Eng Int Syst (2018) 4: 161–167

Engineering
Intelligent Systems

Analysis of Communication Channels Based on Orthogonal Frequency Division Multiplexing

Liguo Zhao and Hanlei Dong*

Department of Computer and Information Engineering, Luoyang Institute of Science and Technology, Luoyang, China

Due to the complexity of the actual application environment of the communication channel system, channel information will be affected by multi-path fading which seriously jeopardizes the system's optimum performance. For this reason, research based on orthogonal frequency-division multiplexing is undertaken to improve the traditional evaluation methods through Fourier transforms. A maximum likelihood criterion fractional frequency offset estimation algorithm for orthogonal frequency division multiplexing system based on FrFT is proposed. This algorithm uses chirp signal-based subcarriers as sinusoidal subcarriers to replace the traditional orthogonal frequency division multiplexing systems in the propagation of communication signals, and analyzes their effects through simulation. Previous studies have shown that this research method has a smaller frequency deviation estimation mean square error and lower error rate, and offers a useful theoretical reference for subsequent research.

Keywords: Orthogonal frequency division multiplexing; communication channel; carrier; power line

1. INTRODUCTION

At present, high-voltage power line carrier communication technology is more mature and has entered the digital era. The research and application of medium-low voltage power line carrier communication technology has also been boosted by the continuous progress of PLC technology and changes in social needs. In order to improve the reliability and completeness of the communication channel, it is necessary to innovate using current technologies as a basis. By combining orthogonal frequency division multiplexing techniques, effective estimation of the communication channel is achieved (Kaddoum, 2016). British NORWEB began researching low-voltage power line communication technology in 1990. It was the first company in the world to study PLC technology. In October 1997, it collaborated with NORTEL in Canada to develop the earliest experimental network of low-voltage PLCs, which can achieve 1Mbps data transmission. Later, on March 25, 1998, the two companies jointly established NOR.WEB Corporation to market the low-voltage PLC technology (Liu H, 2016). At the same time, research institutes in many countries began research and development work on low-voltage power line communication technologies. These institutes in-

*Corresponding author. E-mail: Rodic007@163.com

cluded RWE, Polytrax in Germany, Intellon, ITRAN, Intelogis in the United States, Xeline in Korea, and SPi DCOM in France, ASCOM companies in Switzerland and DS2 companies in Spain. In 1997, Germany's RWE and Switzerland's ASCOM began collaborating on the research and development of low-voltage power line communication products, focusing on the construction and operation of the power line access market and digital home network (Kumar, 2016). The United States Intellon Corporation launched in early 2001 a 14Mbps PLC chip that reached a practical indoor network. In 2004, Spain's DS2, as the global leader in PLC chip technology, pioneered the introduction of broadband PLC technology achieving speeds up to 200Mbps. It also cooperated fully with China National Grid and accelerated the application of broadband PLCs in automated meter reading and home broadband Internet access (Kim, 2016). China's research on PLC technology started late. The main scientific research institutions are the China Electric Power Research Institute and China Electric Power Communication Center. From 1997, China Electric Power Research Institute began investigating low-speed PLC technology for low-voltage meter reading systems. In May 1999, the specific transmission characteristics of China's low-voltage distribution network began to be tested and its parameters were obtained, which provided a basis for the in-depth study of low-voltage power line communication (Peng Y, 2016). In 1999, China Electric Power Communication Center started tracking the development of PLC technology both at home and abroad. In December 2001 and March of the following year, they took the lead in opening China's first PLC broadband access Internet community using low-voltage power lines as the transmission medium, and completed the use of low-voltage power lines for the first time in China to enable access to the Internet and to make calls. The data transmission rate can reach 10Mbps. In addition, domestic research institutes engaged in PLC-related technologies include Fujian Electric Power Research Institute and other research institutes, and Tsinghua University, Huazhong University of Science and Technology, Harbin Institute of Technology, Xi'an Jiaotong University, and North China Electric Power University. Tsinghua University has successfully developed a low-voltage distribution network experimental platform based on spread-spectrum modulation technology, which uses a 220V low-voltage power line to achieve 10kbps data transmission between two computers (Li Z, 2016).Among them, Tsinghua University has successfully developed a low-voltage distribution network experimental platform based on spread-spectrum modulation technology, which uses a 220V low-voltage power line to achieve 10kbps data transmission between two computers (Li Z, 2016). Shenzhen Guodian Technology Co., Ltd. and Beijing Yike Co., Ltd. are engaged in the production of PLC-related products. Shenzhen Guodian Technology Co., Ltd. mainly develops PLC products for indoor networking, and has developed products with data rates up to 20Mbps through the use of foreign high-speed chips; Beijing Yike has also developed a series of low-voltage PLC products for power line audio/video transmission and low-voltage power line broadband access systems (Gajewski, 2016).

This study examines the carrier synchronization technology of orthogonal frequency division multiplexing systems by combining the characteristics of low-voltage power line communication channels. Therefore, orthogonal frequency division multiplexing technology can be better applied to low-voltage power line carrier communication systems to improve the performance of low-voltage power line orthogonal frequency division multiplexing communication systems.

2. RESEARCH METHODS

This research method is based on the fractional Fourier transform, which belongs to the fractional generalization of the ordinary Fourier transform (FT). Its definition has many equivalent forms, of which the integral form is the most common one. Therefore, this definition is adopted here. The basic function is set to $f(t)$, and its Fourier transform process $F^P \quad L^2(R) \rightarrow L^2$ is expressed as the formula (1). $k_\alpha u(t)$ represents the integral kernel and is defined as the form shown in equation (2). α represents the angle of rotation of the fractional Fourier transform, $\alpha = p \cdot \frac{\pi}{2}$. p represents the transformation order (Wang Y, 2016).

$$F^P f(t) = F_P(u) = \int_{-\infty}^{+\infty} f(t) k_\alpha(u \cdot t) dt \tag{1}$$

$$k_\alpha(u \cdot t) = \sqrt{\frac{1 - j\cos(\alpha)}{2\pi} \exp\left[\cot(\alpha)\frac{u^2 + t^2}{2}\right] - csc(\alpha)ut} \tag{2}$$

$$Ff(t) = F(t) = \int_{-\infty}^{+\infty} f(t)\exp(-j2\pi f t)dt \tag{3}$$

If $p = 1$ is set, $\alpha = \frac{\pi}{2}$ can be known at this time. After pushing to the calculation, the transformed form of formula (1) can be obtained, which can be expressed as formula (3). Equation (3) is the Fourier transform form of communication energy. That is, when the transform order is set to 1, the fractional Fourier transform can be converted into the general Fourier transform form. Since there is a linear relationship $w \cdot 2f \cdot f$ between the frequency f and the angular frequency w, the ordinary Fourier transform has two ways of defining f and w. By analogy, the integral form of the fractional Fourier transform also has another definition. Its expression is the same as (4-5), and the definition of the integral kernel (u, t) is as follows:

$$\begin{aligned} k_\alpha(u, t) &= \sqrt{1 - j\cos(\alpha)} \\ &\quad \times \exp\left[j \times 2\pi \times \left(\cot(\alpha)\frac{u^2 + t^2}{2}\right) - csc(\alpha)u\right] \\ &= \sqrt{1 - j\cos(\alpha)}\exp j \times \pi \times (\cot(\alpha)(u^2 + t^2)) \\ &\quad - 2csc(\alpha)u \end{aligned} \tag{4}$$

In the study of communication channels, an FRFT-based orthogonal frequency division multiplexing system mathematical model is constructed as shown in Figure1.The number of subcarriers is N and the cyclic prefix length is G_n. Therefore, the actual length of the symbols of each OFDM symbol is $N + G_n$. In the subsequent analysis of this chapter, it is assumed that the channel is an AWGN channel, and the system simulation performance is given under the AWGN channel and the power line communication channel, respectively (Adebisi, 2016).

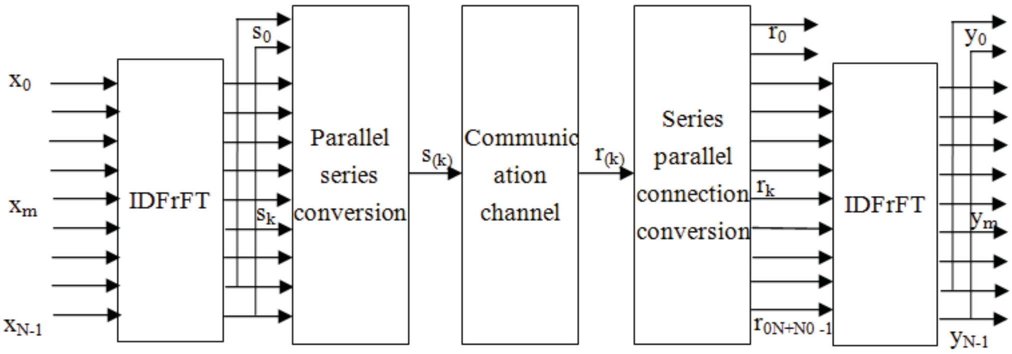

Figure 1 Orthogonal frequency division multiplexing system based on Fr FT.

This research system uses chirp signal-based subcarriers as sinusoidal subcarriers to replace the traditional orthogonal frequency division multiplexing systems in the propagation of communication signals. The chirp signal-based subcarrier signals can be expressed in the form shown in equation (5) ϕ where represents the initial phase, f_0 represents the center frequency, and k represents the frequency of the frequency modulation. It can be seen that the phase of the chirp signal will show a linear change with time, so it can be expressed in the form shown in equation (6), where $w = 2\pi f$, $\frac{df}{dt} = f_0 + kt$. It can be seen that the chirp signal is a chirp signal

(Cruz-Roldán, 2016). $f(t) = \exp j(\phi + 2\pi f_0 + k\pi t^2)$ (5)

$$\frac{dw}{dt} = 2\pi f_0 + kt \tag{6}$$

The actual communication uses a finite-time chirp signal. A rectangular window function can be used to truncate the infinitely long complex chirp signal shown in equation (5). The finite-time complex chirp signal can be written as equation (7) and equation (8), where τ represents the time-domain width of the complex chirp signal with finite duration.

$$\tilde{f}(t) = f(t) \times g(t) \tag{7}$$

$$g(t) = \begin{cases} 1, \ t \in -\tau/2, \tau/2 \\ 0, \ \text{others} \end{cases} \tag{8}$$

Combining the Fourier transform definition, we see that the chirp signal can be transformed when the modulation frequency satisfies a certain relationship. The relationship can be expressed as $k + \cot\alpha = 0$, where k is the chirp signal frequency. So we can express the Fourier transform of the chirp signal as

$$F_p(u) = \int_{-\infty}^{+\infty} \tilde{f}(t) k_\alpha(u,t) dt = \sqrt{1 - j\cot\alpha}\exp(j\pi u^2 \cot\alpha + j\phi) \tag{9}$$

$$\int_{-\infty}^{+\infty} \exp\left[j2\pi\left(\frac{k+\cot\alpha}{2}\right)t^2 + (f_0 - ucsc\alpha)t\right] g(t)dt$$
$$\sqrt{1 - j\cot\alpha}\exp(j\pi u^2)\cot\alpha + j\phi)G(-f_0 + ucsc\alpha) \tag{10}$$

Where $G(-f_0 + ucsc\alpha)$ represents the ordinary Fourier transform of the rectangular window $g(t)$, it can be derived that

$$F_p(u) = \sqrt{1 - j\cot\alpha}\exp(j\pi u^2\cot\alpha + j\phi) \sin c(\tau(ucsc\alpha - f_0)) \tag{11}$$

From the derivation analysis of the above paragraph, it can be seen that $k + \cot\alpha = 0$. Where $\alpha = p \cdot \frac{\pi}{2}$, then $p = \text{arccot}(-k)/(\pi/2)$ can be obtained. Therefore, the amplitude spectrum of a finite-time complex chirp signal in the p-th order fractional domain is the spectrum of the $\sin\alpha$ function after the compression and translation, and then multiplied by a fractional domain chirp signal phase. The amplitude spectrum peak appears at the position of the fractional domain $u = f_0 \sin\alpha$. When the chirp signal is applied to an actual communication system, it is a superposition two conjugate complex chirp signals. The expression is denoted as:

$$\begin{aligned} c(t) &= A\cos(2\pi f_0 + \pi kt^2 + \phi) \\ &= A\{\exp j(2\pi f_0 + \pi kt^2 + \phi)\} \\ &\quad + \{\exp - j(2\pi f_0 + \pi kt^2 + \phi)\}/2 \end{aligned} \tag{12}$$

where $t \in -\tau/2, \tau/2$, τ and A denote the time-domain width and amplitude of the chirp signal, respectively. Chirp signals with the same tuning frequency can generate energy focusing under the same order of fractional Fourier transforms, and the peak positions will be different with different center frequencies.

Based on the above analysis, we simulated the mean square error and bit error rate of ML criterion fractional frequency offset estimation for Fr FT-orthogonal frequency division multiplexing and FT-orthogonal frequency division multiplexing systems over AWGN channel and frequency selective fading power line communication channel, respectively.

3. RESULTS

The fractional frequency deviation estimation mean square error simulation principle diagram is obtained through simulation analysis, as shown in Figure 2. The simulation schematic diagram of fractional frequency offset estimation error rate of power line orthogonal frequency division multiplexing communication system is shown in Figure 3.

IFr FT/Fr FT is used instead of IFFT/FFT to perform subcarrier modulation and demodulation. However, instead of using

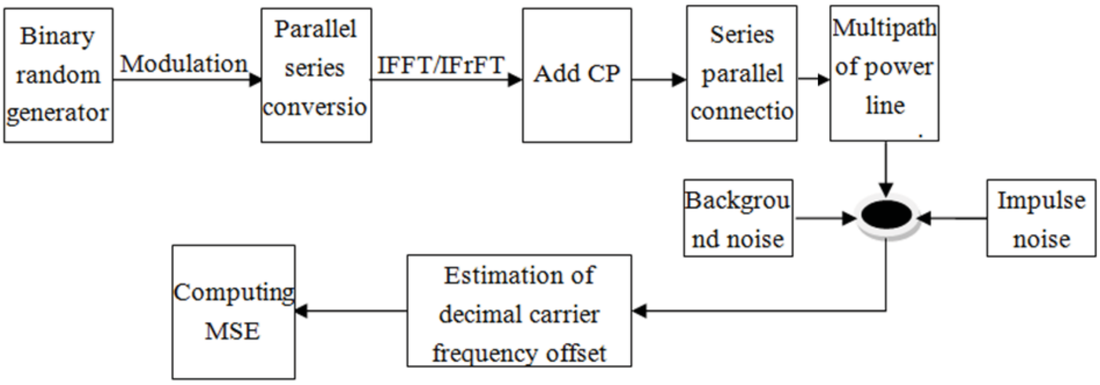

Figure 2 Simulation principle of the fractional frequency deviation estimation mean square error.

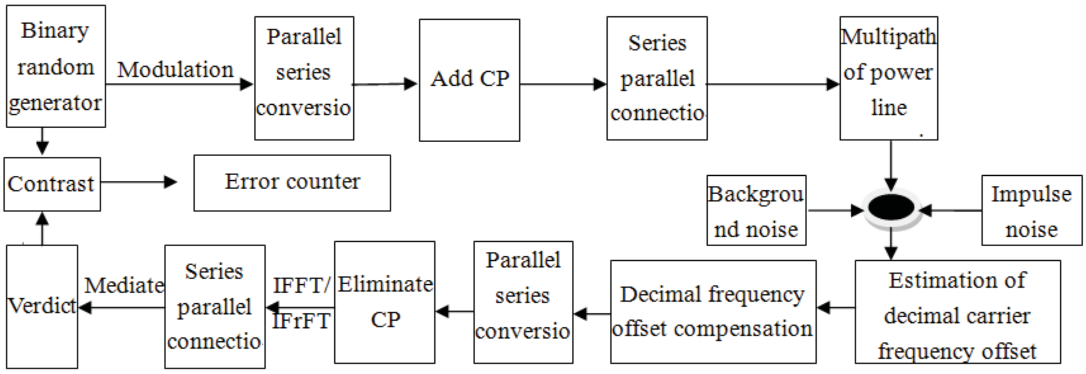

Figure 3 Simulation principle of fractional frequency offset estimation error rate.

Table 1 Simulation performance parameters.

System parameters	Value
FFT/IFFT conversion points	64
CP length	16
Modulation method	BPSK
Signal bandwidth	20MHz
Fractional frequency deviation	0.0064

insertion and removal training sequences, the fractional-time carrier frequency offset estimation and compensation is performed at the receiving end using the algorithm proposed in this chapter. Performance simulation parameters are shown in Table 1.

Figure 4 shows the mean-square error curve of the frequency offset estimation of the maximum likelihood criterion fractional frequency offset estimation algorithm for Fr FT-orthogonal frequency division multiplexing systems over AWGN channels. Figure 5 shows the frequency offset estimation error rate curve of the maximum likelihood criterion fractional frequency offset estimation algorithm for FT-orthogonal frequency division multiplexing systems.

Figure 6 shows the mean squared error simulation curve of ML criterion fractional frequency offset estimation for Fr FT-orthogonal frequency division multiplexing systems and FT-orthogonal frequency division multiplexing systems under power line communication channels. The power line communication channel is a multipath frequency selective fading channel that contains both background noise and impulse noise. The background noise and impulse noise are modeled using the model described in Section 2.1.3; the impulse noise includes burst impulse noise and periodic impulse noise.

Figure 7 shows the BER error curve of the fractional frequency offset estimation of the ML criterion of the Fr FT-orthogonal frequency division multiplexing system and the FT-orthogonal frequency division multiplexing system under the same simulation conditions as in Figure 6.

4. DISCUSSION AND ANALYSIS

The fractional frequency deviation estimation mean square error simulation principle diagram shows that the steps of the fractional frequency deviation estimation mean square error simulation schematic are basically the same as the simulation steps of the integer frequency offset estimation error detection probability. The difference is that subcarrier modulation is performed using IRFPT instead of IFFT in this figure, and no training sequence needs to be added. Through the fractional frequency offset estimation error rate simulation principle diagram, it can be seen that the BER simulation steps of the fractional frequency offset estimation and the BER simulation steps of the integer frequency offset estimation are basically the same. The difference here is that IFrFT/FrFT instead of IFFT/FFT is used for subcarrier modulation and demodulation, and no insertion and removal of training sequences are required, and the receiver uses the algorithm proposed in this

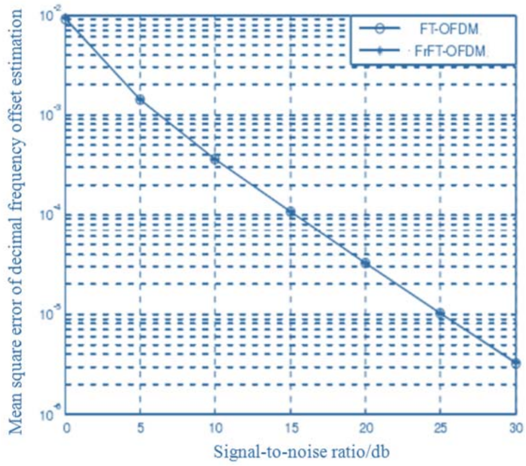

Figure 4 Mean Square Error of Two System Fractional Frequency Offset Estimation for AWGN Channel.

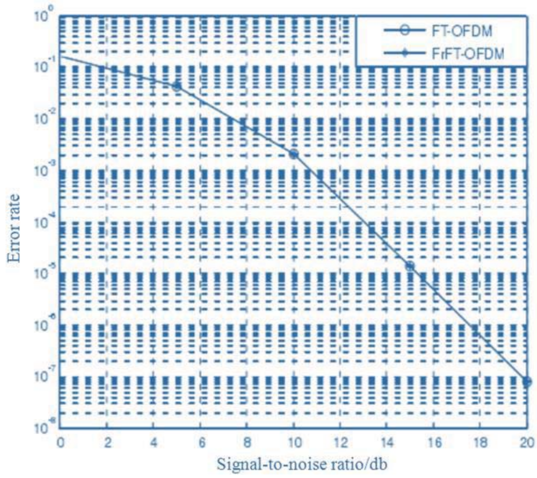

Figure 5 Bit Error Rate of Two-System Fractional Frequency Offset Estimation for AWGN Channels.

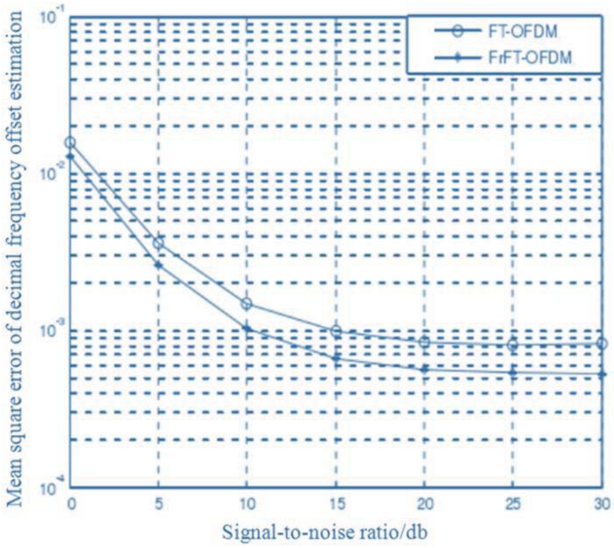

Figure 6 Mean Square Error of Two System Decimal Frequency Offset Estimation for PLC Channel.

chapter to complete fractional carrier frequency offset estimation and compensation.

As shown in Figures 4 and 5, the mean-square error curve and error-error rate curve of the maximum likelihood criterion fractional frequency offset estimation of the two systems coincide. The reason is that the optimal transformation order selection of FrFt under the AWGN channel is chosen as p=1, and it is known from the definition of FrFt that when

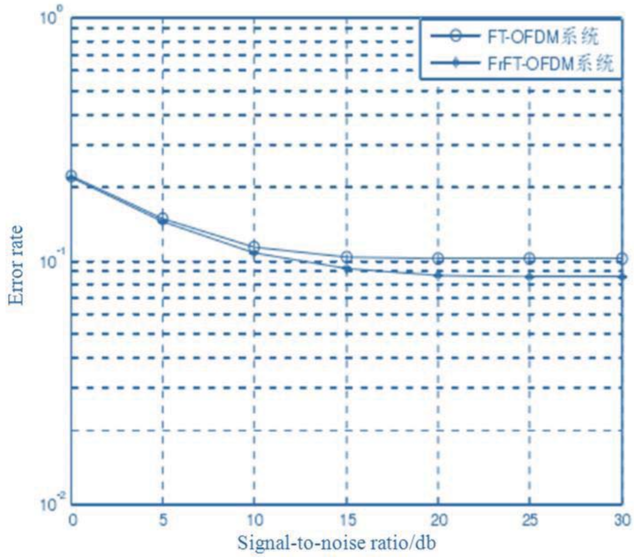

Figure 7 Bit Error Rate of Two Systems Fractional Frequency Offset Estimation for PLC Channels.

the transformation order p=1, FrFt is equivalent to ordinary FT. Therefore, the FrFT-orthogonal frequency division multiplexing system is equivalent to the FT-orthogonal frequency division multiplexing system. At the same time, there will be the same the mean square error performance and bit error rate performance of fractional frequency offset estimation.

Figure 6 shows the mean square error simulation curve of ML criterion fractional frequency offset estimation for FrFT-orthogonal frequency division multiplexing systems and FT-orthogonal frequency division multiplexing systems over power line communication channels. The power line communication channel is a multipath frequency-selective fading channel that includes both background noise and impulse noise which can be a sudden impulse noise or a periodic impulse noise. The frequency selective fading channel environment used in the simulation is: the multipath number is 4, the multipath coefficient is subject to Rayleigh fading, and the relative delay of each path is $\tau = 0, 2, 4, 6 \times 10^7$s, the power distribution of each path at any time is $p(\tau) = 0, -8, -16, -24$dB. Among them, FrFT-orthogonal frequency division multiplexing system's optimal transformation order choice for FrFT is $p = 1$.

As shown in Figures 4 to 8, in the given simulated channel environment, the ML criterion fractional frequency offset estimation algorithm of the FrFT-orthogonal frequency division multiplexing system with a transformation order of $p = 1.01$ has a lower frequency Offset Estimation Mean Square Error than the ML-standard fractional frequency offset estimation algorithm of the FT-orthogonal frequency division multiplexing system. The reason is that the FrFT-orthogonal frequency division multiplexing system uses chirp bases instead of sine bases as subcarriers to carry signals. In frequency-selective fading channels, chirp-based subcarriers can better withstand inter-subcarrier interference caused by fractional frequency offsets compared with sine-based subcarriers.

From Figures 4 to 9, it can be seen that in the multi-path frequency selective fading power line communication channel containing both background noise and impulsive noise, when the system has a fractional frequency offset, the ML criterion fractional frequency offset estimation based on the optimal transform order of the FrFT-orthogonal frequency division multiplexing system shows some improvement in BER performance compared with the FT-orthogonal frequency division multiplexing system. At the same time, lower bit error rate levels can be achieved. The simulation results shown in Figures 4 to 9 show that. The fractional frequency offset estimation algorithm of maximum likelihood criterion for orthogonal frequency division multiplexing system based on FrFT can better resist interference than traditional algorithms. These interferences are generated by fractional carrier frequency offsets in multipath frequency selective fading power line channels that contain both background noise and impulsive noise. This is a fractional frequency offset estimation algorithm suitable for power line orthogonal frequency division multiplexing communication systems.

Based on the above analysis, which addresses the problem of, under multipath frequency selective fading channels, a sharp decline in performance of the maximum likelihood criterion fractional frequency offset estimation algorithm for traditional orthogonal frequency division multiplexing systems based on cyclic prefix of AWGN channel, chirp bases are used as subcarriers instead of sinusoids, and an FrFT-based fractional frequency offset estimation algorithm for orthogonal frequency division multiplexing systems is proposed in this study. The algorithm can better deal with the fractional carrier frequency offset interference in frequency selective fading channels. The simulation results show that, compared with the traditional maximum-likelihood criterion estimation algorithm of orthogonal frequency division multiplexing systems, the maximum likelihood criterion fractional frequency offset estimation algorithm based on FrFT for the orthogonal frequency division multiplexing system proposed in this study has a smaller frequency-estimation mean-square error and a lower bit error rate in the multipath frequency selective fading power line communication channel, in which the background noise and impulse noise of the channel exist simultaneously.

Therefore, this algorithm has practical value for fractional frequency offset estimation of power line orthogonal frequency division multiplexing communication systems.

Power line carrier communication uses the existing power line network for signal transmission and has the advantages of multiple users, wide distribution, long transmission distance, high communication reliability, no need for re-wiring, and synchronization of power grid construction. Because of the complexity of the actual use environment of the power line system, the channel information will be affected by multipath fading, which seriously compromises the system's performance. At this time, we use the channel estimation method to judge and define the response change of the channel. At the same time, however, the accuracy of the channel estimation method will affect the system's performance, so we have been continuously searching for a better solution. This study simulates the PLC channel model, proposes an improved algorithm based on the classical channel estimation method, and then verifies its feasibility with MATLAB. Our work combines the characteristics of low-voltage power line communication channel to study the carrier synchronization technology of orthogonal frequency division multiplexing system, so that the orthogonal frequency division multiplexing technology can be better applied to low-voltage power line carrier communication system and improve the performance of low-voltage power line orthogonal frequency division multiplexing communication systems. Through research, it can be seen that this proposal has good channel communication capability based on orthogonal frequency division multiplexing communication.

5. CONCLUSION

Based on the characteristics of the low-voltage power line communication channel, this paper studies the carrier synchronization technology of orthogonal frequency division multiplexing systems so that orthogonal frequency division multiplexing can be applied to low-voltage power line carrier communication systems. This research is based on orthogonal frequency division multiplexing techniques and takes transformations based on fractional Fourier transforms. The system uses the chirp signal-based subcarriers as sinusoidal subcarriers to replace the traditional orthogonal frequency division multiplexing systems in the propagation of communication signals. In actual communication, chirp signals of finite duration are used, and they can be truncated by a rectangular window function to obtain the infinitely long complex chirp signal shown in equation (5). Based on the above analysis, we simulate the mean squared error and bit error rate of ML criterion fractional frequency offset estimation for Fr FT-orthogonal frequency division multiplexing and FT-orthogonal frequency division multiplexing systems over AWGN channel and frequency selective fading power line communication channel, respectively. Orthogonal frequency division multiplexing system, in this study, based on FrFT, the maximum likelihood criterion fractional frequency offset estimation algorithm has a smaller frequency deviation estimation mean square error and lower bit error rate in the multipath frequency-selective fading power line communication channel existing simultaneously with background noise and impulse noise. It shows that this algorithm has practical value for the fractional frequency offset estimation of a power line orthogonal frequency division multiplexing communication system.

REFERENCES

1. Kaddoum G. Design and Performance Analysis of a Multiuser OFDM Based Differential Chaos Shift Keying Communication System[J]. IEEE Transactions on Communications, 2016, 64(1):249-260.
2. Liu H., Yin Z., Jia M., et al. SER analysis of the MRC-OFDM receiver with pulse blanking over frequency selective fading channel[J]. Eurasip Journal on Wireless Communications & Networking, 2016, 2016(1):135.
3. Kumar A., Magarini M., Joshi H. D., et al. Exact SER Analysis of DFrFT-Based QPSK OFDM System over Frequency Selective Rayleigh Fading Channel with CFO[J]. Journal of Computer Networks & Communications, 2016, 2016(6):2.
4. Kim S. Y., Kim W. C., Song H. K. Relay Selection Scheme for Improved Performance in the Wireless Communication Systems Based on OFDM[J]. Ieice Transactions on Fundamentals of Electronics Communications & Computer Sciences, 2017, 100(10):2200-2203.
5. Peng Y., Wang P., Xiang W., et al. Secret Key Generation Based on Estimated Channel State Information for TDD-OFDM Systems Over Fading Channels[J]. IEEE Transactions on Wireless Communications, 2017, 16(8):5176-5186.
6. Li Z., Xia Y., Pei W., et al. Noncircular Measurement and Mitigation of I/Q Imbalance for OFDM-Based WLAN Transmitters[J]. IEEE Transactions on Instrumentation & Measurement, 2017, 66(3):383-393.
7. Gajewski S. Design of OFDM-Based Radio Communication Systems for Coast-to-Sea and Coast-to-Air Propagation Environments[J]. Polish Maritime Research, 2016, 23(1):12-19.
8. Wang Y., Wang D., Ma J. Performance analysis of multihop coherent OFDM free-space optical communication systems[J]. Optics Communications, 2016, 376:35-40.
9. Adebisi B., Rabie K M., Ikpehai A., et al. Vector OFDM Transmission Over Non-Gaussian Power Line Communication Channels [J]. IEEE Systems Journal, 2017, PP(99):1-9.
10. Cruz-Roldán F., Pinto-Benel F. A., Campo J. D. O. D., et al. A Wavelet OFDM Receiver for Baseband Power Line Communications[J]. Journal of the Franklin Institute, 2016, 353(7):1654-1671.