OFDM System Simulation based on MatLab

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***Abstract*—With the development of 4G network technology, gradually, 5G wireless communication technology has also been derived and has been deeply studied. 5G technology is based on 4G technology to strengthen its advantages, discard its shortcomings, and obtain further breakthroughs in functions. Therefore, communication services such as downloading and transmitting large-volume data are realized. This article mainly discusses the principle of OFDM-based LTE communication technology, the advantages and disadvantages of OFDM, and multi-channel simulation and analysis of the OFDM transmission system based on the MatLab platform. At the end of the article, the research direction of OFDM technology in future communication systems will be proposed.**

***Index Terms*— LTE, OFDM, Wireless Communication**

I. Introduction

FROM ancient times to the present, people have applied many kinds of communication technologies: from the most primitive pigeons and carriages, to ships and trains in the steam age, to the latest derivative 5G technology. These different periods represent different levels of people's technological progress. The most recent decade has been the fastest growing stage in the history of wireless communication technology. With people's increasing demand for multimedia services, wireless communication technology has developed from 3G and 4G to the latest 5G in the direction of larger data volume and faster transmission rate. At present, the communication technology that accounts for the largest share of the global communication market is still 4G, and OFDM (Orthogonal Frequency Division Multiplexing) is the core strategy of the fourth-generation mobile communication.

A. Development History

In the traditional multi-carrier frequency division multiplexing system 0, in order to prevent internal interference between sub-carriers, each sub-channel uses different carriers to transmit data in parallel. In this system, the sub-carriers are separated far enough to prevent spectrum overlap. Due to this compromised isolation technology, the spectrum efficiency of traditional information transmission systems is very low. Before the equalizer was adopted, people used this multi-carrier method for high-speed communication in the channel. In order to overcome the shortcomings of low spectrum efficiency of traditional strategies, in 1970, Weinstein and Ebert proposed the first OFDM prototype. However, due to the limitations of the technological level and hardware conditions at that time, this new technology has not been put into widespread use. Until 2010, with the support of mature electronic device manufacturing processes and the development of digital technology, it took more than 30 years for OFDM to regain the attention of scientific researchers.

B. Basic Idea

The basic idea of OFDM is: First, divide the channel into several orthogonal sub-channels, convert high-speed data signals into parallel low-speed sub-data streams, and then modulate them for transmission on each sub-channel. After that, the orthogonal signals can be separated by using related technologies at the receiving end, which can reduce the mutual interference between sub-channels ICI. The signal bandwidth on each subchannel is smaller than the relevant bandwidth of the channel, so the signal on each subchannel can be regarded as flat fading, which can eliminate inter-symbol interference. After separating multiple orthogonal sub-carriers, discrete Fourier transform (DFT) and its inverse transform (IDFT) are applied to the parallel transmission system as part of the modulation and demodulation process.[2] This solves the problem of transmission and transmission in a multi-carrier transmission system. The application of fast Fourier transform greatly reduces the complexity of the multi-carrier transmission system. In this way, it is possible to realize FDM without applying a band-pass filter and only through baseband processing.

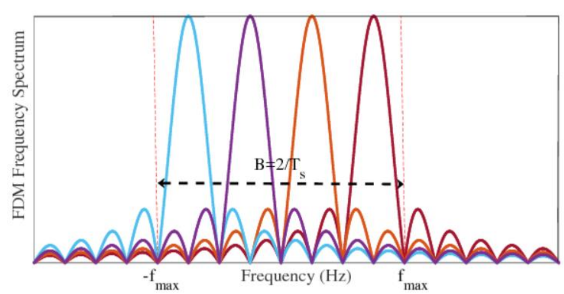


Fig. 1. Frequency Distribution of Subcarriers in FDM

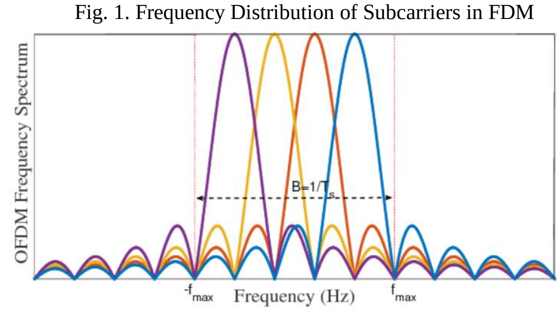


Fig. 2. Frequency Distribution of Subcarriers in OFDM

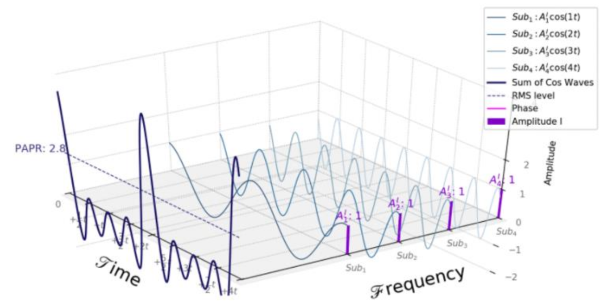


Fig. 3. Time and Freq Response of Subcarriers in OFDM

C. *Pros and Cons*

OFDM system has been widely used in communication technology in recent years mainly due to its following advantages:

1) Higher Spectrum Utilization
As shown in the Fig 1.1 and Fig 1.2, since the sub-channels in the OFDM system are sub-carriers of each other's state and religion, and the sub-carrier spectrum can overlap each other, the frequency space utilization rate is higher. In addition, the sub-carriers in OFDM can be modulated by MPSK, which can further improve the spectrum utilization.

2) Excellent Anti-Multipath Interference Ability
For those data to be transmitted, OFDM method converts high-rate serial information into low-rate parallel information through S/P (Serial to Parallel) conversion. In this way, the symbol rate becomes slower and the period increases, so the ISI (Inter-Symbol Interference) caused by multipath effect is greatly reduced. In addition, OFDM technology also points out that the cyclic prefix is added to serves as a protecting interval between channels, which will not only maintain the orthogonality between channels, but also will reduce even completely eliminate the ISI.

3) Excellent Anti-Fading Ability
For those single-carrier systems, fading and interference can lead to the invalidation of the entire transmission link. However, OFDM uses a modulation mode which is suitable for high-rate information transmission on multipath and fading channels. For this kind of link, fading and interference will only destroy the data of the sub-carriers where they are located, and will not affect other sub-carriers.

4) More Sensitive Resource Allocation
In the process of processing small data, the OFDM system uses IDFT and DFT to achieve modulation and demodulation of orthogonal signals. However, if the amount of sub-carrier data is too large, the system can also use FFT to complete this process. Because the fast-developing DSP technology can easily complete this calculation task.

5) Faster Asymmetrical Transmission Rate
First of all, OFDM uses multiple different sub-channels to control the transmission rate of the link, so it can achieve asymmetrical operation of uplink and downlink speeds. In addition, OFDM realizes data transmission using high-rate channels by loading prepared algorithms.

Although OFDM has the above excellent technical advantages, some problems have gradually emerged in the actual application process.

1) Excessive System Complexity
Because the transmission power and data transmission rate of the OFDM system are determined by the performance of each sub-channel, in order to effectively realize the allocation of signal power and data, the loading algorithm will make the system too complicated. However, if the mobile speed of the terminal is too high, the adaptive modulation method cannot even be successfully used.

2) More Sensitive Frequency Response
In the OFDM system, the frequency response is particularly susceptible to interference from noise and frequency offset. Because the frequency of the overlapping sub-channels changes with time, the orthogonality of the sub-carriers may be destroyed, and therefore, the transmission spectrum may deviate.

3) High PAPR (Peak to Average Power Ratio)
The output of the system consists of overlapping sub-carriers in multiple sub-channels. The accumulation of multiple signals in the same phase may result in extremely high peak power, which will cause the instantaneous power of the overall system to be much greater than the average power, so it will produce a large PAPR.0 Because excessive system power requires more powerful hardware equipment support, under the same conditions, high-power transmission efficiency is lower. However, if an amplifier is used at the emitter, it will cause signal distortion, which will destroy the orthogonality between different sub-channels in OFDM and cause interference to the system.=

II. Description

In this chapter, first the fundamental components of this experiment will be listed. Next, we will introduce the composition of each physical module of OFDM and the workflow of the system. Finally, A flowchart and detailed explanation will be given.

A. *Fundamental Components*

1) Modulation Method
At present, in order to meet people's demand for more and faster data transmission, multi-system digital modulation has become more and more popular. In this experiment, the two modulation methods MPSK and QAM were tested separately. Two modulation techniques are analyzed when the control output is the same variable. The waveform expression after these two modulations is as follows:

$$s_i(t) = \sqrt{E_s}\cos(2\pi f_c t + 2\pi i \;\; M)$$

$$s(t) = \sqrt{E_{min}}\, a_i \cos(2\pi f_c t) + \sqrt{E_{min}}\, b_i \sin(2\pi f_c t)$$

2) Cyclic Prefix

In the traditional protecting plan, there will be no any signal in the protecting interval, which means there will be a free transmitting period. However, in this condition, the multi-path effect will leads to ICI and ISI. In order to maintain the orthogonality of signals and eliminate the interferences, a series of cyclic prefix is needed to be inserted into the protecting interval. In this way, the period difference between one subcarrier and another subcarrier must be an integer. After testing, it shows that if the length of cyclic prefix is greater than or equal to the length of channel's impulse response, the ICI and ISI will be complete eliminated.

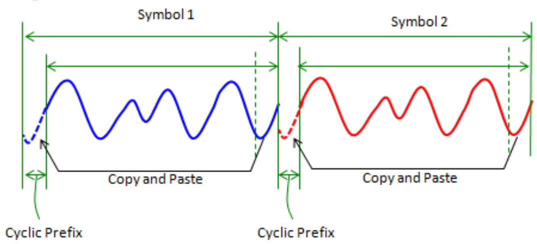


Fig. 4. Subcarrier Frequency after Adding Cyclic Prefix

3) Emitter and Receiver Composition

The following figure shows the transmitter block diagram of the OFDM system after the guard interval is added, so that the loss of power and information rate transmission can be calculated.

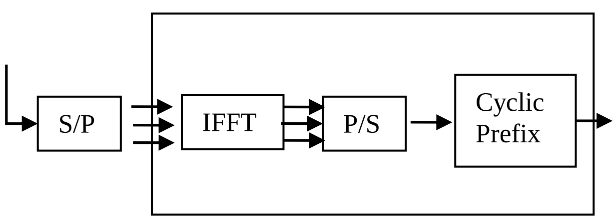


Fig. 5. Emitter of OFDM System

The composition of the receiving electrode is similar to that of the transmitting electrode, but in the opposite direction. The emitter loss function after adding the cyclic prefix can be defined as

$$\text{Loss} = 10*\log((Tg/T) +1)$$

B. *System Workflow*

In this section, the detailed working principle of the system will be discussed. The original source signal is analog and continuous. After baseband modulation (including sampling and filtering), the form of the signal is transformed into a discrete frequency domain signal. Then enter the OFDM module, the discrete signal is decomposed into multiple orthogonal and overlapping parallel sub-carriers, these sub-carriers exist in their respective sub-channels. Next, the motion IDFT or IFFT technology modulates the signal and converts it into an analog signal again.0[3] In this experiment, because the number of subcarriers is relatively large, IFFT is used to reduce the algorithm complexity. After that, the resulting analog model needs to be added to the cyclic prefix to simply and effectively eliminate inter-channel interference caused by multipath effects. It should be noted that in the process of inserting the cyclic prefix, the duration of the guard interval needs to be determined according to the current wireless channel conditions. According to convention, the length of the guard interval should be 2 to 4 times the square root of the time delay extension. Finally, the parallel signal is converted into a serial signal and input to the transmitting filter for transmission. So far, the transmitting end of the OFDM system has completed its transmission task.

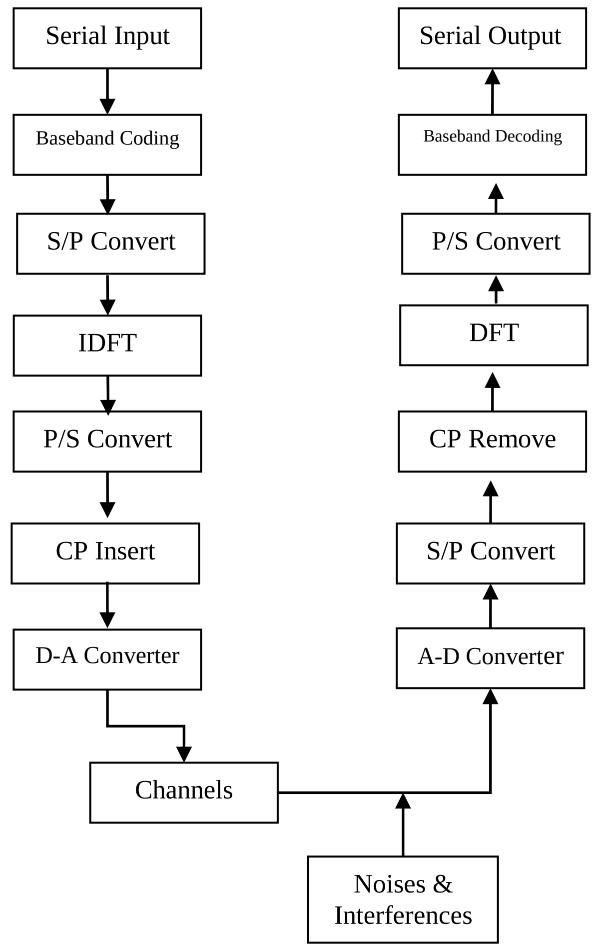


Fig.6. OFDM System Flow Chart

The parallel signal sent by the transmitter passes through the physical channel, and is affected by the weakening and noise caused by the channel transmission, and some details will be lost. The specific loss ratio is related to the signal-to-noise ratio (SNR) of the source signal. In order to easily simulate the signal loss caused by the transmission process, this experiment uses a defined signal-to-noise ratio to explore the relationship between it and the signal-to-noise ratio. After receiving the signal, the receiving end will filter it first, and then transmit the obtained signal to the OFDM receiving end or directly to the information host after demodulation. The specific path selection depends on the result of channel estimation and frame synchronization recovery. After the OFDM receiver receives the continuous serial time domain signal, it first converts it into parallel, and then removes the cyclic prefix of each subcarrier. (Regardless of whether there is a cyclic prefix, only the signal itself is considered when performing FFT or IFFT modulation on the signal, and the cyclic prefix is not considered.) Next, use the FFT method to convert the time domain signal into the frequency domain, and input the converted frequency domain response into In the equalizer. In theory, the processed signal does not have any inter-symbol crosstalk. Finally, perform parallel-to-serial conversion and baseband demodulation on the obtained signal. At this point, the work of the OFDM receiver is completely over.

III. Evaluation

In this part, the simulation part based on Matlab will be discussed in detail. The article will analyze the sequence of the signal changes in the OFDM system.

A. Experimental Design

In order to better control the variables, the experiment did not use randomly generated one-dimensional signals, but used a simple binary image as transmitted data and compare after reception. Other experimental parameters are shown in the table below.

TABLE I
Parameters' Definition in the Experiment

Symbol	Meaning	Contents
SNR	Data / Noise	-10:5:25
N	Number of Subcarriers	512
Slot/Fr	Slot number per frame	20
	Sym number per slot	7
Sym#	Sym num per slot pilot	2
	Sym num per slot data	5
Channel		AWGN
Modulator		QAM and MPSK

B. Analysis of Algorithm's Output

Step 1, we choose Gaussian channel for simulation experiment. The source picture and its time-frequency response are as follows. (In order to save time, from then on, the time frequency analysis is limited to the first 200 sampling points)

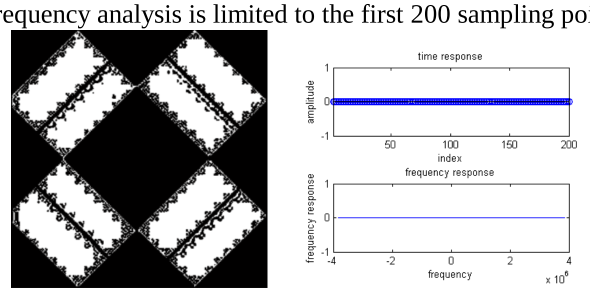


Fig. 7. Data Source and its Time& Freq Response

Step 2, use 100PSK modulation to output the signal as 100 different phase carriers by phase selecting. Then, use 16QAM modulation to differentiate signal changes in amplitude.

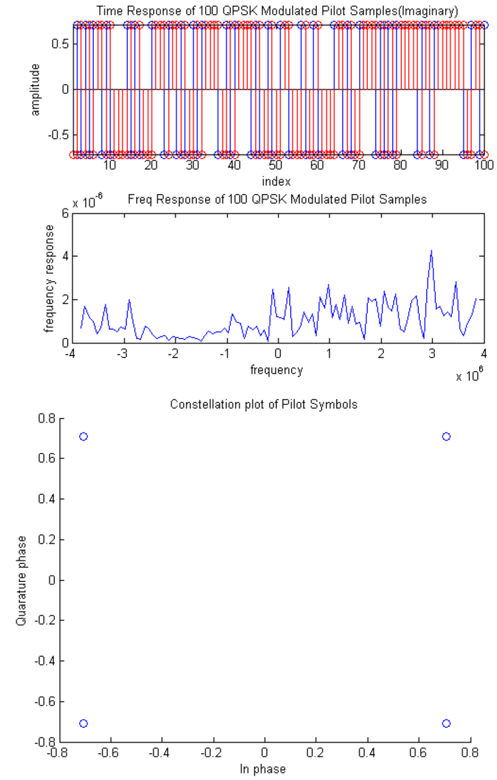


Fig. 8. Time&Freq Response and Constellation Plot after 100PSK

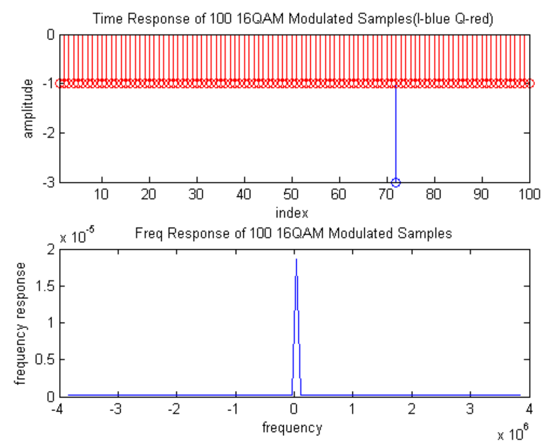


Fig. 9. Time&Freq Response after 16QAM

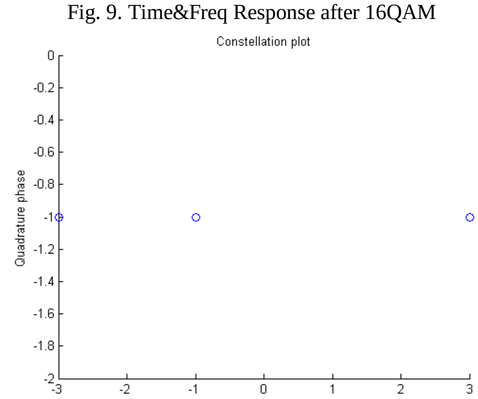


Fig. 10. Constellation Plot after 16QAM

Step3, in order to add cyclic prefix, apply IFFT to the modulated signal to convert it from frequency domain to time domain.

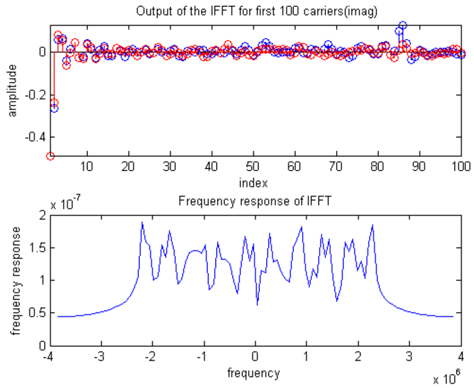


Fig. 11. Output of IFFT

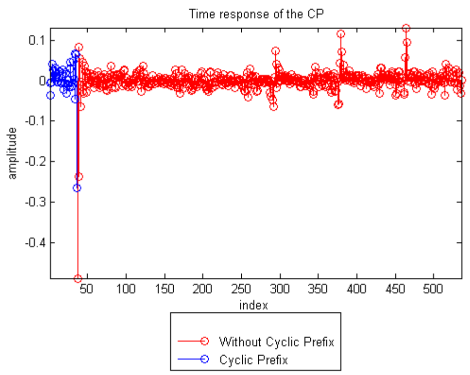


Fig. 12. Time Response with CP

Step 4, Add cyclic prefix to the obtained signal. As shown in the figure, the blue part is the cyclic prefix of the sub-carrier. After the CP is added, the tail of the previous symbol will not fall in the sampling interval of this signal, so that ISI is fully avoided. In addition, due to the cyclic convolution characteristic of the FFT, the signal is regarded as a circle in this step, and a complete signal can be obtained no matter where the FFT window is added. So in this step, CP also eliminates ICI to a certain extent.

Step 5, the signal needs to be up-sampled before the data is transmitted from the transmitter to the channel. After this, Gaussian noise is added to the signal by the simulated AWGN channel, and the mixed signal is input to the receiving terminal. Then, apply a low-pass filter to the received signal. The effect of using a low-pass filter here is mainly to reduce power leakage. Suppress the parts other than the main component of the sub-carrier to reduce the interference between carriers.

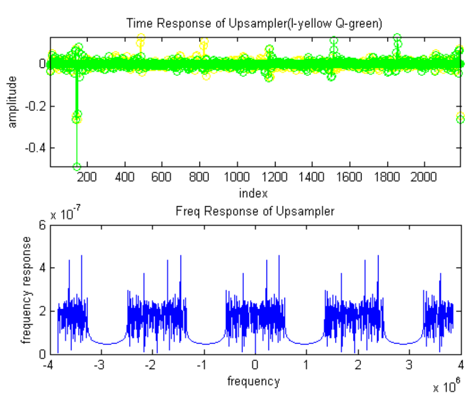


Fig. 13. Time & Freq Response of Umsampler

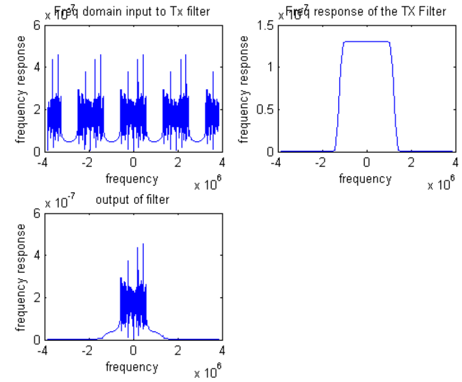


Fig. 14. Output Signal after Tx Filtering

Step 6, apply low-pass filter on receiving terminal to reduce the noise effect, because for image data, the high frequency part is commonly noise.

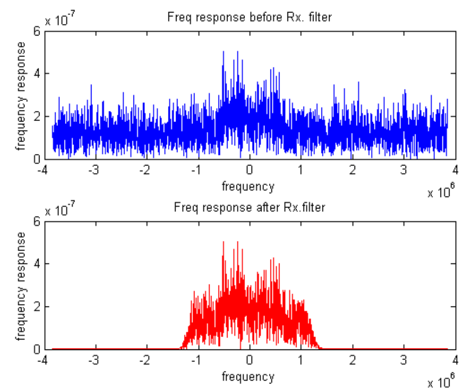


Fig. 15. Rx Filtering

Step 7, after receiving the signal, we do demodulation to the signal we obtained. Note that before the demodulation, the signal must be oversampled, because when these samples without oversampling are sent to the analog-to-digital converter, it may cause false signals to be generated, which is not allowed by the system. 0The performance of this kind of spurious signal is that when sampling at a frequency lower than twice the highest frequency in the signal, that is, when the sampled value is restored, the signal will no longer contain the high-frequency components of the original signal, showing a false Low frequency signal. Therefore, the higher the sampling frequency, the more the signal obtained can represent the details of the symbol.

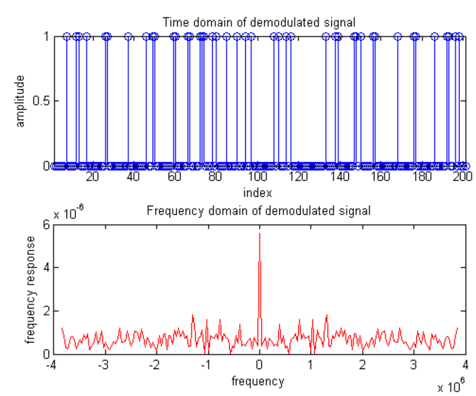


Fig. 16. Time & Freq Response after Demodulation

Step 8, after receiving the signal, we do demodulation to the signal we obtained. Figure 16 shows the signal response after demodulation when SNR equals 5db.

Step 9, after demodulation, we get the restored signal. Ideally, the restored signal should be consistent with the signal sent from the output. In order to explore the relationship between SNR and signal transmission loss, here will compare the signal difference between the emitter and the receiver when the SNR is equal to -10db, 0db, and 10db respectively.

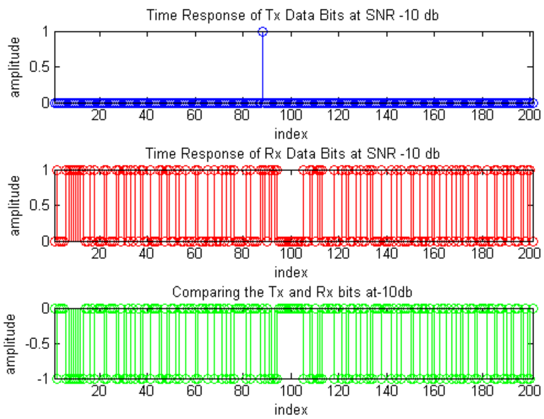


Fig. 17. Comparing when SNR=-10db

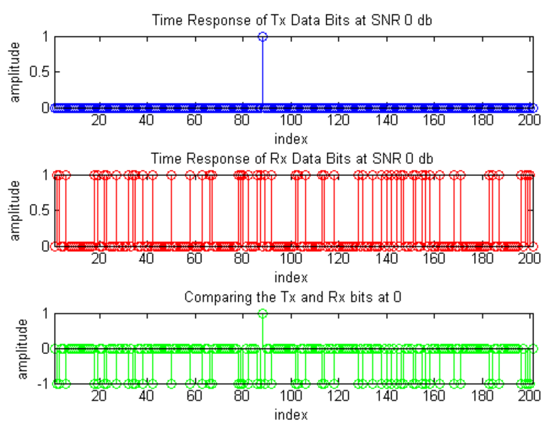


Fig. 18. Comparing when SNR=0db

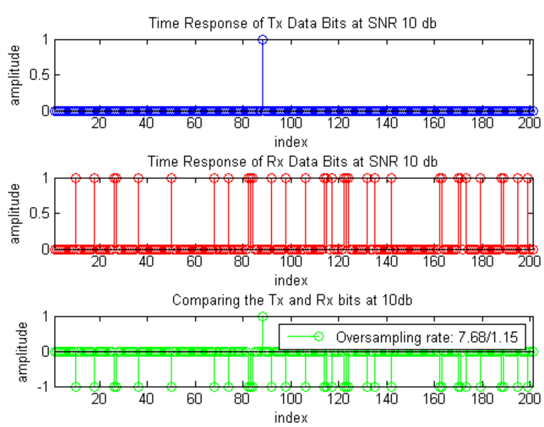


Fig. 19. Comparing when SNR=10db

C. Summary

Comparing Figure 16 and Figure 7, we can find that after demodulation, the picture at the receiving end has a discernible change from the original picture. By comparing the frequency maps of the two, we can see that in the Gaussian channel, the signal is mixed with uniform and random Gaussian white noise.[4] By observing Figure 17 to Figure 19, we can also easily find that as the signal-to-noise ratio gradually increases, the time response of receiving terminal becomes more sparse. Besides, the difference between the output end and the receiving end gradually tends to zero. The mentioned difference above is the Gaussian noise from AWGN channel. From this we can infer that as long as the signal strength is large enough, the OFDM system is fully capable of performing lossless information transmission. We can also conclude that the Gaussian noise obtained from physical channel is uniform and random.

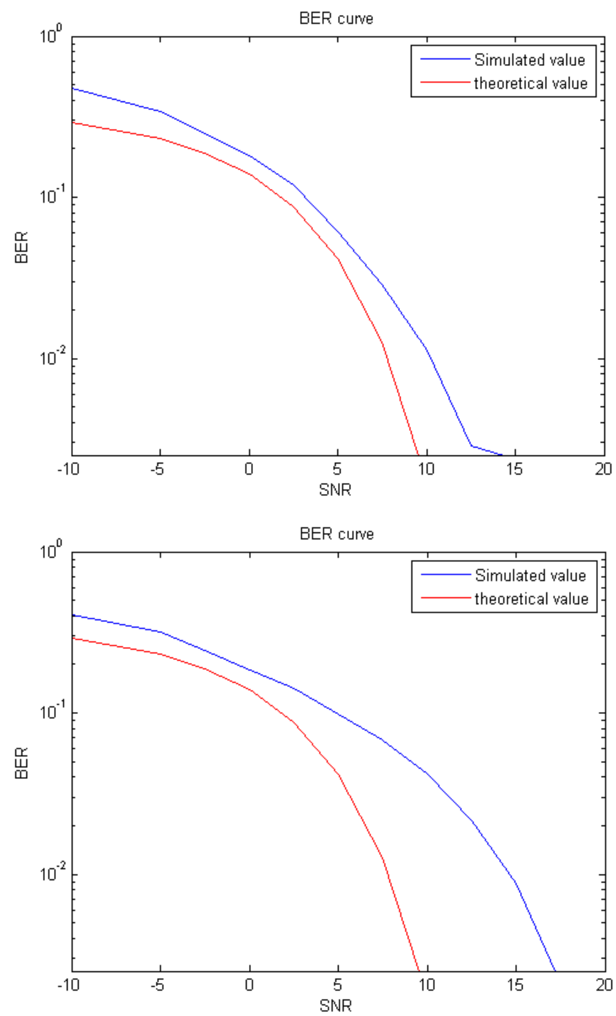
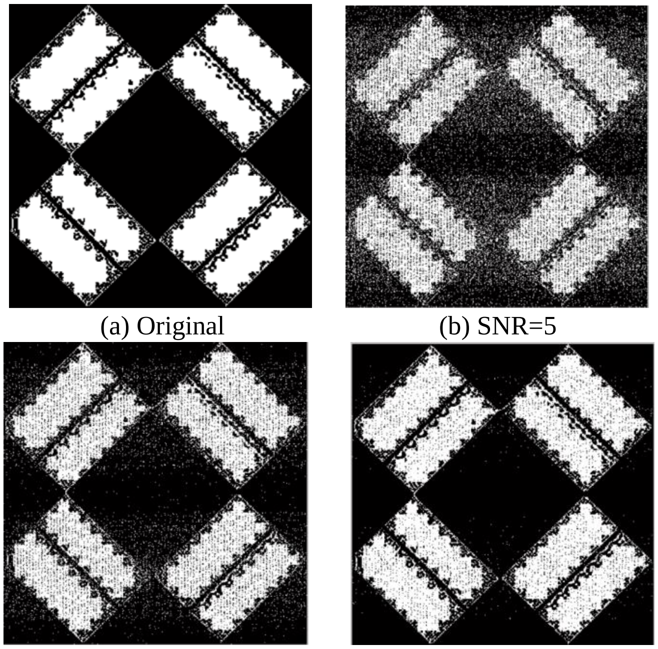


Fig. 20. BER vs. SNR Trend Graph（Top:Image Bottom:Random）

It can be seen from figure 20 above that when the source input frequency is fixed, the BER decreases monotonically with the increase of SNR. In this experiment, in order to simulate the LTE performance, the output image's SNR is limited from 5dB to 25dB.



(a) Original (b) SNR=5

(c) SNR=15 (d) SNR=25

Fig. 21. Comparison at the Receiving Terminal under Different SNR

From the above figure 21, We can find that as the SNR increases, the Gaussian noise contained in the picture of the receiving terminal decreases. For the test picture used in the current experiment, when the value of SNR is between 0-5, the system simulation has the highest degree of excellence, which is closest to the theoretical curve. [5]

In addition, by comparing the output of figure 20, we found that when the system input is random multi-frequency noise, the BER result is roughly the same as the test image. However, as the SNR increases, the goodness of fit of the BER of multi-frequency signals is lower than that of a single frequency.

IV. Related Work

In this part, first will introduce others applications of OFDM system in real life, and then a comparison of OFDM and CDMA technology will be analyzed. Finally, I will discussed the future development trend of OFDM technology.

A. Applications

1) Digital Video Broadcast

Compared with analog broadcasting, digital video broadcasting is more excellent in voice and digital services. In 1995, the European Telecommunications Standards Institute passed the first DAB standard-ETS300401. In addition, the ISDB-T in Japan and the IBOC in the United States also include OFDM technology. OFDM technology is also applied in the DVB-T standard of Digital Video Broadcasting (DVB).

2) 5G

There are many improved versions of OFDM, among which OQAM-OFDM technology has lower spectrum leakage, so it has become a key component of today's 5G technology. Because OQAM-OFDM does not require all sub-carriers to be synchronized, the new system has better compatibility and can adapt to other business requirements.[5] In addition, F-OFDM, the air interface technology uniformly used by 5G, also takes OFDM as the core. It divides the OFDM carrier bandwidth into multiple subbands with different parameters, and filters the subbands, leaving as little as possible between the subbands. Isolate the frequency band. [6]In this way, the system can achieve large-scale coverage of Internet services with low power consumption.

3) HiperWLAN

In the relevant standards of high-speed wireless local area networks, OFDM technology is applied in the HiperLAN/2 physical layer. At the same time, in the ISM frequency band

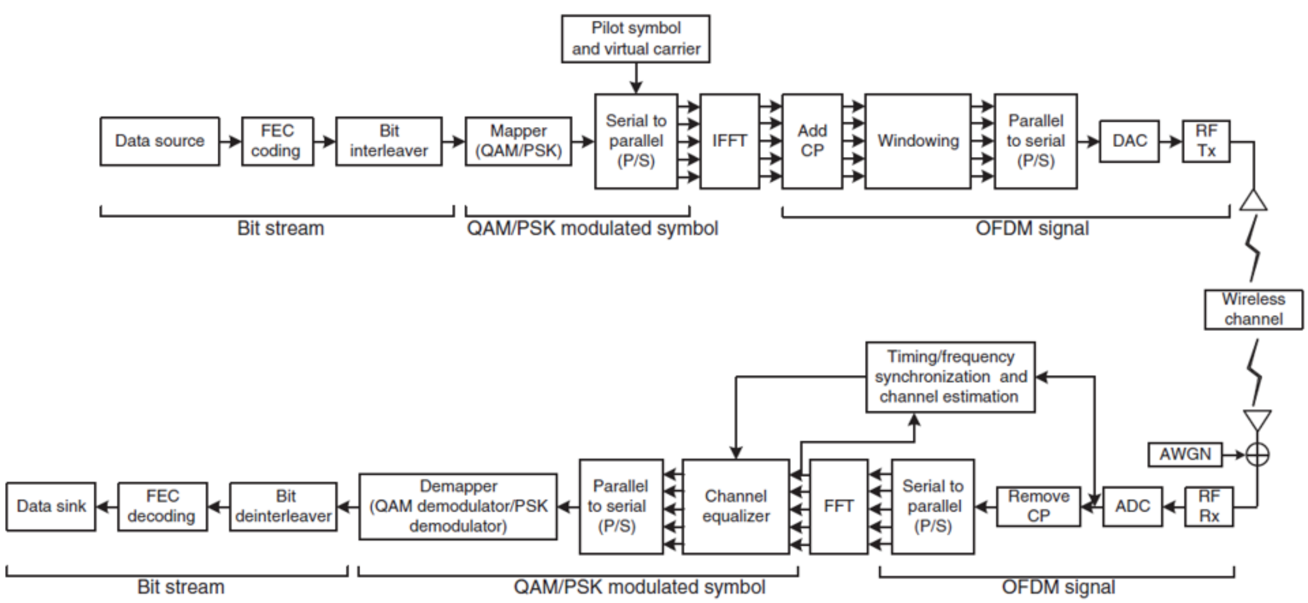


Fig. 22. OFDM System Block Diagram

of the IEEE802.11 standard, both the 2.4 GHz and 5.8 GHz frequency bands use the technology's IEEE802.11a and IEEE802.11g standard.

4) FLASH-OFDM
FLASH-OFDM is a technology that uses fast frequency modulation to spread spectrum with the theme of OFDM. This method itself has frequency diversity capability and can provide users with IP-based broadband access Internet services in a wide mobile environment. Allow users to have the same performance and data volume as LAN. The uplink and downlink are broadband carriers composed of hundreds of sub-channels. [7] FLASH-OFDM allocates sub-channels to each user when transmitting data, and each sub-channel uses adaptive modulation and Vector-LD-PC coding schemes.

B. *Comparison with CDMA*

1) Anti-Multipath Interference
Different from the spread spectrum and cyclic prefix method of OFDM, The CDMA receiver uses discrete multipath and diversity receiving (RAKE) technology to distinguish and bind the energy of multiple signals. The RAKE receiver provides some diversity gain. However, due to the unequal signal energy of the multiple channels, experiments have proved that if the number of paths exceeds 7 or 8, the dispersion of the signal energy will reduce the accuracy of channel estimation, and the RAKE reception performance will drop quickly.

2) Modulation Method
In the CDMA system, the downlink uses multi-carrier modulation technology, but the modulation method on each link must be the same, and the uplink does not support multi-carrier modulation, which makes the CDMA system lose some flexibility; at the same time, because of this chain The non-orthogonality of the road makes users with different modulation methods produce great noise interference. [4] However, in the OFDM system, each link can be independently modulated, so the system can easily accommodate multiple hybrid modulation methods at the same time regardless of the uplink or downlink. This kind of "adaptive modulation" increases the flexibility of the system. For example, when the channel is good, the terminal can use higher order modulation such as 64QAM to obtain the maximum spectral efficiency, and when the channel condition is bad, you can choose QPSK or other Low-level modulation to ensure the SNR. In this way, the system can achieve the best balance between spectrum utilization and BER. In addition, although ICI limits the modulation method of a particular link, this can be solved by means such as network frequency planning and radio resource management.

3) PAPR
The PAPR of a CDMA system is generally 5-11dB, and will increase as the data rate and the number of codes used increase. The OFDM signal is formed by superimposing multiple independent modulated orthogonal sub-carrier signals. This composite signal may generate a relatively large peak power, thereby bringing about a large PAPR.

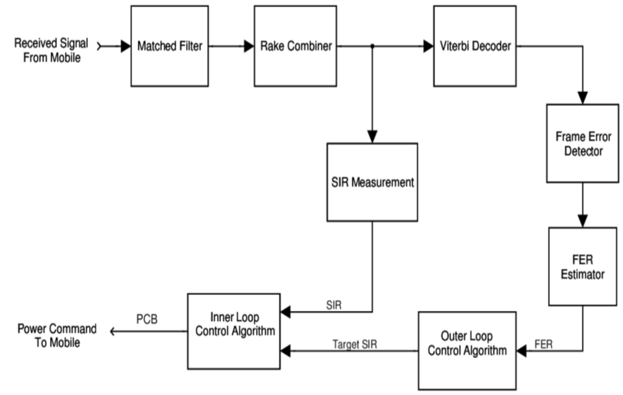


Fig. 23. Block Diagram of CDMA Technology

C. *Future*

The most valuable development direction of OFDM in the future is multi-antenna technology. Because multi-antenna technology can ideally increase system capacity and highlight system characteristics, and can significantly improve network stability and reliability, and greatly increase signal coverage, it is especially suitable for use in Internet and multimedia services. The MIMO-OFDM system combines MIMO technology and OFDM technology, which greatly improves the performance of the system. Some core technologies and calculation methods related to transmit diversity, spatial multiplexing, reception diversity and interference cancellation, adaptive modulation and coding are used in the MIMO-OFDM system. [8]

V. Conclusion

This article first briefly introduced the basic ideas of the OFDM system. Then the working principle of the OFDM system is described in detail according to the module sequence in Fig. 20. Then use experiments to analyze the information transmission performance of the OFDM system under the AWGN channel. The results obtained from the experiment also verify the advantages and disadvantages of OFDM mentioned above. In addition, the experiment can further explore the transmission performance of OFDM under different conditions by adding other channel tests.

OFDM itself is already a very mature technology. Among them, various key technologies such as synchronization, equalization, channel estimation, power control, etc. have been fully optimized in 4G applications. [9]Although the application potential of OFDM is huge, there are still many difficulties to be overcome. Among them, the biggest problem is too high peak-to-average ratio. Although the current 5g technology avoids this technical flaw through the multi-antenna method, power consumption control is still a problem that everyone must face. In the future, only if this shortcoming is overcome, OFDM can play a greater role in the post-5g era.

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