Study of chirp spread spectrum communication system in low frequency atmospheric noise

Wu Yanjun, Wang Huali, Sun Lei
Teaching and Research Center of Electronic Technology, CCE, PLAUST
Nanjing, China

***Abstract*—we present a new communication method at low frequency (LF) of applying a wireless communication system using chirp spread spectrum (CSS) technique. First, we introduce the CSS system, including the modulation and demodulation technique. Then analyze property of LF atmospheric noise in time and frequency domain based on the real atmospheric noise data acquired by superconducting quantum interference device (SQUID) sensor. Finally, we perform the simulation of the CSS system performance in additive white Gaussian noise (AWGN) channel and atmospheric noise channel to verify the feasibility of the application in LF communication system.**

Keywords-Low frequency, Chirp spread spectrum, FRFT, Atmospheric noise,

I. INTRODUCTION

Low frequency (LF) communication is generally referred to use 3Hz to 300 kHz electromagnetic wave to transmit information data in digital communications. LF communication system has many inherent advantages such as high reliability, low propagation fading and long transmission distance, furthermore, it is well suited for underground and underwater communication. Therefore, many countries in the world pay much attention to the LF communication all the time. Early in middle of 20 century, American navy proposed LF magnetism communication technique for submarine communication based on a high sensitive SQUID, they had achieved great success and put it into practice. Owing to high sensitivity of LF communication technique, it is very difficult to know the actual development situation.

Chirp signal is easy to be generated by surface acoustic wave (SAW) devices or digital chirp generators (DCG), and it is a kind of non-stationary signal with low intercepted probability. There are many advantages of sending a chirp signal as the carrier wave in wireless communication system, such as large bandwidth, low power, immune to Doppler frequency offset, robust to multi-path interference, etc. In 1962, M.R.Winkley first proposed transmitting information data by the chirp rate of a chirp signal and used analog technology to actualize the whole CSS communication system [1], In her work, she inferred the rudiments of a binary orthogonal keyed system, where data symbols can be represented by up and down linear chirps. Later, J.pinkley discussed many aspects of the CSS system in his doctor of philosophy (PHD) thesis [2]. However, all their research for the CSS system was based on matched filtering demodulation technique. In 2006, the IEEE committee accepted the CSS system based on coherent demodulation technique as a physical layer criterion implementation of 802.15.4a [3].

Recent years, fractional Fourier transform (FRFT) was proposed by V.Namias, which is viewed as a new transform tool widely applied in non-stationary signal processing such as radar, sonar and communication [4]. The FRFT represents time-frequency information of a signal with single variable and has no cross-term problem. Because of chirp signal has energy concentration in FRFT domain, so the FRFT is well suited for processing non-stationary signal especially chirp-like signal. Upon that, some scholars proposed using FRFT demodulate technique of the CSS system during past decade [5-7]. In this paper, we apply the CSS system based on FRFT demodulation to LF communication system and prove its feasibility.

II. THE FRACTIONAL FOURIER TRANSFORM

The FRFT is a generalization of ordinary Fourier transform with an order parameter p , and it is a one-parameter subclass of linear canonical transform. The FRFT can be viewed as the chirp-basis expansion from its definition, but essentially it can be interpreted as a rotation in the time-frequency domain, so FRFT is also called angular Fourier transform or rotational Fourier transform in some documents [8]. Different physical interpretations have lead to different definitions of the FRFT.

The FRFT of a signal $x(t)$ is defined as

$$X_p(u) = \left\{\mathcal{F}^p[x(t)]\right\}(u) = \int_{-\infty}^{+\infty} K_p(u,t)x(t)dt \tag{1}$$

Where $0<|p|<2$ is the FRFT order, the kernel of the transform $K_p(u,t)$ is defined as

$$K_p(u,t)=\begin{cases} B_\alpha e^{j(\frac{t^2}{2}\cot\alpha - ut\csc\alpha + \frac{u^2}{2}\cot\alpha)} & \alpha \neq n\pi \\ \delta(t\text{-}u) & \alpha=2n\pi \\ \delta(t+u) & \alpha=(2n\pm1)\pi \end{cases} \tag{2}$$

Where $B_\alpha = \sqrt{(1-j\cot\alpha)/2\pi}$, $\alpha = p\pi/2$ indicates the rotational angle of the transformed signal for FRFT.

The inverse FRFT can be given as

$$x(t) = \mathcal{F}^{-p}\left[X_p\right](t) = \int_{-\infty}^{+\infty} X_p(u)K_{-p}(t,u)du \tag{3}$$

It is clear that $x(t)$ can be represented as the summation of a group of orthogonal bases $K_{-p}(t,u)$ with weighted coefficient $X_p(u)$.

Lots of fast algorithms have been put forward to actualize discrete FRFT. In this paper, we use the fast algorithm of discrete FRFT proposed by H.M.Ozaktas [9].

III. CHIRP SPREAD SPECTRUM SYSTEM

A. Modulation

The CSS system is a binary orthogonal keying (BOK) system, and the binary code is digitally modulated on chirp rate. The BOK system uses different chirp rates signal to represent information data. For example, the BOK system takes chirp wave of chirp rate μ ($\mu > 0$) to represent symbol '1', and the chirp wave is called up-chirp signal. Likewise, the chirp wave of a chirp rate $-\mu$ called down-chirp signal is to represent symbol '0'. Figure 1 shows theory of the CSS system transmitter.

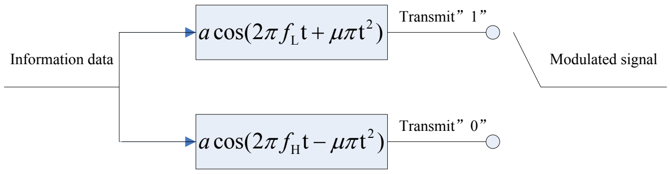

Figure 1 The diagram of chirp rate modulation

Where T, a, μ, f_L, f_H are chirp duration envelop, chirp rate, initial frequency and top frequency respectively. a indicates the chirp envelope and always be set as a constant when $0 < t < T$, others a equals to zero. $B = f_H - f_L = \mu T$ is bandwidth of chirp signal.

B. Matched filtering demodulation

The matched filtering demodulation is a coherent demodulation, owing to excellent autocorrelation property and character of almost orthogonal for different chirp rate signals. Therefore, up-chirp and down-chirp signal can be treated as impulsive response of matched filter for each other [10]. So the BOK system based on matched filtering demodulation diagram can be described as follow.

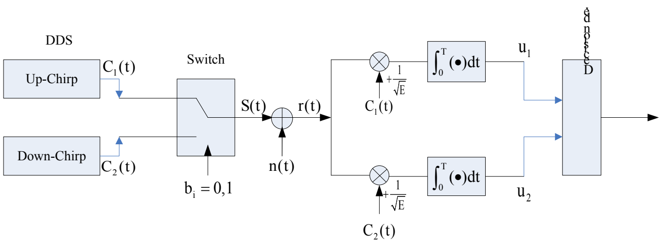

Figure 2 The diagram of match filtering demodulation

C. FRFT demodulation

According to definition of the FRFT, we know the basis functions of the FRFT are a group of orthogonal chirp signals, so chirp signals with different chirp rates have best energy concentration in different FRFT domains. Obviously, there will be a one-to-one relationship between chirp rate μ and transform order p when it varies between 0 and 2, the relationship can be described as

$$\mu = -\cot(p\pi/2) \tag{4}$$

In actual communication system, the transmitted signals are in form of cosine function, so we divide a real up-chirp signal into two parts as

$$s(t) = a\cos(2\pi ft + \pi\mu t^2) = \frac{a}{2}(e^{j(2\pi ft + \pi\mu t^2)} + e^{j(-2\pi ft - \pi\mu t^2)}) \tag{5}$$

The FRFT domain orders of the two conjugate chirp function $\exp[j(2\pi ft + \pi\mu t^2)]$ and $\exp[j(-2\pi ft - \pi\mu t^2)]$ are p and $2-p$, respectively. Therefore, in FRFT domain p, the former part shows property of centralization and position of energy concentration is at right, while energy of the later is dispersed, as illustrated in figure 3. Contrarily, situation for the down-chirp signal in domain p is just the opposite, as shown in figure 4.

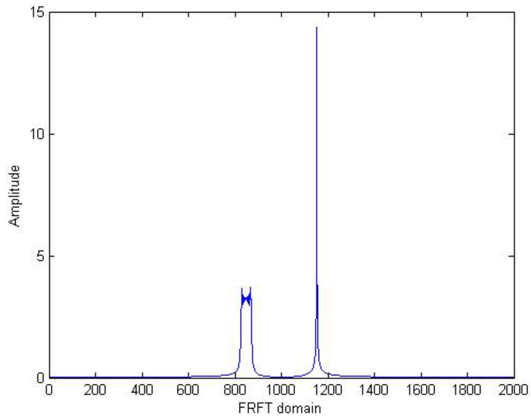

Figure 3 The up-chirp signal in FRFT domain p

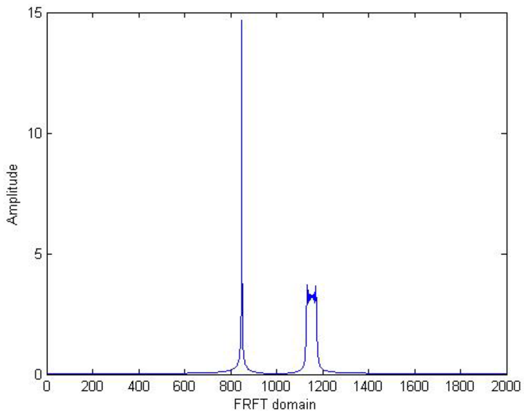

Figure 4 The down-chirp signal in FRFT domain p

Evidently, we can demodulate information according to the energy concentration position of a chirp signal in FRFT domain p. If it is at right, the symbol correspond to the chirp signal is demodulated to be '1', otherwise, it is '0'. Figure 5 shows the block diagram of FRFT demodulation.

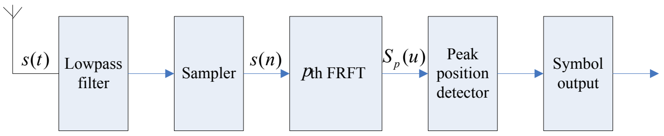

Figure 5 The diagram of FRFT demodulation

IV. ATMOSPHERIC NOISE

As the main noise in LF communication system, atmospheric noise greatly influences performance of LF communication system [11]. Atmospheric noise is the non-Gaussian nature of noise generated by thundering and lighting in atmosphere. It is difficult to analyze the atmospheric noise because of its complex generation and limitation of measurement. Generally speaking, atmospheric noise is summation of impulsive noise and Gaussian noise [12]. In this section, we directly analyze the actual data of atmospheric noise acquired by SQUID sensor.

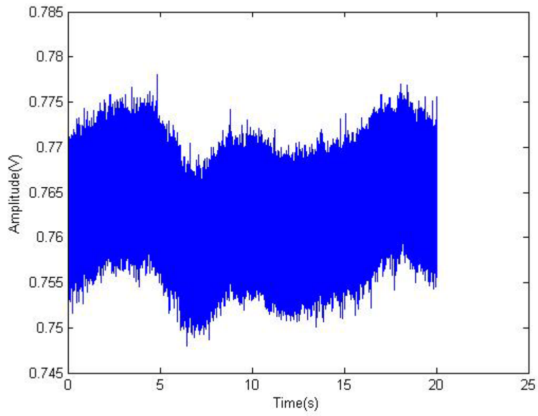

Figure 6 The atmospheric noise wave of 20 seconds duration

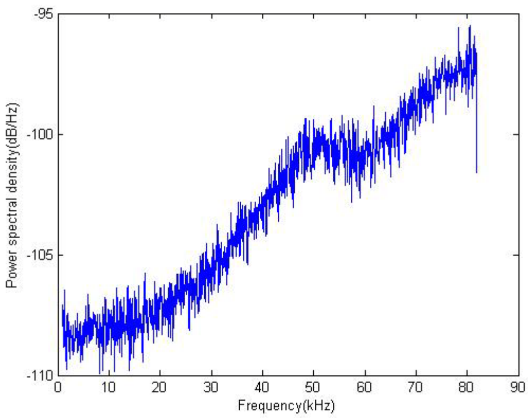

Figure 7 Power spectral density of the atmospheric noise

From figure 6, we can find that the atmospheric noise is stochastic noise with the mean value about 0.765. Because of the mean value of atmospheric noise changes within a narrow range, it is easy to conclude the atmospheric noise property of stochastic and stationary. Additionally, according to power spectral density of atmospheric noise in figure 7, we can see that value of power spectral density is on the increase along with frequency, and the power spectral density value correspond to 75 kHz is 10dB/Hz higher than the value at 15 kHz.

V. SIMULATION

In order to show the feasibility of the CSS system based on FRFT demodulation technique applied in LF communication system. So in this section, we first perform the simulation to show performance of the two demodulations in AWGN channel. Then, we select FRFT demodulation to be demodulation method of the CSS system and compare the system performance in AWGN channel with it in atmospheric noise channel. The simulation parameters are set as follow: sampling rate, code rate, initial frequency and bandwidth are 163.84 kHz, 50 Baud/s, 7 kHz, 1.2 kHz, respectively.

A. Performance in AWGN channel

The matched filtering demodulation is a coherent demodulation which needs to do series of carrier synchronization and phase synchronization. However, the FRFT demodulation is an incoherent demodulation which reduces the difficulty of the system actualization. Owing to the inherent disadvantage of incoherent demodulation, its BER performance is worse off about 3dB towards the coherent demodulation in AWGN channel. From figure 8, we can see that the error rate curve of the FRFT demodulation locates on top of the curve correspond to the matched filtering demodulation, and it is verified that they have performance discrepancy about 3 dB.

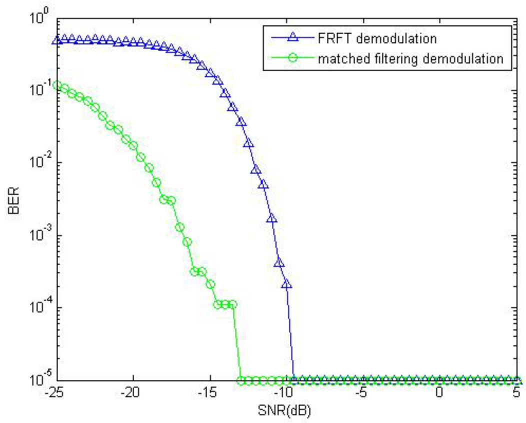

Figure 8 The BER performance of the two demodulations

B. Performance in atmospheric noise channel

Owing to great importance of communication device simplicity in LF communication system and the advantage of FRFT demodulation in low complexity of synchronization actualization, we prefer selecting the FRFT demodulation rather than matched filtering modulation. As a kind of non-Gaussian noise, the property of atmospheric noise is much different from AWGN according to the frequency domain description in figure 7. Therefore, we perform the simulation of the CSS system based on the FRFT demodulation performance in the two channels for the comparison purpose and verify the feasibility in LF communication system.

As is shown in figure 9, the FRFT demodulation performance in atmospheric is worse than in AWGN channel. According to the blue curve, we can find that when the SNR is higher than -5dB, the CSS system based on the FRFT demodulation in atmospheric noise has good BER performance. However, the system fails to work when the SNR is below -5dB. Generally, the SNR in LF communication system is about 0dB.

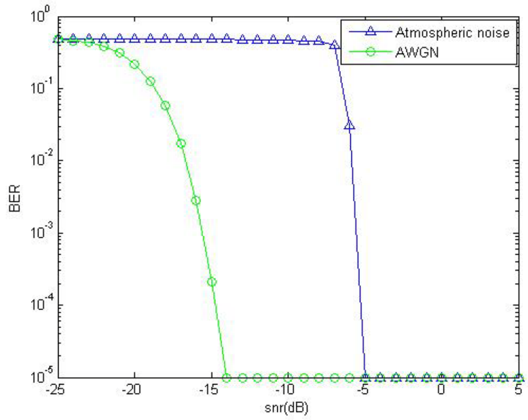

Figure 9 The performance of FRFT demodulation

Therefore, the CSS system based on FRFT demodulation can work normally almost all the cases.

VI. CONCLUSION

Considering that chirp signal has the energy concentration property in FRFT domain, this paper introduced the CSS communication system based on the FRFT incoherent demodulation technique and applied it to LF communication system. Then simulated and compared coherent and incoherent demodulation performance of the CSS system in AWGN channel and atmospheric noise channel, respectively. The simulation results indicated well feasibility of the CSS system based on FRFT demodulation technique in LF communication system.

REFERENCES

[1] M.R.Winkley. Chirp signals for communications [J].proceeding of IEEE WESCON Conference. 1962:14-17.

[2] J. Pinkley. Low Complexity Indoor Wireless Data Links Using Chirp Spread Spectrum, PhD thesis, Dept. Elect. Com. Eng, University of Calgary, Alberta, Canada, 2003.

[3] IEEE Std 802.15.4a-2006, IEEE Stand for information technology –LAN&MAN specific requirements, Part 15.4[S].

[4] V. Namias, The fractional order Fourier transform and its application to quantum mechanics[J]. Inst. Math. Applicat, vol. 25, pp. 241–265, 1980.

[5] B. Deng, R. Tao, D.F. Ping. Study on Chirp-Rate Modulation and Demodulation Based on Fractional Fourier Transform. Acta Electronica Sinica, Chinese Institute of Electronics. Beijing, China, vol. 36, pp. 1078-1083,Jun. 2008.

[6] YuHong Li, Jianhua Lu, YouZheng Wang. A novel chirp based modulation and detection scheme using fractional Fourier transform. IEEE Wireless VITAE 2009, 872-874.

[7] QiMing Zhao, QinYu Zhang, NaiTong Zhang. Multiple chirp-rate modulation based on fractional Fourier transform. IEEE First International Conference on pervasive Computing. signal processing and applications. 2010,688-691.

[8] Tao Ran, Deng Bing, Wang Yue. Research Process of the Fractional Fourier Transform in Signal Processing [J]. Science in China: Series F, 2006, 49(1): 1-25.

[9] H. M. Ozaktas, M. A. Kutay, G. Bozdagi. Digital computation of the fractional fourier transform[J]. IEEE Transactions on Signal Processing. 1996,44(9):2141-2150.

[10] XiaoWei Wang, Minrui Fei, Xin Li. Perforamance of chirp spread spectrum in wireless communication systems. IEEE,ICCS, 2008:466-469.

[11] J. Schwartz. Application of simulation based analysis to receiver design for operation in impulsive atmospheric noise[J]. IEEE Miltary Communication Conference 1989, vol.2, 570-576.

[12] C. R. Warber, E. C. Field, M. J. Shearer. Modeling ELF atmospheric noise[J]. IEEE International Symposium on Electromagetic compatibility, 1993.144-149.