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Research Article

Research on a Unified Framework Based on Linear Frequency Modulation and Orthogonal Frequency-Division Multiplexing

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This paper proposes a unified system framework based on linear frequency modulation (LFM) and orthogonal frequency-division multiplexing (OFDM) as a solution for resource sharing, especially sharing space and hardware. The proposed OFDM-LFM framework can not only transmit data flow by OFDM but also make it possible to extract features from the signal by LFM. Further, the signal features are used to construct a pseudospectrum related to the target speed and distance, thereby estimating the speed and distance of the target. Unified means using signal features to estimate target speed and distance while ensuring data transmission including communication and remote control data information. Besides the traditional data transmission mode, the ability of estimating target speed and distance is an additional benefit. The proposed unified framework makes control of transmission easier and saves more hardware resources. The simulation results show that the proposed LFM-OFDM framework can not only transmit data information including communication and remote control data information, but also estimate the speed and distance of the target by its signal features.

1. Introduction

The increasing demand for different electronic applications results in multiusage of both hardware and space resources. As a solution, resources and space sharing can efficiently alleviate this issue. Illuminated by a communication and computation resources method proposed in [1], this paper proposes a resource-sharing framework to estimate distance, velocity, and data together. As one of the solutions for shared resources, as far as authors know, current scholars have proposed sharing frameworks such as estimating both distance and velocity together [2], both obtaining angles and frequencies together [3, 4], and so on. However, the resource-sharing model for three or more different kinds of dimensions such as location, velocity, and data obtaining is still needed to be explored. Specifically, this paper mainly focuses on how to use a signal to fulfil a variety of signal functions, such as measurement, control, and communications. This paper proposes a unified framework based on OFDM-LFM, in which orthogonal LFM signals are used as subcarriers, and the fractional Fourier transform (FrFT) is used as a modulation and demodulation method. So far, OFDM-LFM is mainly used in waveform design [5] and MIMO radar [6]. This kind of usage has a common limit that LFMs do not carry data information, only using the changes of amplitude and distance to estimate velocity and distance. The innovation of this paper is that OFDM-LFM framework is not only utilized in measurements such as velocity and distance but also undertakes the task of data transition such as communication and remote control.

This paper takes the FrFT to analyse OFDM-LFM signals. Specifically, the FrFT plays the role of rotating the time-frequency structure of the LMF signal with a given angle; thus, the signal is transferred to an FrFT domain. For the approximation of the optimal angle of transform in FrFT-OFDM systems, refer to [7]. The signal can be processed according to the aggregation of the LMF signal in the FrFT domain. So far, FrFT is mainly used in DOA [8] to estimate the DOA of wideband LFM signals instead of FFT [9], detect moving target [10], underwater communications [11], and so on. In frame design, Wang et al. [12] exploited the wireless channel response and FrFT to achieve anti-eavesdropping downlink transmission over a multipath channel. In the unified framework of this paper, FrFT is used to analyse the time-frequency structure of OFDM-LMF signal, which separates two dimensions, relating to velocity and distance that cannot be distinguished by FFT, so as to ensure the effective transition of data flow.

In this unified framework, a variety of functions are integrated. In this way, the interference caused by the channel frequency response can be overcome. Moreover, using the orthogonal LFM signals as subcarriers can not only improve the spectrum utilization and external measurement performance but also effectively cope with the impact of time-selective fading and then improve the anti-Doppler effect.

The article structure is as follows. In Section 2, the basic theory of OFDM-LFM is described firstly. Section 3 proposes a unified system of measurement, control, and communication based on OFDM-LFM. In Section 4, a signal processing method based on the modulation code domain is proposed by using FrFT instead of Fourier transform (FT). The Section 5 presents digital simulations focusing on the aforementioned methods. Simulation results show that the proposed unified framework can meet the requirements of velocity and distance estimation. In further research, authors would simulate the reliability and stability of the unified framework.

2. Unified System Framework Based on OFDM-LFM and FrFT

In this section, this paper proposes a framework for a unified measurement, control, and communication system based on FrFT. The OFDM-LFM signal is generated by orthogonal chirp rectangular pulse signals. A signal can be decomposed into a combination of mutually orthogonal chirp signals by FrFT.

2.1. A Unified Framework Based on OFDM-LFM and FrFT. As an important multicarrier modulation technology, OFDM has a strong antipulse interference and anti-multipath effect, suitable for high-velocity transmission of wireless data. However, in channels with simultaneous changes in time and frequency, the channel will have both time selectivity and frequency selectivity. The OFDM system cannot analyse the channel frequency changes in real time and thus cannot effectively deal with nonstationary signals. On the other hand, the OFDM system is very sensitive to the Doppler shift. Subcarrier orthogonality will be weakened, causing serious ICI when there is a large Doppler shift.

OFDM-LFM signal can be composed of orthogonal linear frequency modulation (LFM) rectangular pulse signal, and the signal can be expressed as follows:

$$s(t) = \sum_{m=0}^{M-1} \sum_{n=0}^{N-1} d_{m,n} \exp\left(j2\pi f_n t + j\pi\mu t^2\right) \cdot \mathrm{rect}(t - m \cdot T), \tag{1}$$

where $\exp(j2\pi f_n t + j\pi\mu t^2)$ is n^{th} linear frequency modulated subcarrier, N is the number of subcarriers, M is the number of symbols, $d_{m,n}$ is the m^{th} data symbol modulated on the n^{th} subcarrier, f_n is the carrier frequency of the n^{th} subcarrier which can be expressed as $n \cdot \Delta f$, Δf is the interval of subcarriers, T is the OFDM symbol cycle, $\mathrm{rect}(t)$ is the rectangular window function, $\mu = B_s/T_p$ is the frequency modulation slope, B_s is the frequency change width, and T_p is pulse width.

It can be proved that the OFDM-LFM signals modulated on adjacent subcarriers are orthogonal to each other within a pulse width; thus, there is no mutual interference among subcarriers.

As can be seen from Figure 1, the total bandwidth of the OFDM-LFM signal is determined by the combination of the LFM subcarrier bandwidth and the carrier frequency interval between subcarriers. The total bandwidth of the OFDM-LFM signal can be expressed as

$$B = B_s + (N - 1) \cdot \Delta f. \tag{2}$$

It is advantageous to avoid generating two additional side lobes during the reception of the signal processing at critical condition of $B_s = \Delta f$. Therefore, this paper will use this critical condition for the analysis of subsequent results.

The LFM signal is a time-varying signal, with a large Doppler margin. The subcarrier LFM signal can suppress the influence of the frequency shift caused by the Doppler effect. Moreover, the compensation of the Doppler effect is lower or even without compensation, which is conducive to reducing the complexity of system design and improve the overall performance of the system. The proposed OFDM-LFM unified system measurement, control, and communication system framework based on the FrFT is shown in Figure 2.

In the previous framework, functional units are separated from each other and different functions are supported by different units. After then, different functional information is integrated at a backend processing unit. This approach leads to a waste of time as well as hardware resources. In the proposed unified OFDM-LFM framework, its “unified” means that telemetry, remote control, and communication functions can be implemented in only one system. Among them, the OFDM part utilizes 16-QAM to modulate/demodulate communication and remote control data. After processes such as IDFrFT and symbol domain-based algorithm, the pseudo spectrum of the Doppler shift and propagation delay could be characterized. Thereby, we could estimate the speed and distance of the target.

In the transmitter, firstly, the binary data, after the subframe grouping and serial-parallel conversion, are converted into data in the form of complex numbers by symbol mapping. Then, via IDFrFT modulation, it is transformed into a unified measurement, control, and communication signal. After the modulation process, the parallel data stream is transformed into a serial data stream formed by a parallel conversion. After then, in order to avoid the effects of multipath propagation and maintain the orthogonality between subcarriers, it is necessary to add a

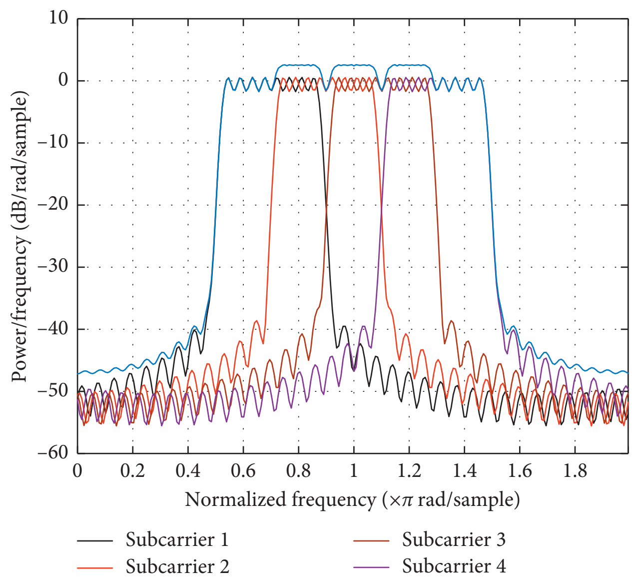

Figure 1: Spectrum of OFDM-LFM with four subcarriers in which sub-bands are four square waves that are orthogonal to each other.

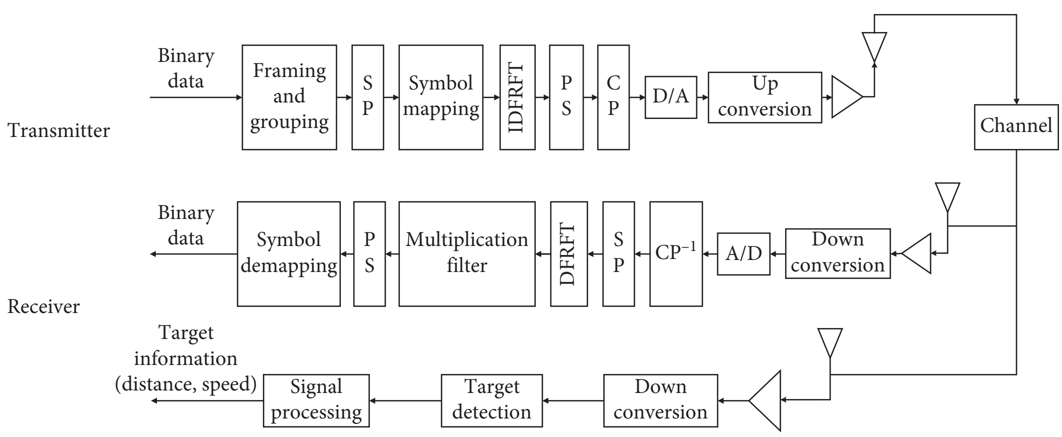

Figure 2: OFDM-LFM unified system measurement, control, and communication system framework based on the FrFT.

cyclic prefix to the serial data stream. And then, the unified measurement, control, and communication signal is converted into an analog signal by digital-to-analog conversion. After the upconversion and power amplification, the unified signal is finally transmitted over the channel to the receiver.

In the receiver, the received signal is multiutilized in two paths. In the first path, the received signal is converted into a digital baseband signal through a low-noise amplifier, a down-converter, and an analog-to-digital converter. Then, the added cyclic prefix is removed and the data stream is converted from serial to parallel. Subsequently, a series of operations such as DFrFT demodulation, fractional Fourier multiplication, and serial conversion from parallel to serial are performed. Finally, binary data will be obtained by demapping the complex form of data symbols. In the second path, the receiver receives the target echo, based on the modulation symbol domain signal processing method, to estimate the target velocity, distance, and other information.

Among them, the specific algorithms involved in modulation and demodulation will be present in the following sections.

2.2. The Theoretical Basis of Fractional Fourier Transform. The integral operation of the p^{th} order FFT and IFFT of the time domain signal $x(t)$ can be expressed as follows [13, 14]:

$$\begin{aligned} x_p(u) &= \{F^p[x(t)]\}(u) = \int_{-\infty}^{+\infty} K_p(u,t)x(t)dt, \\ x(t) &= \left\{F^{-p}\left[x_p(u)\right]\right\}(t) = \int_{-\infty}^{+\infty} K_{-p}(u,t)x_p(u)du, \end{aligned} \tag{3}$$

where F^p is the FrFT operator, p is the order of FrFT, u is the FrFT domain, and $K_p(u,t)$ is the kernel function of FrFT, which can be expressed as follows [13, 14]:

$$K_p(u,t) = A_\alpha \exp\left[j\pi\left(u^2 \cot\alpha - 2ut\csc\alpha + t^2\cot\alpha\right)\right], \tag{4}$$

where $\alpha = p\pi/2$ is the rotation angle of the time-frequency axis and $p \neq 2n$ (n is an integer). A_α can be expressed as follows [13, 14]:

$$A_\alpha = \sqrt{1 - j\cot\alpha}. \tag{5}$$

It can be seen from equation (3) that $x(t)$ can be expressed as a set of orthogonal basis functions $K_{-p}(t,u)$ with a set of weights $x_p(u)$. Therefore, the FrFT can be regarded as the base decomposition form of the LFM. Moreover, the FrFT of the LFM signal has a better time-frequency aggregation. If the current FT is regarded as the decomposition of the signal on the harmonic signal, the FrFT is the decomposition of the signal on the LFM. When the order p is 0 and 2, FrFT corresponds to the signal itself and its flip on the time axis, respectively. When the order is 1 and −1, FrFT corresponds to the signal FT and inverse Fourier transform (IFT), respectively.

In order to apply the FrFT to the actual digital signal processing, we need to use the decomposing fractional discretization algorithm. The decomposing fractional discretization algorithm divides the signal into convolutional form according to the FrFT expression. Thus, we could utilize the fast Fourier transform (FFT) algorithm to compute the FrFT after sampling, $x_p(u)$ in equation (3) can be expressed as follows:

$$x_p\left(\frac{m}{2\Delta x}\right) = \frac{A_\alpha}{2\Delta x}\exp\left[\frac{j\pi m^2(\cot\alpha - \csc\alpha)}{(2\Delta x)^2}\right]\cdot\sum, \tag{6}$$

where

$$\sum = \sum_{n=-N}^{N}\exp\left[\frac{j\pi(m-n)^2\cot\alpha}{(2\Delta x)^2}\right]\exp\left[\frac{j\pi n^2(\cot\alpha - \csc\alpha)}{(2\Delta x)^2}\right] \cdot x\left(\frac{n}{2\Delta x}\right). \tag{7}$$

The equation above is a convolution operation of two signals, which can be performed by FFT. After the summation operation, the final output sample value is obtained by LFM. The overall computational complexity is $O(N\log N)$. From the DFrFT property, it could be known that FrFT will degrade to a DFT when p is 1.

2.3. Signal Processing Method Based on Modulated Symbol Domain. Due to the Doppler effect and delay of the channel, the received OFDM-LFM signal will additionally carry signal features, which could be used to estimate the distance and velocity of the target. This section proposes to utilize the modulation symbol domain algorithm to estimate the distance and velocity information of the transmitter in the OFDM-LFM framework, thereby completing the telemetry requirements of the proposed unified system.

We assume that the velocity and distance between the transmitter and the receiver are v and R, respectively. The received OFDM-LFM signal can be expressed as

$$\begin{aligned} y(t) &= \sum_{m=0}^{M-1}\exp\left(j2\pi\left(f_d - \mu\tau\right)t\right)\cdot\sum_N\cdot\operatorname{rect}(t-\tau-mT),\\ \sum_N &= \sum_{n=0}^{N-1} d_{Tx}(mN+n)\cdot\exp\left(j2\pi\left(f_n + \frac{\mu}{2}t\right)t\right)\\ &\quad\cdot\exp\left(-j2\pi\left(f_n - \frac{\mu}{2}\tau\right)\tau\right), \end{aligned} \tag{8}$$

where τ is the time delay caused by the relative distance R and f is the Doppler shift caused by the relative velocity v, which can be expressed as

$$\begin{aligned} \tau &= \frac{2R}{c},\\ f_d &= \frac{2vf_c}{c}. \end{aligned} \tag{9}$$

For a fixed OFDM-LFM symbol index m, the Doppler shift and the time delay have orthogonal effects on the modulation symbols. The time delay and Doppler information can be extracted by a certain processing method. The function $\operatorname{rect}(\cdot)$ can be ignored by selecting the loop prefix reasonably.

According to the equations above, the target echo signal is DFrFT demodulated, and the reception modulation symbol $d_{Rx}(mN+n)$ carrying the time delay and Doppler shift information can be expressed as

$$\begin{aligned} d_{Rx}(mN+n) &= d_{Tx}(mN+n)\\ &\quad\cdot\exp\left(-j2\pi\left(n\Delta f - \frac{\mu R}{c}\right)\frac{2R}{c}\right)\\ &\quad\cdot\exp\left(j2\pi mT\left(\frac{2vf_c - 2\mu R}{c}\right)\right). \end{aligned} \tag{10}$$

In order to be able to estimate the distance and velocity, it is necessary to remove the transmitted modulation symbol information from the received modulation symbol information by the following equation:

$$\begin{aligned} \frac{d_{Rx}(mN+n)}{d_{Tx}(mN+n)} &= \exp\left(-j2\pi\left(n\Delta f - \frac{\mu R}{c}\right)\frac{2R}{c}\right)\\ &\quad\cdot\exp\left(j2\pi mT\left(\frac{2vf_c - 2\mu R}{c}\right)\right). \end{aligned} \tag{11}$$

Two kernel functions that contain distance and velocity information could be defined as follows:

$$\begin{aligned} k_R(n) &= \exp\left(-j2\pi\left(n\Delta f - \frac{\mu R}{c}\right)\frac{2R}{c}\right),\\ k_v(m) &= \exp\left(j2\pi mT\left(\frac{2vf_c - 2\mu R}{c}\right)\right). \end{aligned} \tag{12}$$

After IDFT of $k_R(n)$, a pseudospectrum associated with the target distance can be obtained by the following equation:

$$r_k(i) = \mathrm{IDFT}[k_R(n)] = \frac{1}{N}\sum_{n=0}^{N-1}\exp\left(-j2\pi\left(n\Delta f - \frac{\mu R}{c}\right)\frac{2R}{c}\right) \cdot \exp\left(j2\pi\frac{ni}{N}\right). \tag{13}$$

When $R \ll nc\Delta f/\mu$, target distance would be obtained by locating the maximum value of the $r_k(i)$ and the corresponding index i. The estimated distance is

$$R \approx \frac{ic}{2\Delta f N}. \tag{14}$$

Identically, after IDFT of $k_v(m)$, a pseudospectrum associated with the target distance can be obtained:

$$v_k(j) = \mathrm{DFT}[k_v(m)] = \sum_{m=0}^{M-1}\exp\left(j2\pi mT\left(\frac{2vf_c - 2\mu R}{c}\right)\right) \cdot \exp\left(-j2\pi\frac{mj}{M}\right). \tag{15}$$

Target velocity would be obtained by locating the maximum value of the $v_k(j)$ and the corresponding index j. The estimated velocity is

$$\hat{v} = \frac{\mu R}{f_c} + \frac{jc}{2f_c MT}. \tag{16}$$

The relative velocity and relative distance of the target can be obtained based on equations (14) and (16). With the prior knowledge of estimated distance and velocity, 16-QAM data information such as communication, control, and others can be demodulated based on the following equation:

$$r(t) = \sum_{n=0}^{N-1} y(t)\exp\left(-j\frac{\pi}{c^2}\left(\mu ct + 2f_n c + 4\hat{v}f_c - 2\mu R\right)(ct - 2R)\right). \tag{17}$$

In summary, this section presents the data flow and algorithms for the proposed OFDM-LFM framework. In the proposed unified Tx/Rx framework, the distance and speed of the target can be additionally estimated when the data are transmitted. Specifically, 16-QAM is used to carry data flow, including communication and remote control data. The signal features are extracted by IDFrFT and symbol domain-based algorithm to form pseudospectrums of time stamp and phase, and then the velocity and relative distance of the target are further estimated. The simulation results will be described in the next section.

3. Simulation

This section simulates the measurement and data demodulation of the algorithm. After the binary data generation, 16-QAM modulation and OFDM-LFM modulation, the authors use the signal processing method based on the modulation symbol domain to verify the external measurement and data demodulation capability of the unified system. The target relative distance is $R = 4\,\mathrm{km}$, the relative velocity is $v = 300\,\mathrm{m/s}$, and the other main simulation environments are shown as follows (see Table 1).

Figures of the pseudospectrum associated with the target distance and velocity based on OFDM-LFM framework are shown below.

It can be seen from Figure 3, based on the OFDM-LFM modulation symbol processing method the peak value corresponds to the target relative distance. Similarly, from Figure 4, the peak value corresponds to the target relative velocity. Wherein the modulation symbol processing method can effectively suppress the side lobes generated by the communication modulation symbols. Thus, the processing method can effectively avoid the influence of the communication information on the distance and the Doppler information, and then it reduces the influence between the external instrumentation part and the communication part.

Next, the authors simulated focusing on data transmission using a linear demodulation method. As far as authors know, LFM is mostly used in radar waveform design in which LFM does not carry data information, and only use amplitude and frequency changes of LFM to obtain velocity and distance information. One of the innovations of this paper lies in the usage of OFDM-LFM to carry data information such as communication and remote control, meanwhile to obtain the external measurement information by signal features of the received signal.

In the current OFDM demodulation, multiplication and addition of the equal-interval sub-band can be equivalent to FFT/IFFT transform, so the FFT/IFFT is widely used in OFDM data demodulation. However, the FFT/IFFT method does not adapt to OFDM-LFM. Since the carrier frequency of the OFDM in the sub-band is constant but that of the OFDM-LFM grows linearly. In addition, the current low-pass filtering method is not applicable. The low-pass filtering method is a noncoherent demodulation method, often used in signal blind detection, i.e., the carrier frequency may be dynamically transformed. The low-pass filter cannot remove the frequency offset, which would thus lead to the rotation of the constellation and then lost of the lock.

Therefore, this paper adopts a linear demodulation method. Although the center frequency is linearly transformed in each sub-band, in cooperative communication, the receiver can simulate this linear transformation locally and obtain effective data through coherent demodulation. The constellation simulation result is shown below.

As shown in Figure 5, the simulated constellation distribution is similar to the expected: data points are distributed around 4×4 constellation points. But there are still a few data points at (0, 0), which means that there still exists bit error due to misjudgment. This is also the focus of the work of further research.

Table 1: Main simulation parameters of unified measurement and control communication system.

Parameter	Value
Symbol cycle (s)	0.1 ms
Number of subcarriers	63
Number of symbols	16
Central frequency	30 MHz
Carrier frequency interval	10 kHz
LFM subcarrier bandwidth	10 kHz

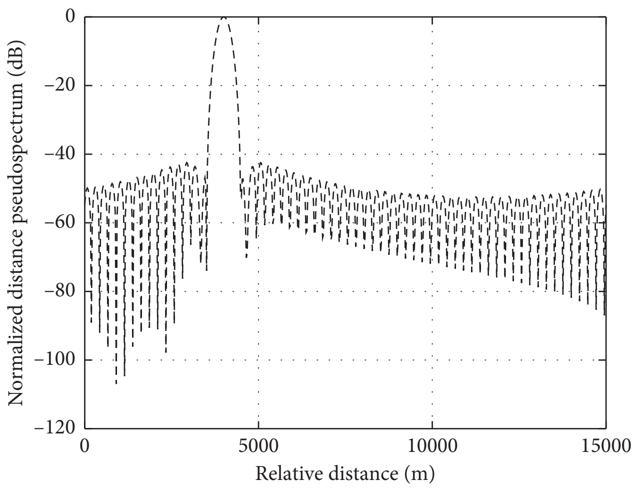

Figure 3: Pseudospectrum associated with the target distance based on the OFDM-LFM framework.

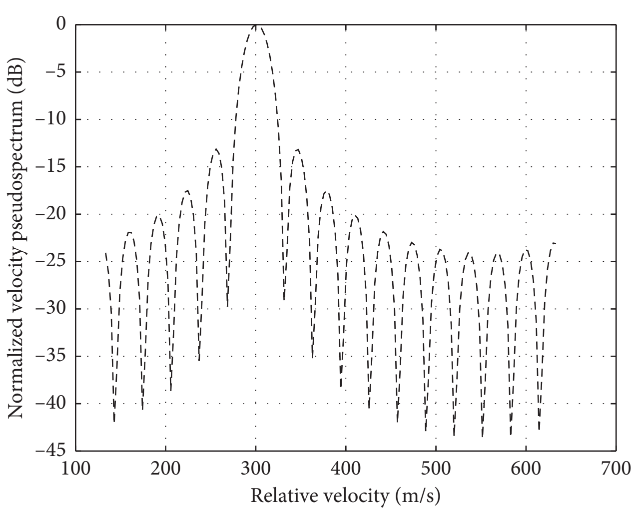

Figure 4: Pseudospectrum associated with the target velocity based on the OFDM-LFM framework.

4. Conclusions

In this paper, the FrFT is introduced into the OFDM-LFM unified framework design to estimate the target velocity and distance besides demodulate binary data. This paper proposed a unified measurement, control, and communication system framework that will integrate multiple signal functions into a framework. Traditional LFM does not carry data information, only using amplitude and frequency changes of LFM to obtain velocity and distance information. In the proposed OFDM-LFM framework, the received signal also carries additional channel information besides the data flow due to its linear carrier frequency. The additional signal features are related to time delay and frequency offset, which makes it possible to estimate the velocity and distance of the target. That is to say, in the proposed unified system, a unified backend algorithm can be used to demodulate telemetry, remote control, and communication data at the same time. Instead of using multiple separate units to perform multiple functions, simulation results show that the unified system can effectively satisfy the need for velocity and distance estimation. The linear demodulation method overcomes the linear and frequency offset drawbacks caused by the current demodulation methods. In further research, the authors will pay more attention to the exploration of the bit error rate.

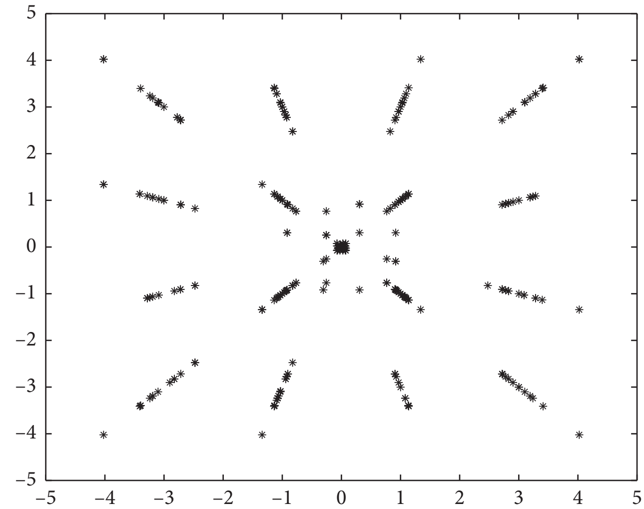

Figure 5: Coordinate reception signal constellation using linear demodulation method.

Data Availability

The data used to support the findings of this study are available from the corresponding author upon request.

Conflicts of Interest

The authors declare that there are no conflicts of interest regarding the publication of this paper.

Acknowledgments

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