Design and Simulation of FFT-OFDM System Based on MATLAB

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Abstract

With the rapid development of network technology, people's demand for mobile communication and broadband power line communication (PLC) services is increasing, and the requirements for network transmission speed are getting higher and higher. One of the most immediate challenges is to overcome the severe frequency selective fading caused by the channel. How to further improve communication performance and achieve high-speed, reliable communication has become one of the key issues. Orthogonal Frequency Division Multiplexing (OFDM) technology can well overcome the frequency selective fading of the channel. Due to its simplicity and efficiency, OFDM has become one of the core technologies for implementing high-speed wireless communication and power line communication systems. This paper will mainly introduce the principle, key technology of OFDM and FFT-OFDM system design and simulation based on MATLAB.

Keywords

Orthogonal Frequency Division Multiplexing, MATLAB, Simulation.

1. Introduction

OFDM is a special multi-carrier transmission mode. Because of the orthogonality between sub-carriers, the spectrum of sub-channels is allowed to overlap each other. Compared with conventional frequency division multiplexing systems, OFDM can make maximum use of spectrum resources. At the same time, it converts high-speed data through serial-to-parallel conversion, so that the duration of data symbols on each sub-carrier is relatively increased, the information rate of the sub-channel is reduced, and the frequency selective fading channel is converted into a flat fading channel, thereby having good anti-noise, The ability to resist multipath interference is suitable for high speed data transmission in frequency selective fading channels.

In addition, the introduction of a cyclic prefix in OFDM overcomes the interference between adjacent blocks of OFDM (IBI), maintains the orthogonality between carriers, and the cyclic prefix length is greater than the channel extension length, effectively suppressing inter-symbol interference (ISI).). It can be seen that OFDM technology has strong anti-multipath capability, high spectrum utilization and easy implementation, and provides a new solution for solving channel frequency selective fading, improving communication spectrum utilization rate and transmission rate [1].

2. Basic principles of OFDM systems

2.1 Introduction to OFDM Principle.

2.1.1 OFDM signal generation

Orthogonal Frequency Division Multiplexing (OFDM) is one of the Multi-Carrier Modulation (MCM) techniques. The basic idea of MCM is to transform the data stream into N sub-streams with lower rate, and use them to separately modulate N subcarriers and then transmit them in parallel. The rate of the factor data stream is the original, that is, the symbol period is expanded to the original multiple, which is much larger than the maximum delay spread of the channel - so that the MCM divides a wideband frequency selective channel into a narrow-band flat fading channel (balanced simple) Therefore, "congenital" has strong anti-multipath fading and anti-pulse interference capability, and is especially suitable for high-speed wireless data transmission and power line carrier communication. OFDM is an MCM in which subcarriers are aliased to each other, so that it has higher spectrum utilization in addition to the advantages of the above MCM. OFDM selects subcarriers whose time domains are orthogonal to each other. Although they overlap each other in the frequency domain, they can still be separated at the receiving end. The block diagram of the OFDM system is show in Figure 1.

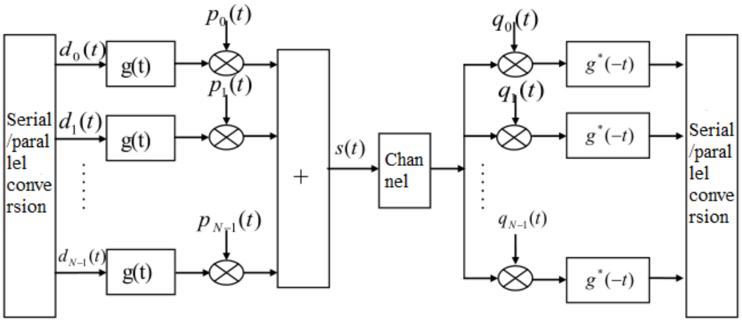

Fig. 1 OFDM system block diagram

One OFDM symbol contains a plurality of subcarriers that are Phase Shift Keying (PSK) or Quadrature Amplitude Modulation (QAM).

The OFDM symbol can be expressed as equation (1)

$$s(t) = \sum_{i=0}^{N-1} d_i rect(t - t_s - \frac{T}{2}) e^{j2\pi f_i (t-t_s)}, \quad t_s \le t \le t_s + T \tag{1}$$

In the middle N ——The number of subcarriers;

T ——The duration (period) of the OFDM symbol;

d_i ——Data symbols assigned to each channel;

f_i ——Carrier frequency of the i -th subcarrier;

$rect(t)$ ——Rectangle function,

$$rect(t) = 1, |t| \le T/2$$

$$s(t) = 0, t < t_s \text{或} t > T + t_s\text{。}$$

In the middle f_i ——Each subcarrier contains an integer multiple of one cycle in one OFDM symbol period, $f_i = f_c + i/T$,and modulating the j -th subcarrier in equation (1), and then integrating over time length T , ie

$$\begin{aligned}\hat{d}_i &= \frac{1}{T}\int_{t_s}^{T+t_s} e^{-j2\pi\frac{j}{t}(t-t_s)} \sum_{i=0}^{N-1} d_i e^{-j2\pi\frac{i}{t}(t-t_s)} dt \\ &= \frac{1}{T}\sum_{i=0}^{N-1} d_i \int_{t_s}^{T+t_s} e^{j2\pi\frac{i-j}{T}(t-t_s)} dt \\ &= d_j\end{aligned} \tag{2}$$

It can be seen from equation (2) that demodulation of the j th subcarrier can recover the desired symbol, and for other subcarriers, since the frequency difference $(i-j)/T$ can generate an integer multiple of the period in the integration interval , so the result of the integration is zero.

Therefore, the OFDM signal spectrum actually satisfies the Nyquist criterion, that is, there is no mutual interference between multiple subcarriers [2].

2.1.2 OFDM modulation and demodulation with FFT

With N subcarrier frequencies, the OFDM modulated signal can be represented in the i th symbol interval.

$$s_i(t)=\sum_{k=0}^{N-1}X_i(k,t)e^{j2\pi f_k t} \tag{3}$$

In the middle $X_i(k,t)$——The information carried by the signal during the ith symbol interval, which determines the amplitude and phase. In general, they are complex constants only associated with symbol labels that carry the information to be transmitted.

For example, if the k -th subcarrier uses QPSK modulation, a $\pi/4$ -mode constellation is used. When the k -th symbol is "00", $X_i(k,t)=\sqrt{2}(1+j)/2$ can be known according to the mapping relationship between the symbol and the constellation. For convenience of description, the symbol label is often omitted when only one multi-carrier signal symbol is to be studied; and when the sub-carrier is modulated by ordinary (no waveform formation) QAM or (multi-ary phase modulation), $X_i(k,t)$ is independent of t, thus abbreviating $X_i(k,t)$ to $X(k)$, which does not cause ambiguity depending on the context.According to the above convention, formula (3) can be written as

$$s(t)=\sum_{k=0}^{N-1}X(k)e^{j2\pi f_k t} \tag{4}$$

After careful analysis, it can be found that the modulation and demodulation of the above multi-carrier transmission system can be realized by Discrete Fourier Transform (DFT). Because DFT has the famous Fast Fourier Transform (FFT), multi-carrier is made. The transmission system is greatly simplified in implementation, especially the OFDM system realized by FFT, which has been widely recognized for its simple structure and high spectrum utilization.

The following is an analysis of the conditions that a multi-carrier transmission system can implement with FFT. To determine the frequency spacing between subcarriers, we consider how the receiver demodulates the signal. We sample the received signal (without considering the effects of noise and distortion) at the sampling frequency f_s and demodulate the sampled signal using FFT. Using the FFT of N points, the k th frequency component of the signal can be calculated as

$$S(k\Delta f)=\sum_{n=0}^{N-1}s(\frac{n}{f_s})e^{-j\frac{2\pi nk}{N}} \tag{5}$$

In the middle $S(k\Delta f)$——The kth spectral component;

$s(\frac{n}{f_s})$——Sampling signal, $n=0,1,2,\cdots,N-1$;

$\Delta f=\frac{f_s}{N}$——The resolution of the FFT.

In order for the FFT to correctly calculate the spectrum, the signal must be periodically repeated outside the N -point sampling. When the signal contains only the harmonic components of the FFT, the condition can be satisfied.Will be $t = n/f_s$ into the formula (4)

$$s(\frac{n}{f_s}) = \sum_{j=0}^{N-1} X(j) e^{j\frac{2\pi f_j n}{f_s}} \tag{6}$$

Substituting formula (6) into formula (5)

$$\begin{aligned} S(k\Delta f) &= \sum_{n=0}^{N-1}\sum_{j=0}^{N-1} X(j) e^{j\frac{2\pi f_j n}{f_s}} e^{-j\frac{2\pi nk}{N}} \\ &= \sum_{j=0}^{N-1} X(j) \sum_{n=0}^{N-1} e^{j\frac{2\pi f_j n}{f_s}} e^{-j\frac{2\pi nk}{N}} \\ &= \sum_{j=0}^{N-1} X(j) \delta(\frac{f_j}{f_s} - \frac{k}{N}) \end{aligned} \tag{7}$$

Observing the above formula, we can find that when the frequency of the multi-carrier modulated signal satisfies the equation (8), there is $S(k\Delta f) = CX(k)$, where C is a constant, that is, when the frequency of each subcarrier is the FFT resolution for demodulation. At integer multiples, the signal can be demodulated with an FFT. From the above analysis, it is necessary to keep $X(k)$ constant in one symbol interval to ensure correct demodulation. If the subcarrier QAM or MPSK modulation uses waveform forming techniques, such as using a cosine roll-off waveform, Special processing is required for FFT demodulation.

$$f_k = \frac{kf_s}{N} \tag{8}$$

From the above analysis, when the frequency of each subcarrier is an integer multiple of the FFT resolution for demodulation, demodulation can be performed on the multicarrier sampled signal by FFT. In particular, when the frequency interval of the subcarriers is f_s/N, there is a formula (6)

$$\begin{aligned} s(\frac{n}{f_s}) &= \sum_{k=0}^{N-1} X(k) e^{j\frac{2\pi\frac{kf_s}{N}n}{f_s}} \\ &= \sum_{k=0}^{N-1} X(k) e^{j\frac{2\pi n}{N}} \end{aligned} \tag{9}$$

Equation (2-9) is just the IFFT (Inverse Discrete Fourier Transform) of the $X(k)(k = 0,1,2,\cdots,N-1)$ sequence (hereinafter we will abbreviate the sequence as $X(N)$), that is, when the subcarrier frequency interval is f_s/N, the multi-carrier modulated signal is used. The domain sample sequence can be calculated from IFFT.

Since the sequence carrying the information is exactly the FFT of the multi-carrier modulated signal sampling sequence, we say that the modulation of the multi-carrier modulation system implemented by FFT is performed in the frequency domain.

It can be seen from the above analysis that the modulation of the multi-carrier modulation system can be completed by IFFT, and the demodulation can be completed by the FFT.

2.1.3 Protection interval and cyclic prefix

If a certain symbol block sequence sdfsd is input, the corresponding output is represented by a matrix as follows:

$$\begin{bmatrix} y_k \\ y_{k-1} \\ \vdots \\ y_{k-N+1} \end{bmatrix} = \begin{bmatrix} h_0 & h_1 & \cdots & h_M & 0 & \cdots & 0 \\ 0 & h_0 & h_1 & \cdots & h_M & 0 & \cdots \\ \vdots & \ddots & & & & & \vdots \\ 0 & \cdots & 0 & h_0 & h_1 & \cdots & h_M \end{bmatrix} \begin{bmatrix} x_k \\ x_{k-1} \\ \vdots \\ x_{k-N-M+1} \end{bmatrix} + \begin{bmatrix} n_k \\ n_{k-1} \\ \vdots \\ n_{k-N+1} \end{bmatrix} \quad (10)$$

Due to the memory of the channel, the resulting output block is not only related to the current input block, but also to the last M inputs of the previous block, which results in IBI (inter-block interference).

In order to eliminate the IBI, a guard interval (GI) may be inserted between each OFDM symbol, and the guard interval length is generally greater than the maximum delay spread in the wireless channel, that is, after the N data blocks, M zeros are added. . As shown in Figure 2.

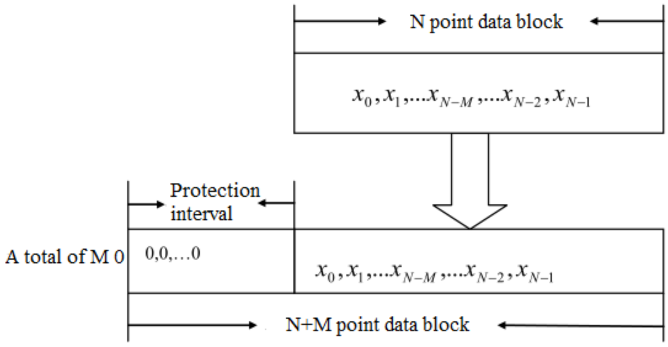

Fig. 2 Insert protection interval diagram

However, in this case, inter-carrier interference (ICI) occurs due to the influence of multipath propagation, that is, the orthogonality between subcarriers is destroyed, as shown in Figures 3.

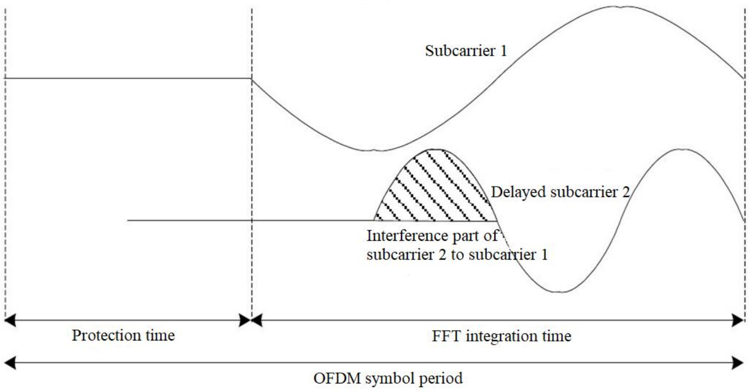

Fig. 3 Orthogonality is destroyed

Since the difference between the periods between the first subcarrier and the second subcarrier is no longer an integer within the length of the FFT operation, it is proved by the above orthogonality that the two subcarriers are no longer orthogonal, so when the receiver When attempting to demodulate the first subcarrier, the second subcarrier will cause interference to the first subcarrier.

To solve the orthogonality problem, a cyclic prefix (CP) or cyclic extension can be introduced into OFDM. To overcome ICI, a cyclic extension of the OFDM symbol can be added to the guard interval instead of using a blank guard interval, as shown in Figure 4.

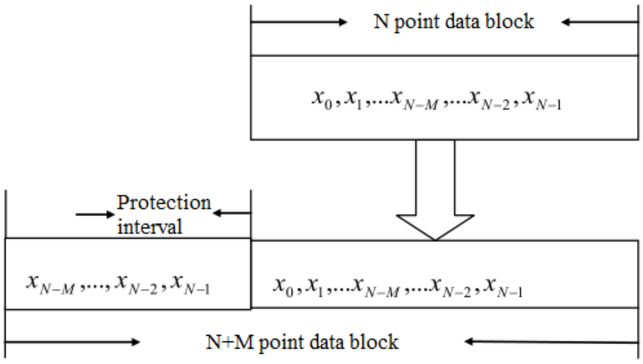

Fig. 4 Add the CP to the guard interval

After adding CP, the relationship between input and output is

$$\begin{bmatrix} y_k \\ y_{k-1} \\ \vdots \\ y_{k-N+1} \end{bmatrix} = \begin{bmatrix} h_0 & h_1 & \cdots & h_M & 0 & \cdots & 0 \\ 0 & h_0 & h_1 & \cdots & h_M & 0 & \cdots \\ \vdots & \ddots & & & & & \vdots \\ 0 & \cdots & 0 & h_0 & h_1 & \cdots & h_M \\ h_M & 0 & \cdots & 0 & h_0 & h_1 & \cdots \\ \vdots & h_M & 0 & \cdots & 0 & h_0 & h_1 \\ h_1 & \cdots & h_M & 0 & \cdots & 0 & h_0 \end{bmatrix} \begin{bmatrix} x_k \\ x_{k-1} \\ \vdots \\ x_{k-N+1} \end{bmatrix} + \begin{bmatrix} n_k \\ n_{k-1} \\ \vdots \\ n_{k-N+1} \end{bmatrix}$$

It can be seen from Fig. 5 that after the cyclic prefix is used, as long as the multipath delay is less than the guard interval, no signal phase hopping occurs during the operation time of the FFT, so the OFDM receiver only accepts the existence. Some phases are offset by a superposed signal of a plurality of simple continuous sinusoids, and such overlap does not destroy the orthogonality between subcarriers.

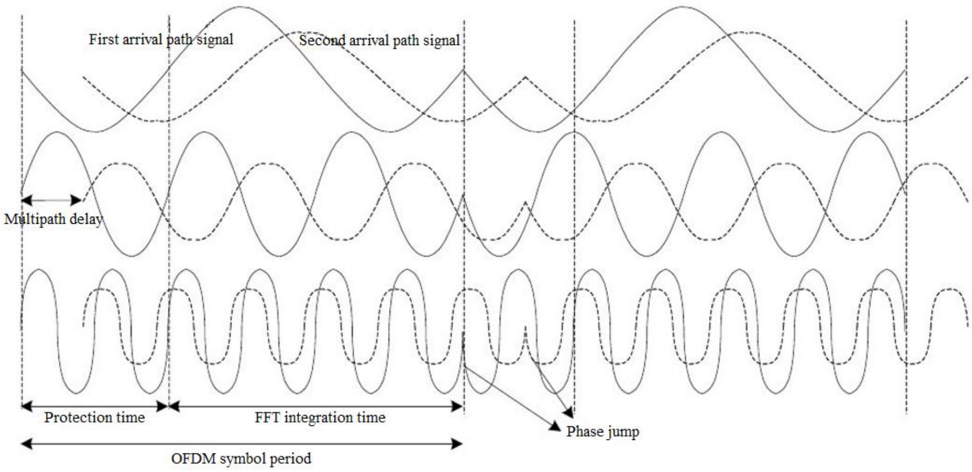

Fig. 5 Multipath delay is less than guard interval

In order to more intuitively explain the impact on the OFDM system due to the multipath delay exceeding the guard interval, Figure 6 shows the 16QAM constellation under three different guard time interval lengths in an OFDM system including 64 subcarriers. In the figure, the source symbols are equally selected from the 16QAM constellation points.

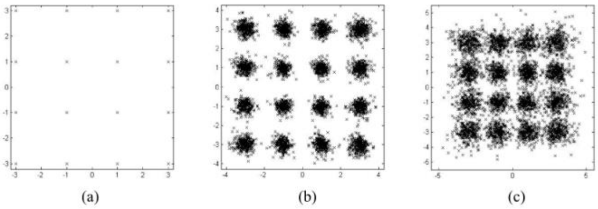

Fig. 6 The effect of inserting guard intervals of different lengths on the received symbols of OFDM systems

Delay spread <protection interval b）The delay spread exceeds the guard interval by 3% of the FFT integration period c）The delay spread exceeds the guard interval by 10% of the FFT integration period

The block diagram of the complete OFDM system after adding the cyclic prefix is shown in Figure 7.

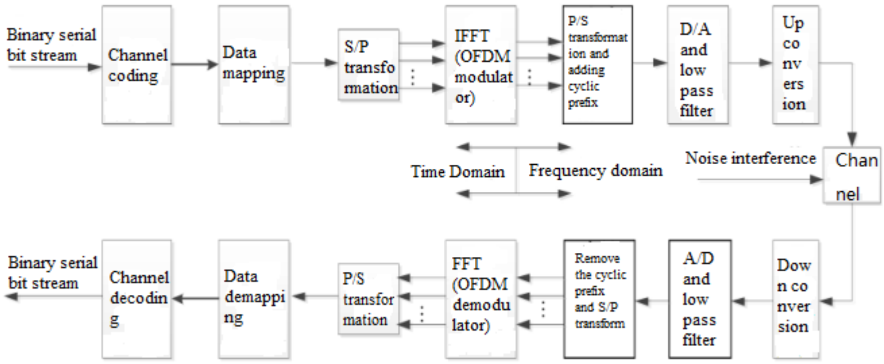

Fig. 7 OFDM system structure

After the input bit sequence completes the serial/parallel transform, according to the adopted modulation mode, the corresponding modulation map is completed, a modulation information sequence is formed, and IFFT is performed to calculate a time domain sampling sequence of the OFDM modulated signal, plus a cyclic prefix CP (The cyclic prefix can make the OFDM system completely eliminate inter-symbol interference (ISI) and inter-carrier interference (ICI) caused by multipath propagation of the signal, and then perform D/A conversion to obtain the time domain waveform of the OFDM modulated signal. The receiving end first performs A/D conversion on the received signal, removes the cyclic prefix CP, and obtains a sampling sequence of the OFDM modulated signal, and performs FFT on the sampled sequence to obtain the original modulated information sequence.

The introduction of the cyclic prefix CP makes OFDM transmission completely eliminate the influence of inter-symbol interference (ISI) and inter-carrier interference (ICI) caused by multipath propagation under certain conditions, and greatly promotes the practical process of OFDM technology.

2.1.4 Spectral characteristics of OFDM signals

When each subcarrier is modulated by QAM or MPSK, if the baseband signal adopts a rectangular wave, the spectrum of the modulated signal on each subchannel is $Sa(x)$ shape, and the main lobe width is $2/T_s$ Hz, where T_s is an OFDM signal. Length (excluding CP). Since the N samples of the OFDM signal are shared in the T_s time, the frequency domain sampling period of the OFDM signal is T_s/N. Since the frequency interval between adjacent subcarriers is $\Delta f = f_s/N$, where f_s is the sampling frequency of the OFDM signal, that is, $f_s = N/T_s$,so

$$\Delta f = \frac{f_s}{N} = \frac{1}{T_s} \tag{11}$$

That is, the main lobe width of the spectrum of the modulated carrier signal spectrum $Sa(x)$ is $2/T_s$, and the interval is $1/T_s$. Depending on the nature of the function, it is known that they are orthogonal in the time domain, which is the origin of the Orthogonal Frequency Division Multiplexing (OFDM) name.

We know that there is a certain guard band between each subchannel of a general frequency division multiplexing transmission system, so that the signal of each subchannel can be separated by a band pass filter at the receiving end. The guard band reduces the spectrum utilization of the entire system. The sub-channels of the OFDM system not only have no guard bands, but also the signal spectrums of the sub-channels overlap each other, as shown in Figure 8.

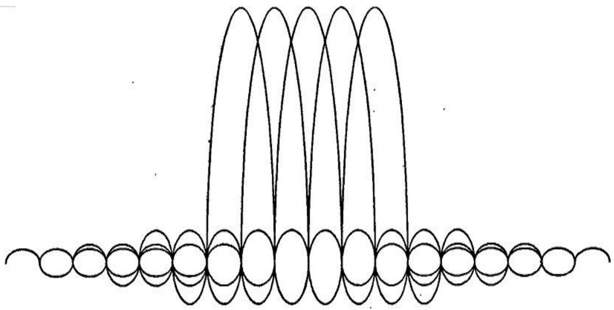

Fig. 8 Spectrogram of each subchannel in an OFDM system

This makes the spectrum utilization of the OFDM system much higher than that of the conventional frequency division multiplexing system, and each subcarrier can adopt the spectrally efficient QAM and MPSK modulation modes, which further improves the spectrum efficiency of the OFDM system.

It should be noted that due to the influence of the cyclic prefix, the spectral structure of the OFDM signal will change somewhat, but this only enhances certain spectral components of the signal without adding new frequency components to the OFDM signal.

The spacing between OFDM subchannels also has a large impact on the performance of the system. The larger the subchannel spacing, the smaller the interference between subchannels due to various factors, but the lower the spectral efficiency of the system. As the bandwidth of the subchannel increases, the ability of the system to resist frequency selective fading also decreases. In order to improve the spectral efficiency of the system and reduce the interval between sub-channels, the interference between sub-carriers of the system is inevitably increased. The channel bandwidth and the number of FFT points determine the interval between OFDM subchannels. The general principle for determining the subchannel spacing is to increase the sub-channel bandwidth as much as possible and to ensure the good OFDM system's good anti-frequency selective fading. The spacing between carriers.

2.2 Key technologies of OFDM.

The key technologies of OFDM systems are as follows:

2.2.1 Time domain and frequency domain synchronization

OFDM systems are sensitive to timing and frequency offset, especially in practical applications with FDMA (Frequency Division Multiple Access), TDMA (Time Division Multiple Access), and CDMA (Code Division Multiple Access). Time domain and frequency synchronization are especially important when multiple access methods are used in combination. As with other digital communication systems, synchronization is divided into two phases, capture and tracking, which are easier to implement. In the uplink, signals from different mobile terminals must arrive at the base station synchronously to ensure orthogonality between subcarriers. The base station extracts the time domain and frequency domain synchronization information according to the subcarrier carrying information sent by each mobile terminal, and then sends the mobile terminal back to the mobile terminal to synchronize the mobile terminal. In the specific implementation, the synchronization will be divided into time domain synchronization and frequency domain synchronization, and the time domain and the frequency domain may be simultaneously synchronized.

2.2.2 Channel estimation

In OFDM systems, the design of the channel estimator has two main problems: First, the selection of pilot information. Since the wireless channel is often a fading channel, the channel needs to be continuously tracked, so the pilot information must be continuously transmitted. Second, the channel estimator with low complexity and good pilot tracking capability is designed. In actual design, the choice of pilot information and the design of the best estimator are usually interrelated, since the performance of the estimator is related to the way the pilot information is transmitted.

2.2.3 Channel coding and interleaving

In order to improve the performance of digital communication systems, channel coding and interleaving are commonly used methods. For random errors in fading channels, channel coding may be employed; for burst errors in fading channels, interleaving techniques may be employed. In practical applications, channel coding and interleaving are usually used at the same time to further improve the performance of the entire system. In OFDM systems, if channel fading is not too severe, equalization can no longer utilize the diversity characteristics of the channel to improve system performance, because the OFDM system itself has the ability to utilize channel diversity characteristics, and general channel characteristic information has been modulated by OFDM. The method itself is utilized. However, the structure of the OFDM system provides an opportunity to encode between subcarriers, and forms a COFDM (Coded Orthogonal Frequency Division Multiplexing) method. The coding can use various codes, such as a block code, a convolutional code, etc., wherein the effect of the convolutional code is better than the block code.

2.2.4 Reduce peak-to-average power ratio

Since the OFDM channel appears as a superposition of N orthogonal subcarrier signals in the time domain, when the N signals are exactly superimposed with peaks, the OFDM signal will also produce a maximum peak, which is N times the average power. Although the probability of occurrence of peak power is low, in order to transmit these high PAPR (Peak-to-Average Power Ratio) OFDM signals without distortion, the transmitting end is high power amplifier (HPA). Linearity requirements are also high. Therefore, the high PAPR makes the performance of the OFDM system greatly degraded and even directly affects the practical application. In order to solve this problem, a method based on signal distortion technology, signal scrambling technology and PAPR based on signal space expansion is proposed.

2.2.5 Balanced

In a general fading environment, the equalization of an OFDM system is not a method to effectively improve system performance. Since the equalization is to compensate the inter-symbol interference caused by the multipath channel, and the OFDM technology itself has utilized the diversity characteristics of the multipath channel, in general, the OFDM system does not have to be equalized. In a highly scatter channel, the channel memory length is very long, and the cyclic prefix length must be long enough to make ISI not appear as much as possible. However, if the length of the CP is too long, it will inevitably lead to a large loss of energy, especially for systems where the number of subcarriers is not very large. This is to consider adding an equalizer to appropriately reduce the length of the CP, that is, by increasing the complexity of the system in exchange for an increase in the band utilization.

3. OFDM system design

3.1 MATLAB overview.

MATLAB is a set of high performance numerical calculation software from MathWorks. MATLAB is the meaning of the Matrix Lab. In addition to its excellent numerical calculation capabilities, MATLAB also provides professional level symbolic calculations, word processing, visual modeling simulation and real-time control. The basic data unit of MATLAB is matrix. Its instruction expression is very similar to the ones commonly used in mathematics and engineering. Therefore, it is much simpler to solve the problem with MATLAB than C, FORTRAN and other languages.

MATLAB is also becoming more and more widely used in other scientific computing and engineering fields besides mathematical calculations, and has broader application prospects and endless potential. It frees the user from the cumbersome underlying programming, which will undoubtedly increase work efficiency. A major feature of MATLAB is the provision of a number of specialized toolboxes and module libraries, such as communication toolboxes and module libraries, digital signal processing toolboxes and module libraries, control toolboxes, and module libraries. MATLAB provides many commonly used functions and modules in these toolboxes and module libraries, making simulation easier to implement. At present, MATLAB's functions are getting stronger and stronger, and constantly adapting to new requirements and proposing new solutions. It is foreseeable that MATLAB will continue to maintain its unique position in the fields of scientific computing, automatic control, scientific mapping, and communication simulation [3].

3.2 OFDM design process.

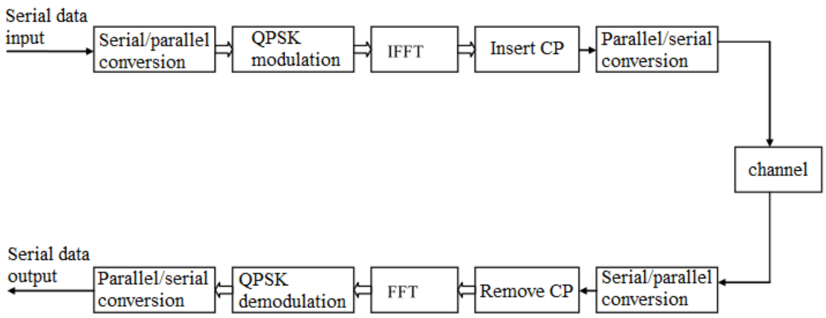

Fig. 9 OFDM system simulation block diagram based on IFFT/FFT

The sender first randomly generates bit streams of 0 and 1 by the source generator, and sets equal probability distributions of 0 and 1, because according to information theory, the probability of 0 and 1 is the purpose of source coding. Then enter the serial to parallel converter, the bit stream becomes a number of parallel signals. The QPSK modulator then modulates each parallel signal. The IFFT converter then performs an IFFT operation on all parallel signals. A cyclic prefix is added and an additive white Gaussian white noise AWGN channel is transmitted for transmission.

After arriving at the receiving end. In contrast to the sender and the sender, the cyclic prefix is first removed and then the FFT operation is performed on each OFDM (recycled cyclic prefix) symbol. QPSK demodulation is then performed on each parallel signal. Finally, parallel and serial conversion is performed to form an output bit stream.

3.2.1 Source generator design

In MATLAB, because rand() produces a random number that is evenly distributed between (0,1). Then as long as the rand() function performs well, the probability of generating a random number greater than 0.5 and less than 0.5 is the same. So we can use the code "Signal=rand()>0.5;" to randomly generate 0 and 1 randomly.

3.2.2 Modulation and demodulation of QPSK

QPSK (Quadrature Phase Shift Keying) uses four different phases of a carrier to characterize digital information. Since each carrier phase represents two bits of information, each quaternary symbol is also referred to as a two-bit symbol. We represent the previous bit that makes up the two-bit symbol with a, and the latter symbol with b. The two information bits a and b in the two-bit symbol are usually arranged in Gray code. The phase relationship between the two bits is shown in Table 1, and the vector relationship is shown in Figure 2.

Table 1 The relationship between two-bit symbols and carrier phase

Double bit symbol		Carrier phase
a	*b*	
0	0	-0.75π
1	0	-0.25π
1	1	0.25π
0	1	0.75π

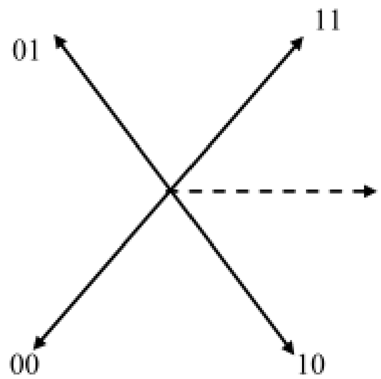

Fig. 10 Vector illustration of QPSK symbol

Since QPSK modulation can be seen as a synthesis of two orthogonal BPSK (Binary Phase Shift Keying). Therefore, QPSK, like BPSK, can be generated by phase modulation and phase selection.

3.2.3 Insert and remove cyclic prefixes

The cyclic prefix is to copy the last N_g samples of the OFDM symbol to the front of the OFDM symbol to isolate the previous symbol. The length of the prefix is greater than the maximum delay spread to maintain the orthogonality between the subcarriers of the OFDM symbol, otherwise ICI (Inter-Carrier Interference) will be generated.

3.2.4 FFT/IFFT

Discrete Fourier Transform (DFT) is widely used in digital signal processing. It establishes the relationship between discrete time domain and discrete frequency domain. FFT algorithm is a fast algorithm of DFT, which can greatly reduce the number of calculations. In the simulation, we use the IFFT and FFT functions to perform Fourier transform (inverse) transformation on the data.

3.2.5 String/parallel/string conversion

In MATLAB, the data is stored in a matrix form, and the reshape() function is a formal transformation of the specified matrix. With this function, the purpose of serial/parallel/string conversion can be achieved.

4. OFDM system simulation

After the above analysis, the MATLAB simulation of the OFDM system based on IFFT/FFT is performed using the block diagram shown in Figure 3-1.

4.1 Set system parameters.

Assume that the simulation parameters are: the number of subcarriers is 128, the length of IFFT/FFT is 128, and the modulation mode uses QPSK modulation. In order to minimize the loss of signal-to-noise ratio caused by the insertion of the guard interval, it is desirable that the OFDM period length is much larger than the guard interval length, but the larger the OFDM symbol period, the more sub-carriers are included in the system, and the sub-carrier spacing is correspondingly reduced. The complexity of the system increases, and the peak-to-average power ratio of the system is increased, while making the system more sensitive to frequency deviations. Therefore, in practical applications, the symbol period length is generally selected to be five times the guard interval length, so that the signal-to-noise ratio loss caused by the insertion of the guard bits is only about 1 dB. Therefore, the length of the guard interval is 1/4 of the effective symbol period, which is 1/4 of the length of the IFFT/FFT. Therefore, the length of the cyclic prefix is 32, and each frame contains 6 OFDM symbols, and the signal-to-noise ratio is 10 dB.

Let para denote the number of channels transmitted in parallel, Ns denote the number of OFDM symbols included in each frame, and ml is the number of modulation levels. According to the system parameters, it is known that para=128, Ns=6. Since QPSK uses four different phases of the carrier to characterize the digital information, and each carrier phase represents 2-bit information, ml=2. The length of the serial sequence can be calculated by the expression para*Ns*ml to be 1536, but for the convenience of observation and analysis, only the first 20 samples are taken.

```
SNR=10; %Signal to noise ratio, in dB
fl=128; %Set the IFFT/FFT length
Ns=6; %Set the number of OFDM signals in a frame structure
ml=2; %Set the number of modulation levels
para=128;%Set the number of subcarriers to be transmitted in parallel
sr=250000; %Set symbol rate
br=sr.*2;%Set the bit rate of each subcarrier
gl=32; %Set the length of the protection slot
```

4.2 Source generates a transmission signal.

```
Signal=rand(1,para.*Ns.*2)>0.5;%Generate a 0,1 random sequence, the number of symbols is para*Ns*2
%Fig1.Signal sent
figure(1)
stem(Signal(1:20));
title('Signal sent');
```

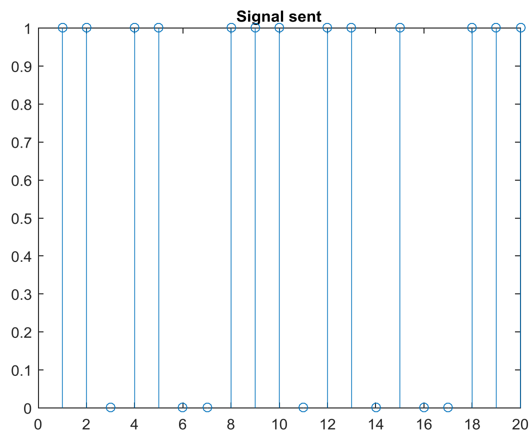

Fig. 11 Signal generated by the source

4.3 String/parallel conversion.

There are many ways to implement serial-to-parallel conversion. In MATLAB, reshape is used to change the shape of the specified matrix, but the number of elements does not change. In this program, the reshape function is used to implement serial-to-parallel conversion. In the system parameters, the number of parallel channels is 128, and the amount of information is 128 × 6 × 2 bits. Therefore, the sequence is converted into a matrix of 128 rows and 12 columns, the function is set to reshape (Signal, 128, 12), and Signal represents the serial sequence of the transmitting end. The first 128 bits of data become the first column, the subsequent 128 bits become the second column, and so on. The parallel data obtained after the conversion is a matrix of 128 rows and 12 columns, represented by paradata.

```
Paradata=reshape(Signal,para,Ns.*2);% will be randomly produced
```

The resulting binary matrix is transformed into a matrix with a number of rows of para and a number of columns of 2*Ns.

4.4 QPSK modulation.

In this paper, the modulation method of QPSK in the B mode is adopted. Before the modulation is performed, the parallel data signal paradata converted from the serialization needs to be divided into two paths, and the data of the I channel and the Q channel are both a matrix of 64 rows and 6 columns. After the matrix of the I and Q channels is processed by QPSK modulation, the data 1 remains unchanged, and the data 0 becomes -1. The processed matrix is ich and qch.

The matrices ich and qch are multiplied by a coefficient of $\sqrt{2}/2$, respectively, to generate new matrices ich1 and qch1, and the matrices are combined to convert the frequency domain data into time domain data to complete modulation. The data in the time domain is obtained by modulating the parallel data of the above-mentioned transmission segment as qpsk_x.

```
m2=ml./2;%ml is the number of modulation levels
paradata2=paradata.*2-1;
count2=0;
for j=1:Ns
   isi=zeros(para,1);
   isq=zeros(para,1);
   for i=1:m2
       isi=isi+2.^(m2-i).*paradata2((1:para),i+count2);
  isq=isq+2.^(m2-i).*paradata2((1:para),m2+i+count2);
   end
   ich((1:para),j)=isi;
   qch((1:para),j)=isq;
   count2=count2+ml;
end
kmod=1./sqrt(2);
ich1=ich.*kmod;
qch1=qch.*kmod;
qpsk_x=ich1+qch1.*sqrt(-1);%Generating a complex signal

%Fig2.QPSK modulated graphics
figure(2)
subplot(2,1,1),stem(ich1(1:20));
title('I-channel waveform after QPSK modulation');
subplot(2,1,2),stem(qch1(1:20));
title('Q-channel waveform after QPSK modulation') ;
```

```
%Fig3.Constellation diagram of QPSK modulated signal
figure(3)
alfa=0:0.001.*pi:2.*pi;
x=cos(alfa);
y=sin(alfa);
plot(x,y,'-',0,0,'.');
hold on   %Drawing unit circle
for i=1:Ns.*para
plot(ich1(i),qch1(i),'ro');
hold on
end
grid on;
xlabel('I road');
ylabel('Q road');
title('Constellation diagram of QPSK modulated signal');
hold off;
```

The modulated waveform is shown in Figure 13.

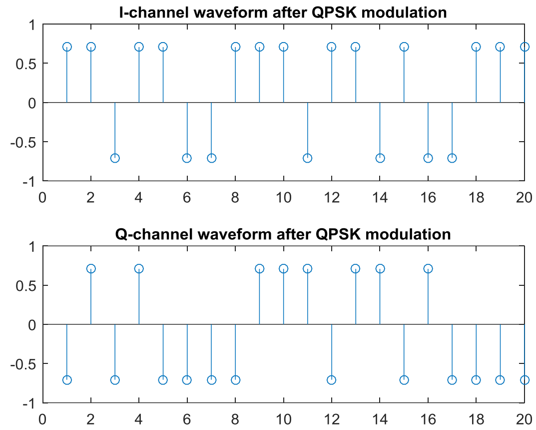

Fig. 12 QPSK modulated waveform

In order to be able to observe the modulation of QPSK well, the QPSK modulated constellation is drawn in the program. The graph obtained after the program runs is shown in Figure 14. Note: The vertical and horizontal coordinates are in-phase and quadrature components, respectively.

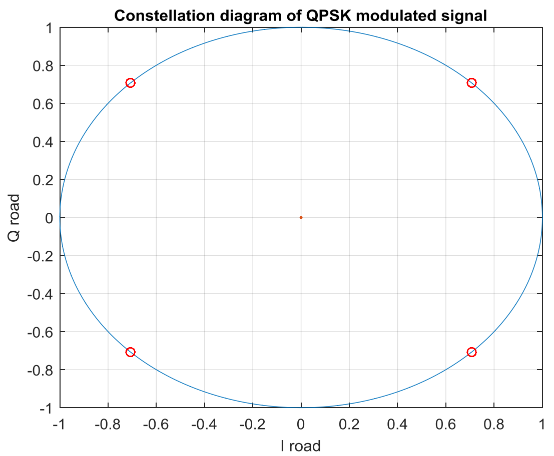

Fig.13 Constellation diagram of QPSK modulated signal

4.5 IFFT transform.

In the MATLAB software, the functions fft() and ifpt() can be used to perform FFT/IFFT operations on the data, which can save a lot of complicated operations. The calculated waveform is shown in Figure 2-6.

```
fy=ifft(qpsk_x);
ich2=real(fy);
qch2=imag(fy);
%Fig4.IFFT transformed waveform
figure(4)
subplot(2,1,1),stem(ich2(1:20)),grid off;
title('I-channel waveform after IFFT transformation')
subplot(2,1,2),stem(qch2(1:20)),grid off;
title('Q-path waveform after IFFT transformation')
```

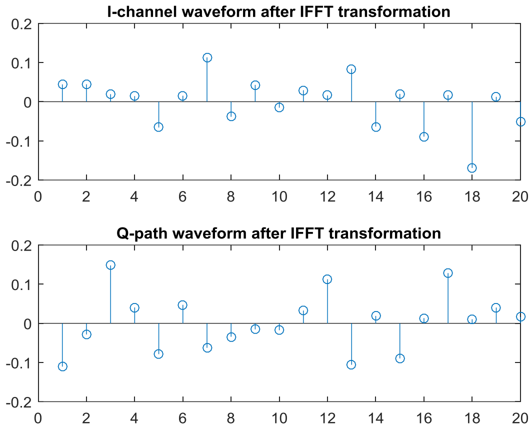

Fig.14 IFFT transformed waveform

4.6 Insert protection interval CP.

In practical applications, a guard interval (GI) is formed by introducing a cyclic prefix, thereby effectively combating inter-symbol interference due to multipath delay by inserting a subsequent portion of the OFDM symbol into the beginning portion of the symbol in the time domain to form Cyclic prefix. The length of the guard interval should be greater than the maximum of the multipath delay spread. A schematic diagram of adding a guard interval and a cyclic prefix to an OFDM symbol is shown in FIGS. 1-2 and 1-4.

The data obtained by the IFFT operation is subjected to real virtual and partial separation, and the obtained results are ich2 and qch2.

In MATLAB, some special operands and matrices are used to copy the sample points of the post Tg time of each symbol to the front of the OFDM symbol. The colon is a special operation symbol in MATLAB. ich2(fl-gl+1:fl,:) indicates that the (fl-gl+1) line in the matrix ich2 is output to the last line, and the output data is output. Adding to the original matrix to form a new matrix ich3, that is, the insertion protection interval and the addition of the cyclic prefix are completed, and the implementation of the imaginary part is the same.

```
ich3=[ich2(fl-gl+1:fl,:);ich2];
qch3=[qch2(fl-gl+1:fl,:);qch2];
```

4.7 Parallel/serial conversion.

This process is the inverse of the serial-to-parallel conversion. The data of N subcarriers is transmitted to a carrier channel, and the parallel data is converted into a serial data sequence for transmission. The parallel and serial conversions are performed on the real part and the imaginary part respectively, and the reshape() function is still used in the program to perform the transformation.

```
ich4=reshape(ich3,1,(fl+gl) .*Ns) ;
qch4=reshape(qch3,1,(fl+gl) .*Ns);
TrData=ich4+qch4.*sqrt(-1);%Forming complex transmit data
```

4.8 Adding Gaussian white noise.

White noise is defined based on whether the power spectral density of the noise is uniform, and Gaussian noise is defined according to its probability density function as a normal distribution. In the theoretical analysis of communication systems, especially when analyzing and calculating the anti-noise performance of the system, it is often assumed that the channel noise in the system is Gaussian white noise. The reason is that Gaussian white noise can be expressed by a specific mathematical expression.

There are generally two functions for generating Gaussian noise in MATLAB software, WGN and AWGN. This program uses ReData=awgn(TrData, SNR, 'measured') to add Gaussian noise to the transmitted data TrData.

```
ReData=awgn(TrData,SNR,'measured');
%Fig5.Waveforms of I and Q paths after adding noise
figure(5)
subplot(2,1,1),stem(idata(1:20)),grid off;
xlabel('time'),ylabel('Amplitude');
title('I-channel waveform after adding noise')
subplot(2,1,2),stem(qdata(1:20)),grid off;
xlabel('time'),ylabel('Amplitude');
title('Q-waveform after adding noise')
```

The waveform after adding noise is shown in Figure 4-5.

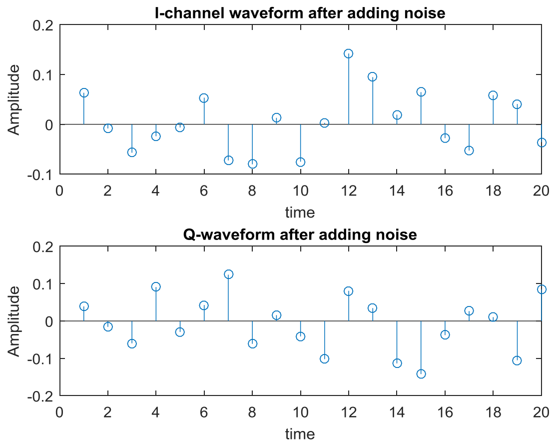

Fig. 15 Waveforms of I and Q paths after adding noise

4.9 Receiver, serial/parallel conversion.

```
idata=real(ReData);
qdata=imag(ReData);
idata1=reshape(idata,fl+gl,Ns);
qdata1=reshape(qdata,fl+gl,Ns);
```

4.10 Remove protection interval CP.

Before demodulating, the signal is completed to remove the guard interval and perform the FFT operation. Removing the guard interval also removes interference between symbols.

Code:

```
idata2=idata1(gl+1:gl+fl,:);
qdata2=qdata1(gl+1:gl+fl,:);
```

4.11 FFT transform.

```
Rex=idata2+qdata2.*sqrt(-1);
ry=fft(Rex);
ReIChan=real(ry);
ReQChan=imag(ry);
ReIchan=ReIChan/kmod;
ReQchan=ReQChan/kmod;

%Fig6.Signal vector after FFT transformation at the receiving end
figure(6)
plot(ReIchan,ReQChan,'o'),grid;
title('Signal vector after FFT transformation at the receiving end')
```

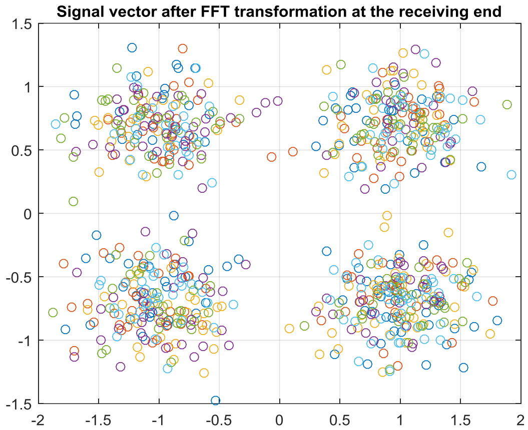

Fig. 16 Signal vector after FFT transformation at the receiving end

```
%Fig7.FFT transformed waveform
figure(7)
subplot(2,1,1),stem(ReIChan(1:20)),grid off ;
title('I-path waveform after FFT transformation')
subplot(2,1,2),stem(ReQChan(1:20)),grid off;
title('Q-path waveform after FFT transformation')
```

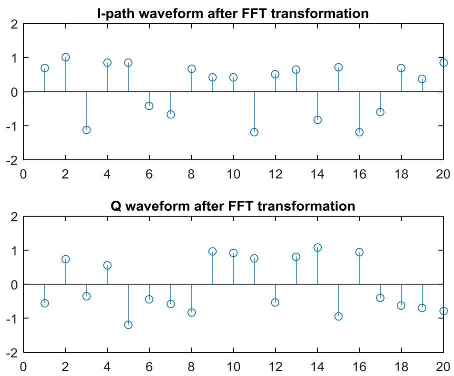

Fig.17 FFT transformed waveform

4.12 QPSK demodulation.

```
demodata=zeros( para,ml*Ns );
demodata((1:para),(1:ml:ml*Ns-1))=ReIchan((1:para),(1:Ns))>=0;
demodata((1:para),(2:ml:ml*Ns))=ReQchan((1:para),(1:Ns))>=0;
RePara=demodata;
```

4.13 And / string conversion, get the received signal.

After the demodulation is completed, the following is the decision of the demodulated signal to obtain the received signal. The waveform of the receiver signal is output in the program, as shown in Figure 10. By comparing the transmitted data and the received data, it is found that after the transmission of the OFDM system, the signal has a bit error rate of 0, which has a good effect against inter-symbol interference and delay spread. In an actual OFDM system, when the number of subcarriers is large, the error rate of the system is also very low.

```
 ReSig=reshape(RePara,1,para.*Ns.* 2);
%Fig8.Received signal
figure(8)
stem(ReSig(1:20)),grid;
title('Received signal');
```

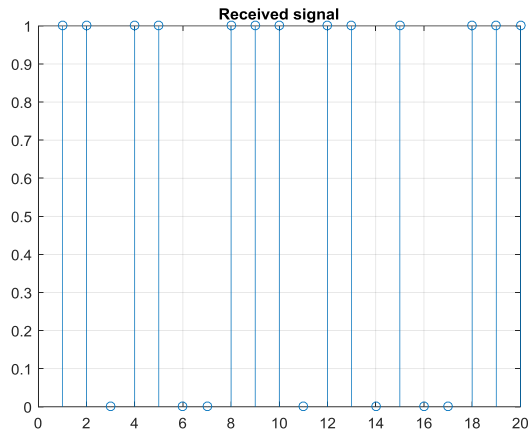

Fig. 18 receive signal

4.14 Analysis of the results of MATLAB code implementation.

The previous section focused on the entire process of system simulation execution and made waveforms or vector diagrams for various stages of signal transmission. Figure 3-1 shows the signal waveform from the source. It is a series of 0 and 1 sequences (only the first 20 samples are taken). Then perform serial-to-parallel conversion and QPSK modulation. The vector relationship of the modulated signal is shown in Figure 3-3. Figure 3-6 is the vector relationship diagram of the signal after FFT transformation at the receiving end. As can be seen from this figure, After the transmission of the additive Gaussian white noise channel, the signal is affected by multipath delay, etc., so that the relationship between the transmitted signal and the original signal vector is greatly different. Figure 19 shows the signal diagram after the decision. The signal at this time is the binary signal recovered by the receiver, which is consistent with the original signal sample.

In the case of considering only the influence of the signal multipath transmission delay on the transmission, we reduce the signal-to-noise ratio of the channel noise to 6 dB and re-simulate. At this time, the number of error symbols is still 0, as shown in the figure:

Figure 20, Figure21.

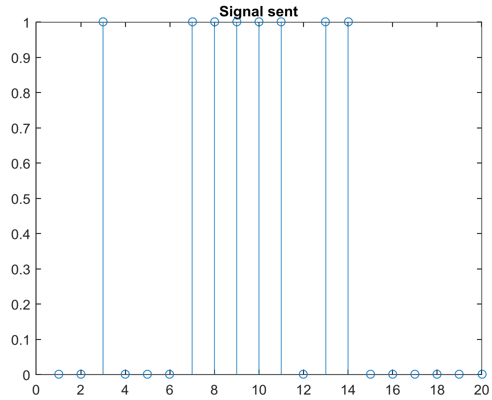

Fig. 19 Transmitter waveform (SNR=6dB)

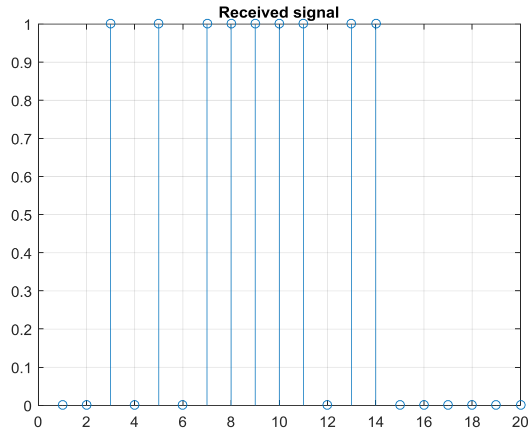

Fig. 20 Receiver waveform (SNR=6dB)

If the signal-to-noise ratio of the channel is reduced (SNR=3dB), the waveforms of the source and receiver at the time of editing and re-running are:

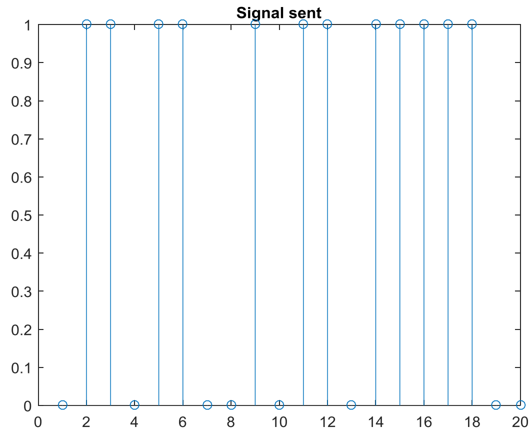

Fig.21 Source waveform (SNR=3dB)

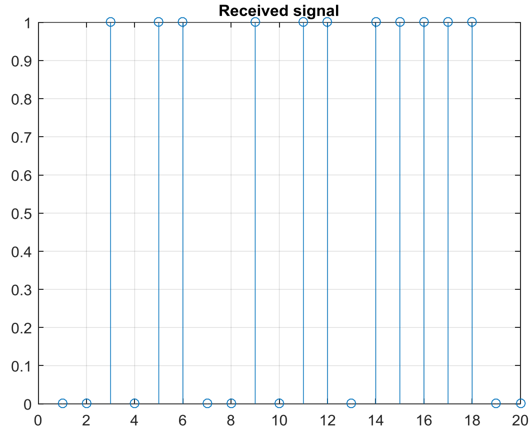

Fig. 22 Waveform recovered at the receiving end (SNR=3dB)

The source signal is: 01101100101101111100

The signal recovered by the receiving end is: 00101100101101111100

It can be seen that the second sample has an error when the receiving end recovers the waveform.

The simulation results are mainly affected by the length of the cyclic prefix and the channel signal-to-noise ratio. We first set the signal-to-noise ratio to 10 and the cyclic prefix length to 32. At this time, the multipath delay of the signal in the wireless channel is less than the loop. The length of the prefix, the receiving end removes the cyclic prefix when restoring the original signal, eliminating the influence of the previous symbol multipath component on the latter symbol. At the same time, the orthogonality between the OFDM symbol subcarriers is maintained, and therefore, the signal passes through the white noise channel, and the demodulated waveform and the source waveform are identical.

However, when the signal-to-noise ratio is reduced to 6, the maximum multipath delay of the symbol is still less than the length of the cyclic prefix, which eliminates the influence of the previous symbol multipath component on the latter symbol, and the number of errors is still zero. However, when the signal-to-noise ratio continues to decrease, the maximum multipath delay of the previous symbol is greater than the length of the cyclic prefix of the symbol, and the previous symbol has an effect on the demodulation of the latter symbol, causing an error in demodulation.

The above analysis shows that the OFDM transmission system has a strong ability to resist multipath interference of transmission, and only when the channel interference is very serious will the error occur. For the multipath delay with the maximum delay unit being less than the loop length (gl=32), the inter-code crosstalk ISI can be effectively eliminated. Nevertheless, the spectrum of the received signal is still heavily degraded by the channel frequency. The OFDM system does not eliminate the frequency selective attenuation of the channel, but the inter-symbol crosstalk is effectively eliminated by using the cyclic prefix technique during demodulation. When the cyclic prefix is large, most of the multipath interference can be eliminated, but the spectrum utilization will be reduced. Therefore, it is unnecessary to use the cyclic prefix as the maximum delay of the channel transmission. This is a problem that needs to be solved properly for designing an OFDM system. .

It can be seen from the simulation that OFDM has good performance in Gaussian channel, and the bit error rate is relatively low when the signal-to-noise ratio is relatively large.

5. Conclusion

As a highly promising technology, OFDM has many advantages not found in other transmission technologies. It has high spectrum utilization, strong resistance to multipath fading, anti-burst, and supports high-speed data transmission. It has been widely used in many fields.

This paper first gives a general overview of OFDM, including its application field, development history, advantages and disadvantages, and detailed description of each module of OFDM. The code is realized and the corresponding simulation waveform is obtained. in conclusion.

Of course, this article has many shortcomings. In verifying the anti-interference ability of OFDM systems, the characteristics of various channels, including Gaussian white noise, Rice channel, Jake mobile channel, multipath fading channel, etc., should be analyzed and discussed in depth so that the OFDM system can be studied more accurately. Their anti-interference performance. Due to my limited ability, I have not been able to complete these aspects of research.

References

[1] Peng Mugen, Wang Wenbo. Next Generation Broadband Wireless Communication System—OFDM and WiMAX[M]. Beijing: Mechanical Industry Press, 2007: 46-53.

[2] Wang Yumin. Key Technologies and Applications of OFDM[M]. Beijing: Mechanical Industry Press, 2006.

[3] Xu Mingyuan, Shao Yubin. Application of MATLAB Simulation in Communication and Electronic Engineering[M]. Xi'an: Xi'an University of Electronic Science and Technology Press, 2006.