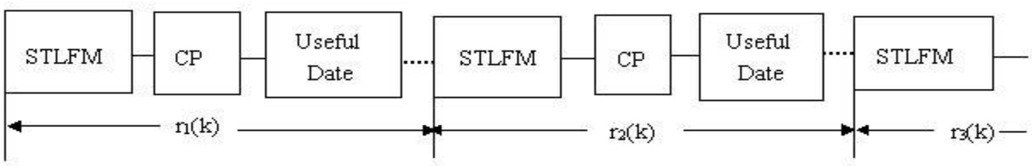

Figure 3. Structure of sent OFDM symbol

From the analysis of STLFM signal on FRFT, when $p_1 = -2arc\cot u_1/\pi$, $p_1 = -2arc\cot u_2/\pi$, STLFM signal showing energy spikes. Random interception of a received signal of 3N_s, the length of each N_s constituted by $r_1(k)$, $r_2(k)$ and $r_3(k)$. Can be expressed as:

$$r_m(k) = r_{L_m}(k) + r_{cp_m}(k) + r_{s_m}(k), m = 1,2,3 \tag{12}$$

where $r_{L_m}(k)$, $r_{cp_m}(k)$, $r_{s_m}(k)$ are represented as STLFM signal, CP and useful data of reception signal. Combine the (10) formula and (11) formula, $r_1(k)$ can be expressed as:

$$r_1(k) = \exp\{j2\pi\Delta f_c[(n-1)N_s + (k-k_0)]T_r\}\{L_1(k-k_0)A_{-\alpha}\exp\left\{-j\pi\left[\frac{(k-k_0)T_r}{N}\right]^2\cot\alpha\right\} * h(k-k_0)\} \tag{13}$$

$r_1(k)$ is transformed in p_1 and p_2 on FRFT, we can obtain:

$$F^{p_1}[r_1(k)] = F^{p_1}[r_{L_1}(k)] + F^{p_1}[r_{cp}(k)] + F^{p_1}[r_s(k)] \tag{14}$$

$$F^{p_2}[r_1(k)] = F^{p_2}[r_{L_1}(k)] + F^{p_2}[r_{cp}(k)] + F^{p_2}[r_s(k)] \tag{15}$$

We can see the (14) formula and (15) formula, only the first items are containing STLFM signal. So we can ignore the other items.

According to linear characteristic of FRFT in the formula (4), we can know that:

$$F^{p_1}[L(k)] = F^{p_1}[L_1(k) + L_2(k)] = F^{p_1}[L_1(k)] + F^{p_1}[L_2(k)] \tag{16}$$

$$F^{p_2}[L(k)] = F^{p_2}[L_1(k) + L_2(k)] = F^{p_2}[L_1(k)] + F^{p_2}[L_2(k)] \tag{17}$$

From the formula (16) and (17), we can know that if p=p_1, $L_1(k)$ will produce power spike and if p=p_2, $L_2(k)$ will produce power spike. Thus, it can produce twice power spike. This greatly improves the target resolution.

Analysis STLFM signals in p_1 on FRFT about the first items in the formula (13), we can obtain:

$$\begin{aligned} F^{p_1}[r_{L_1}(k)] &= \exp\{j2\pi\Delta f_c[(n-1)N_s - k_0]T_r\} \\ &\sum_{l=0}^{L-1} h_l A_{-\alpha} \exp\left\{-j\pi\left[\frac{(k_0+\tau_l)T_s}{N - T_s\Delta f_s}\right]^2 \cot\alpha_1\right\} \\ &F^{p_1}\left\{\exp\{j(kT_L)^2\left\{-\pi\left[\frac{T_s}{(N-T_s\Delta f_s)T_L}\right]^2\right.\right. \\ &\left.\left.\cot\alpha_1\right\}\right\}.\exp\left\{j2\pi(kT_L)\left[\Delta f_c \frac{T_r}{T_L} + \right.\right. \\ &\left.\left.\frac{(k_0+\tau_l)T_s^2}{(N-T_s\Delta f_s)^2}\cot\alpha_1\right]\right\} L_1[k-(k_0+\tau_l)]\right\} \end{aligned} \tag{18}$$

where $h_l(k)$ is the channel impulse response, τ_l is delay time, α_1 is the FRFT transformation angle and k_0 is symbol timing parameter.

We can define $f(k)=1$, so we can obtain:

$$F^{p_1}[f(k)] = F^{p_1}(1) = \sqrt{1 + j\tan\alpha_1}\,\exp\left(-j\frac{u^2}{2}\tan\alpha_1\right) \tag{19}$$

Then we define that

$$g(k) = \exp\left\{j2\pi(kT_L)\left[\Delta f_c\frac{T_r}{T_L} + \frac{(k_0+\tau_l)T_s^2}{(N-T_s\Delta f_s)^2}\cot\alpha_1\right]\right\}. \\ L_1[k-(k_0+\tau_l)]$$

According to time shift characteristic and phase shift characteristic of FRFT respectively in the formula (5) and (6), we can know that

$$\begin{aligned} F^{p_1}[g(k)] &= A_{p_1}\sigma[u-(k_0+\tau_l)\cos\alpha_1 - \theta_1\sin\alpha_1]. \\ &\exp\{j\pi\{[(k_0+\tau_l)^2 - \theta_1^2]\sin\alpha_1\cos\alpha_1 - \\ &2u[(k_0+\tau_l)\sin\alpha_1 - \theta_1\cos\alpha_1]\}\} \end{aligned} \tag{20}$$

where $\theta_1 = \Delta f_c\dfrac{T_r}{T_L} + \dfrac{(k_0+\tau_l)T_s^2}{(N-T_s\Delta f_s)^2 T_L}\cot\alpha_1$.

According to literature [12], combine fractional convolution properties and convolution theorem, bring the formula (19) and (20) into the formula (18), it can be shown as:

$$\begin{aligned} F^{p_1}[r_{L_1}(k)] &= \exp\{j2\pi\Delta f_c[(n-1)N_s - k_0]T_r\} \\ &\sum_{l=0}^{L-1} h_l A_{-\alpha_1}\exp\left\{-j\pi\left[\frac{(k_0+\tau_l)T_s}{N-T_s\Delta f_s}\right]^2\cot\alpha_1\right\} \\ &\frac{B_{\alpha_1}C_{-\alpha_1}}{\sqrt{2\pi}}\exp\left(-j\frac{\cot\alpha_1}{2}u^2\right)\left\{\left\{\sqrt{1+\tan\alpha_1}\exp\right.\right. \\ &\left.\left[j\frac{u^2}{2}(\cot\alpha_1 - \tan\alpha_1)\right]\right\} * \{A_{p_1}\sigma[u-(k_0+\tau_l) \\ &.\cos\alpha_1 - \theta_1\sin\alpha_1]\exp\{j\pi\{[(k_0+\tau_l)^2 - \theta_1^2] \\ &.\sin\alpha_1\cos\alpha_1 - 2u[(k_0+\tau_l)\sin\alpha_1 - \theta_1\cos\alpha_1]\} \\ &\left.+ j\frac{\cot\alpha_1}{2}u^2\}\}\right\} \end{aligned} \tag{21}$$

where $B_{\alpha_1} = \sqrt{1 - j\cot\alpha_1}$, $\alpha_1 = p_1\pi/2$, $C_{\alpha_1} = \cot\alpha_1/2$, when the center frequency of STLFM signal $f = 0$, $p = 2/\pi\arctan(-1/u)$, symbols after FRFT can be expressed as $F^p[x(t)] = A_p\delta(u)$, A_p is the coefficient which associated with p on FRFT.

Due to the impact function has symmetry, convolution result is still symmetric of the (21) formula. The symmetrical point corresponds to the location of impact function. Because of multipath propagation, it will appear L symmetrical points in convolution results. Search for the first point of symmetry, the first path of multi-path channel, when the delay $\tau_0 = 0$, the location of a_1 can be obtained:

$$a_1 = k_0\cos\alpha_1 + \left[\Delta f_c\frac{NT_s}{(N-T_s\Delta f_s)T_L} + \frac{k_0 T_s^2\cot\alpha_1}{(N-T_s\Delta f_s)^2 T_L}\right]\sin\alpha_1 \tag{22}$$

Similarly a_2 can be obtained:

$$a_2 = k_0\cos\beta_1 + \left[\Delta f_c\frac{NT_s}{(N-T_s\Delta f_s)T_L} + \frac{k_0 T_s^2\cot\beta_1}{(N-T_s\Delta f_s)^2 T_L} + \frac{N\csc\beta_1}{(N-T_s\Delta f_s)T_L}\right]\sin\beta_1 \tag{23}$$

$$a_3 = k_0\cos\gamma_1 + \left[\Delta f_c\frac{NT_s}{(N-T_s\Delta f_s)T_L} + \frac{k_0 T_s^2\cot\gamma_1}{(N-T_s\Delta f_s)^2 T_L} + \frac{(N-1)\csc\gamma_1}{(N-T_s\Delta f_s)T_L}\right]\sin\gamma_1 \tag{24}$$

Combine formula (22), (23) and (24) can be obtained:

$$\begin{cases} \Delta f_s' = \dfrac{N - \varepsilon_1}{T_s} \\ \Delta f_c' = \dfrac{(a_2 \cos\alpha_1 - a_1 \cos\beta_1) T_L \varepsilon_1 - N \cos\alpha_1}{N T_s \sin(\beta_1 - \alpha_1)} \\ k_0' = \dfrac{(a_2 \sin\alpha_1 - a_1 \sin\beta_1) T_L \varepsilon_1^{\,2} - N\varepsilon_1 \sin\alpha_1}{(T_L \varepsilon_1^{\,2} + T_s^2)\sin(\alpha_1 - \beta_1)} \end{cases} \tag{25}$$

where ε_1 can be showed as (26) formula.

Similarly, the STLFM signal can be analyzed in p_2. Do not repeat them here.

So far, the STLFM signal parameter estimation such as sampling frequency Δf_s, carrier frequency Δf_c and symbol timing k_0 has been completed in p_1 and p_2.

III. Simulation and Results Analysis

Fig. 4 is block diagram of the FRFT-OFDM system [13]. On the transmit side, the source sends a serial data stream. Firstly, we can obtain the phase data stream by coding map. We convert the dates through series - parallel conversion. Then, the data have done Fractional inverse transformation. To reduce inter-symbol interference, we can insert cyclic prefix between each frame signal as a guard interval. Before each cyclic prefix we add STLFM signal as synchronization code. Through this figure we can see that when $\alpha = \pi/2$, the system is a traditional OFDM system. The different thing is that added the length of N_L STLFM signal before each cyclic prefix as preamble signal.

$$\varepsilon_1 = \frac{1}{T_L} \cdot \frac{N[\cos\alpha_1 \sin(\beta_1 - \gamma_1) - (\cos\gamma_1 - \cos\beta_1)\sin(\beta_1 - \alpha_1)] - \cos\beta_1 \sin(\beta_1 - \alpha_1)}{(a_2 \cos\alpha_1 - a_1 \cos\beta_1)\sin(\beta_1 - \gamma_1) - (a_2 \cos\gamma_1 - a_3 \cos\beta_1)\sin(\beta_1 - \alpha_1)} \tag{26}$$

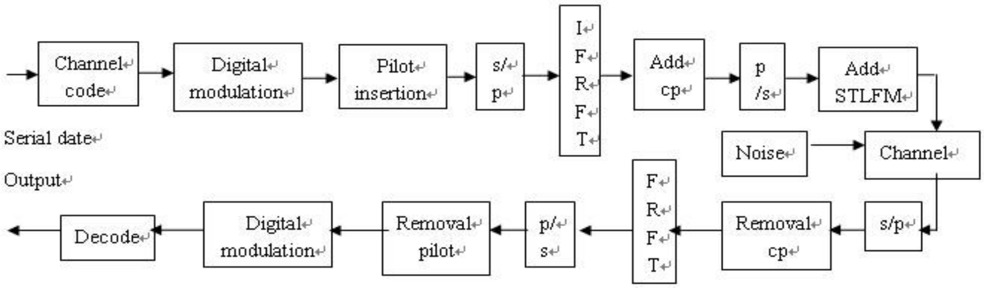

Figure 4. FRFT-OFDM system simulation model for underwater acoustic communication

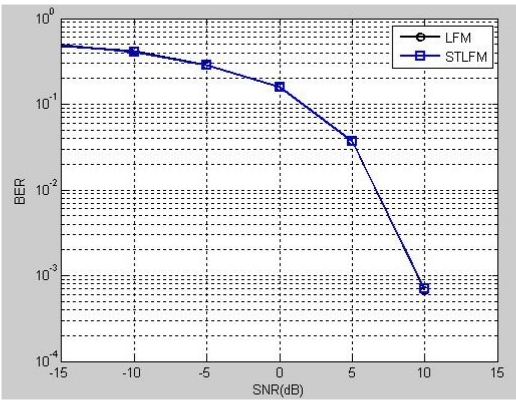

Figure 5(a). BER of the noise-only

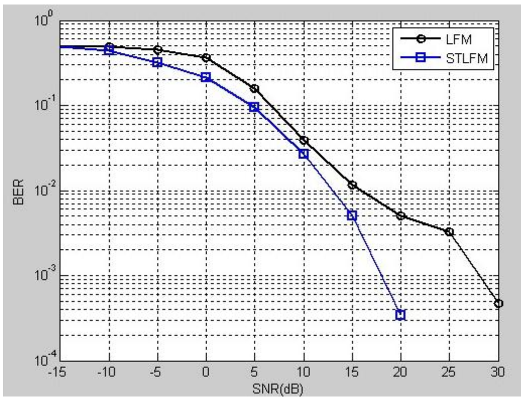

Figure 6(a). BER of existing noise and multipath transmission

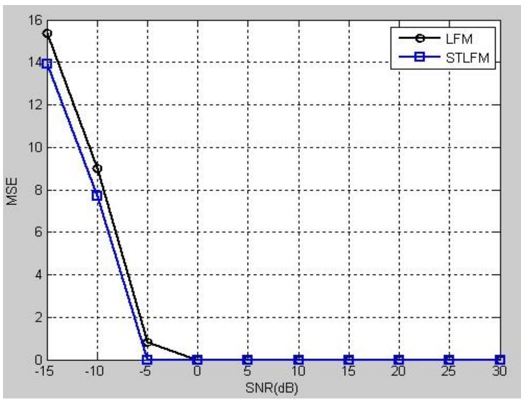

Figure 5(b). MSE of the noise-only

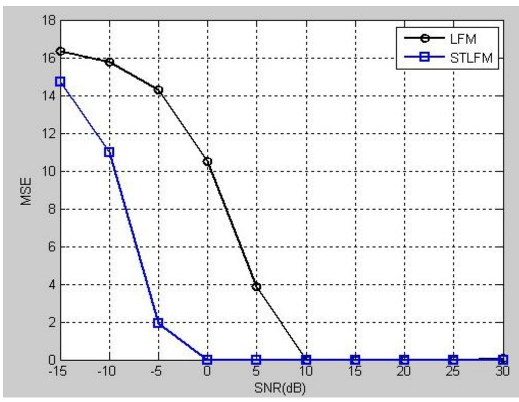

Figure 6(b). MSE of existing noise and multipath transmission

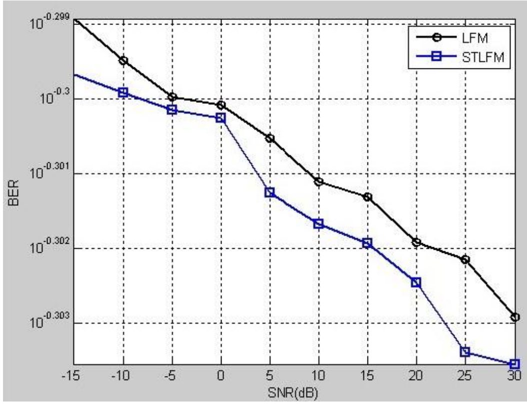

Figure 7(a). BER of existing three interferences

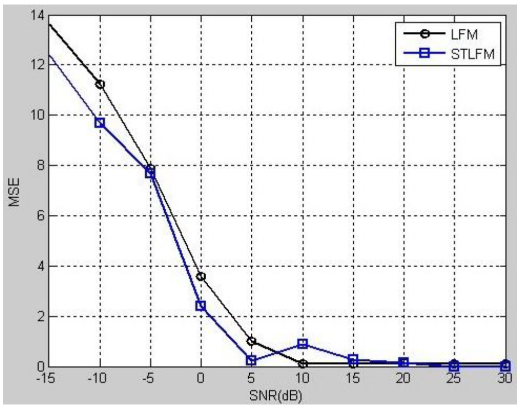

Figure 7(b). MSE of existing three interferences

The parameters of system are 5kHz bandwidth, QPSK modulation, sampling frequency is 48kHz, the length of FRFT is 256, the length of cyclic prefix is 64, each frame contains 100 FRFT-OFDM symbols, the number of underwater acoustic channel path is 5, and the relative velocity of acoustical transducer and acoustical transducer is 20m/s. The simulation results are showed in Fig. 5~Fig. 7.

In Fig. 5(a) and Fig. 5(b), the system only have noise interference, BER is the same toughly. For MSE, the proposed system has advantage by about (-5dB) about ERN. Under the interference of the noise and multipath, Fig. 6(a) and Fig. 6(b) show that the proposed system is better than the system using LFM. In order to achieve the lower BER, the proposed system has advantage by about 10dB about ERN. In Fig. 7(a) and Fig. 7(b), the system has interference of noise, multipath and Doppler simultaneously. When the BER is more accurate, the proposed system have superior performance obviously. For MSE, the proposed system has advantage by about (5dB) about ERN. Therefore, I proposed the scheme that to use STLFM signal as preamble code is better than before.

IV. Conclusion

In this paper, according to STLFM signal with good energy aggregation in the "best" Fractional, I proposed to use STLFM signal as preamble code. Subsequently, a comparison of STLFM signal as preamble code with tradition use LFM signal as preamble code has been made based on the parameters viz. BER and MSE. The simulation results that the presented use STLFM signal as preamble code is more suitable for the Multi-interference channel than the classic scheme. The results are in the conformity of "use STLFM signal as preamble code as a better and superior technique".

Acknowledgment

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