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OFDM Modulation for 4G LTE Mobile

EEEE3087 Mobile technologies—Coursework1

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March 29, 2023

Abstract

OFDM technology started to become rapidly popular after the 1990s. This paper introduces the main principles and implementation of OFDM, and introduces the important role of OFDM at the level of 4G and 5G mobile networks. In the second part, I have done the simulation of a 16-QAM based OFDM transceiver in Simulink® and observed the constellation diagram, power spectrum and calculated the BER.

Through this article, I learned how OFDM is implemented and how to complete a complete transceiver design in Simulink® and understand the impact of different channels and different signal-to-noise ratios on communication quality.

Keywords: OFDM, QAM, BER

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Part I

Introduction and Background Research

1 Introduction

Orthogonal Frequency Division Multiplexing (OFDM) is one of the most powerful modulation techniques. It is designed for high-data-rate transmission. In general, it will convert a high-rate data stream into several low-rate data streams which can be transmitted in parallel [1]. These streams or sub-carriers are orthogonal to each other, which means they don't interfere with each other, allowing multiple sub-carriers to be transmitted simultaneously over the same channel without causing interference. Figure 1.1 shows the spectrum of sub-carriers of OFDM, as you can see all the sub-carriers do not overlap and they are orthogonal to each other [2].

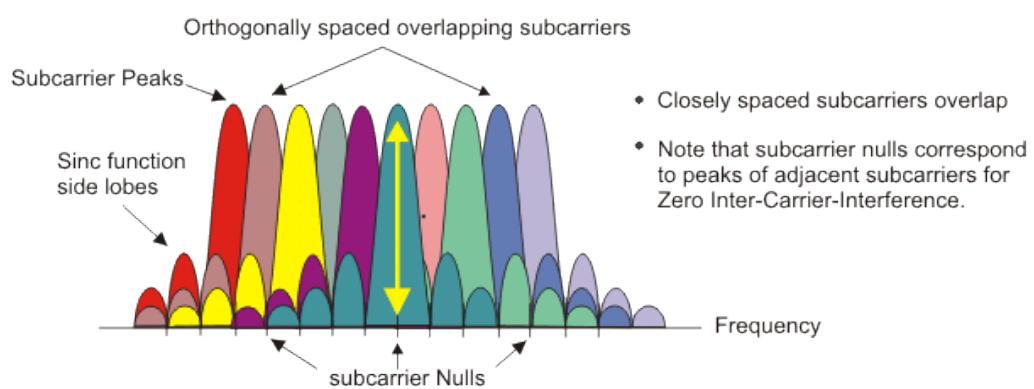


Figure 1.1: The spectrum of sub-carriers of OFDM

1.1 A Brief Implementation of OFDM

At the transmitter, it is required to apply a series-parallel (SP) conversion, i.e., from a single point to N points. Then use *Inverse Fast Fourier Transform* (IFFT) to create the time-domain OFDM signal from the modulated signal. In the end, add a *Digital-to-Analogue Converter* (DAC) to from the signal which can be transmitted in the channel.

At the receiver, the OFDM signal is first demodulated to recover the sub-carriers. Then, each sub-carrier is processed individually to recover the raw data. A parallel-serial converter is then used to convert the low-speed data stream to a high-speed data stream for use by the terminal.

Overall, the principle of OFDM allows for high-speed data transmission over limited bandwidth channels, with robustness against interference and distortion caused by multi-path propagation.

1.2 Role in Mobile Networks

OFDM plays an important role in both 4G and 5G LTE (Long-term Evolution) mobile networks.

- Strong anti-interference capability: When the signal is transmitted in the air, it is very likely to be interfered and distorted by multi-path propagation which is shown in Figure 1.2. Hence, people are considering transmitting multiple non-interference sub-carriers which can be recovered easily by their orthogonality.

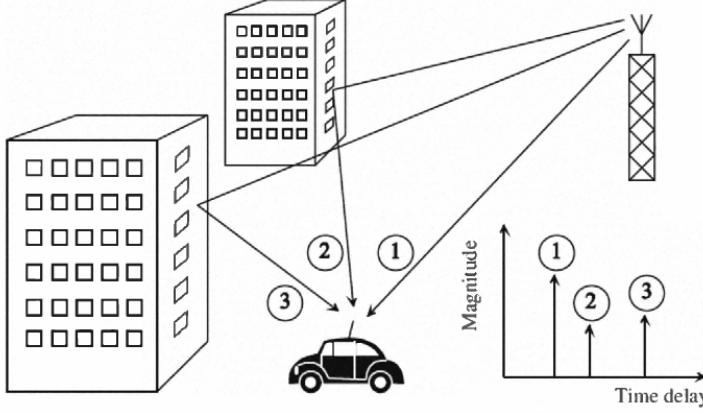


Figure 1.2: The multi-path propagation

- High data rates: As OFDM owns several channels to transmit data, it can gain higher rates. That is, it can be considered as a *Multiple-Input Multiple-Output* (MIMO) system.
- High spectrum utilization: OFDM can be used to transmit multiple sub-carriers simultaneously over the same channel, which can be used to increase the spectral efficiency of the system.

OFDM is used in many different communication systems, including digital television, Wi-Fi, 4G and 5G LTE mobile networks, and *Digital Subscriber Line* (DSL) modems over copper-based telephone access lines. Due to its excellent performance, OFDM has been standardized by IEEE into standards such as 802.11g and 802.11a. The *asynchronous digital subscriber line* (ADSL) and *high-bit-rate digital subscriber line* (HDSL) technologies use OFDM for fixed-wire applications. [1, 3].

2 Implementations of OFDM Based on QAM

2.1 QAM Modulation

Quadrature Amplitude Modulation (QAM) is a digital modulation which uses two sinusoidal carriers that have a phase difference of $\pi/2$, known as orthogonality or quadrature. Each of them can be modulated independently, transmitted over the same frequency band, and demodulated at the receiver. Both mobile radio and satellite communication technologies use QAM and its variations [4].

Based on this theory, there are many QAM variants, such as 64-QAM, 256-QAM, 1024-QAM, which are widely used [4]. The diagram below shows the constellation of QAM.

2.2 Implementations of Transceiver

2.2.1 Implementations of QAM

When the signal is sent under the QAM modulation, it will change the amplitude and phase of it.

One possible and easiest way to implement is generate two carrier which are sine and cosine. They are obviously quadrature. The symbols that go through the cosine

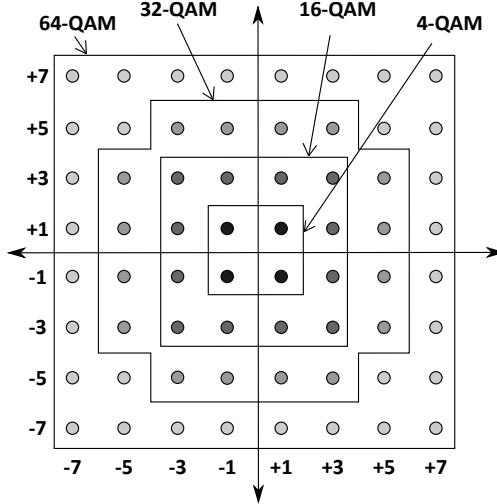


Figure 2.1: Constellation plot for 4-QAM, 16-QAM, 32-QAM, and 64-QAM

carrier are called *in-phase* (I) signal and the others are called *quadrature* (Q). They can be represented as:

$$I = A \cos \varphi \quad (2.1)$$

and

$$Q = A \sin \varphi \quad (2.2)$$

After that, mix these two signals. This modulation scheme is called 4QAM, and in fact, it is not different from *Quadrature Phase Shift Keying* (QPSK).

At the same time, we can increase the order of QAM. M-decimal QAM is denoted as MQAM. As an example, I will briefly describe 16-QAM. The 16-QAM modulation scheme is shown in Figure 2.2.

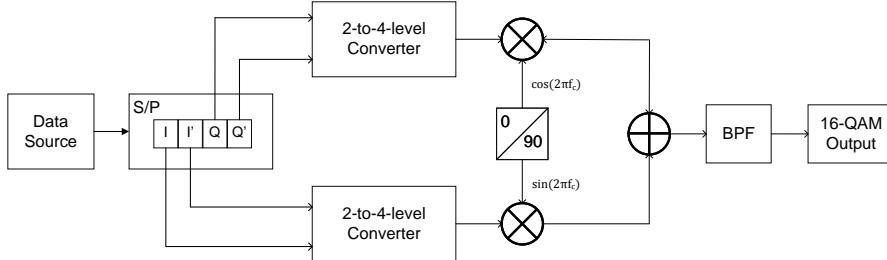


Figure 2.2: Block diagram of 16-QAM modulator

Mathematically, it can be expressed as,

$$S_{16-QAM}(t) = I(t) \cos 2\pi f_c t - Q(t) \sin 2\pi f_c t \quad (2.3)$$

where $I(t) = \pm 1, \pm 3$; $Q(t) = \pm 1, \pm 3$. Since there are 16 possible combinations of $I(t)$ and $Q(t)$, the synthesized QAM signal has 16 states. In a period, there will be $\log_2 16 = 4$ bits to be transmitted, and it will increase the data rate. Hence, we will use the *Series-Parallel* (SP) conversion, i.e., from a single point to N points. In this scenario, $N = 2$. In the I/Q channel respectively apply a 2-to-4 level converter. This mapper will transfer the four combinations of two bits into four amplitude levels. After that, the I/Q channel will multiply by the sine and cosine waves.

2.2.2 Implementations of OFDM

In order to make their sub-carriers orthogonal to each other or not overlap each other in the frequency domain, the inner product of any two sub-carriers is zero. That is, in the time domain, the cross-correlation of any two sub-carriers is zero. As shown in the following Equation 2.4,

$$(f \star g) \triangleq \int_{-\infty}^{\infty} \text{sub-carrier}_N(t) \cdot \text{sub-carrier}_{N+1}(t) dt = 0 \quad (2.4)$$

Before mapping each low-rate date to sub-carriers, we first need to use a serial to parallel converter. The IFFT can be performed only after SP conversion. At the same time, this operation corresponds to an N-fold increase in the duration of each symbol, increasing the system's immunity to interference.

Secondly, it's common to use the *Inverse Discrete Fourier Transform* (IDFT) technique to map to sub-carriers. The IDFT can be represented as:

$$\hat{x}[k] = \sum_{n=0}^{N-1} e^{-i\frac{2\pi}{N}nk} x[n] \quad k = 0, 1, \dots, N - 1. \quad (2.5)$$

We usually us the *Inverse Fast Fourier transform* (IFFT) technique to complete that as it will perform a more efficient way to compute. The process of generating an OFDM signal using IFFT involves taking the data to be transmitted and mapping it onto the sub-carriers. The sub-carrier signals are then modulated using the appropriate phase and amplitude information, and then combined using the IFFT to create the time-domain OFDM signal.

At the receiver, the process is reversed. When the signal passes through the channel, it is first sampled. Then, a PS converter is used to feed the FFT with sub-carriers. After that, write a block of N symbols into a vector which is PS converter. Hence, the structure of OFDM transceiver is shown in the Figure 2.3.

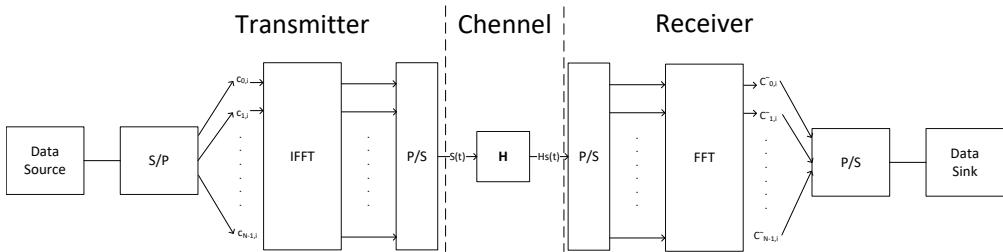


Figure 2.3: Structure of OFDM Transceiver

2.2.3 Typical BER

In order to provide a typical *Bit Error Rate* (BER) of OFDM and 16-QAM, I use MATLAB to simulate the BER of OFDM and 16-QAM. The simulation results are shown in the Figure 2.4.

2.3 Advantages and Disadvantages

When OFDM was first invented in the 1960s at Nokia Bell Lab [5], it was not taken seriously because of several technical limitations that made it challenging to implement in practical communication systems. Some of these limitations include: high complexity, sensitivity to frequency offset, limited channel estimation and so on. It was not until

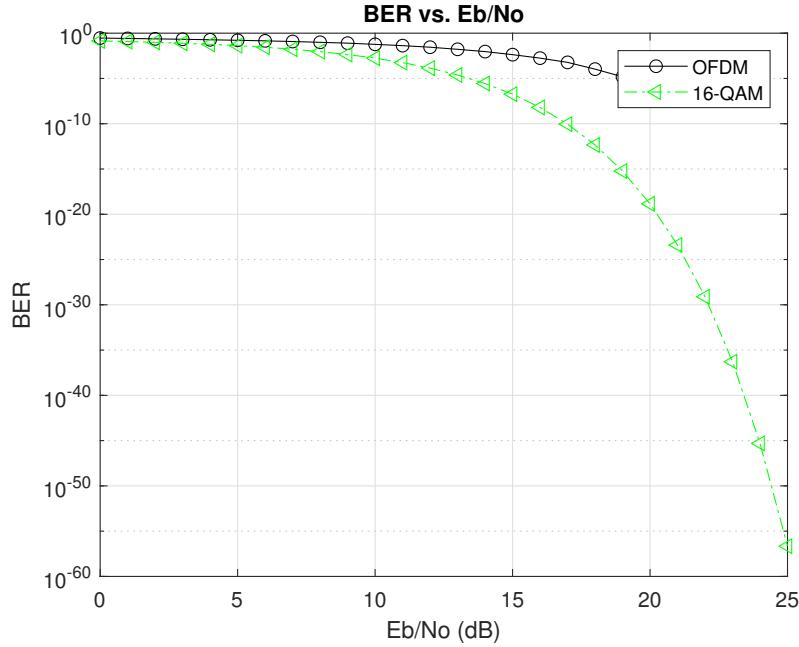


Figure 2.4: Typical BER of OFDM and 16-QAM

the 1990s, when advances in DSP, computing technology and FFT algorithms, made it possible to overcome these technical limitations, that OFDM started to gain widespread attention and adoption in communication systems.

Its advantages includes robustness in the presence of multi-path transmission, relative insensitivity to timing offsets, compatibility with MIMO systems and the ability to support multiple access in the form of *Orthogonal Frequency Division Multiple Access* (OFDMA).

Though, it still has some drawbacks, high *Out-of-Band* (OOB) power, sensitivity to frequency offset, and high *Peak-to-Average Power Ratio* (PAPR) [6].

3 Practical OFDM Modulator or Demodulator Design

The most ordinary way to implement OFDM digitally on hardware is using *Field Programmable Gate Array* (FPGA). However, when the OFDM is invented, there are still many ways to implement it in an analogue circuit. The the structure of OFDM transceiver implementing in analogue circuit is shown in the Figure 3.1 [1]. We can

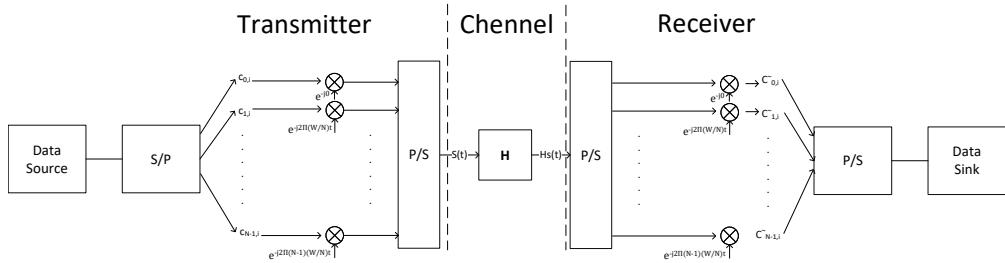


Figure 3.1: Structure of OFDM Analogue Transceiver

use an oscillator to generate a continuous wave (CW) signal, and then use a frequency multiplier and a comb generator to generate the subcarriers at the desired frequencies. The comb generator can be implemented using a phase-locked loop (PLL) or a delay-line

filter. The subcarriers are then modulated using QAM or other modulation schemes, and combined using a mixer and a filter to generate the final OFDM signal.

- Mixer: Mixer is an important device in the RF circuit, it is often used for modulation, the signal will be loaded on the high frequency signal.

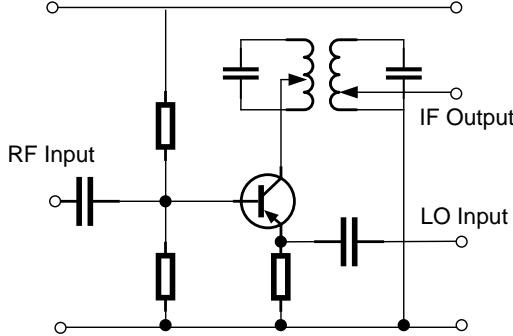


Figure 3.2: Schematic of a Mixer

- LPF: *Low Pass Filter* (LPF) is a filter that passes low-frequency signals and attenuates high-frequency signals. It is very useful in the analogue OFDM transceiver.

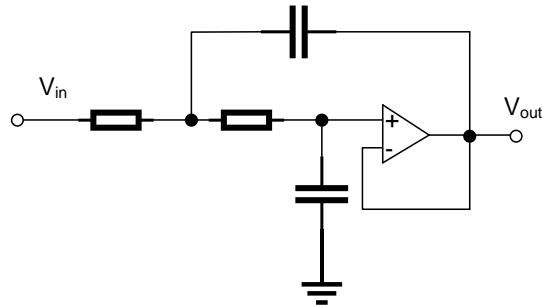


Figure 3.3: Schematic of a LPF

Part II

BER Analysis

4 Blocks of the OFDM Transceiver in Simulink®

A simulation software called Simulink® is frequently used in the planning and evaluation of communication systems, including OFDM. Simulink® offers a graphical interface for creating communication system models, making it simpler to develop and test various OFDM system configurations. Figure 4.1 shows the full schematic of 16-QAM-based OFDM transceiver.

- Random Integer Generator: This block can provide a random sequence of numbers as the input raw data.
- 16-QAM: This block can modulate or demodulate the data by 16-QAM modulation. This process is called baseband modulation. After that, we can convert baseband signals into frequency band signals and map the data to I/Q.

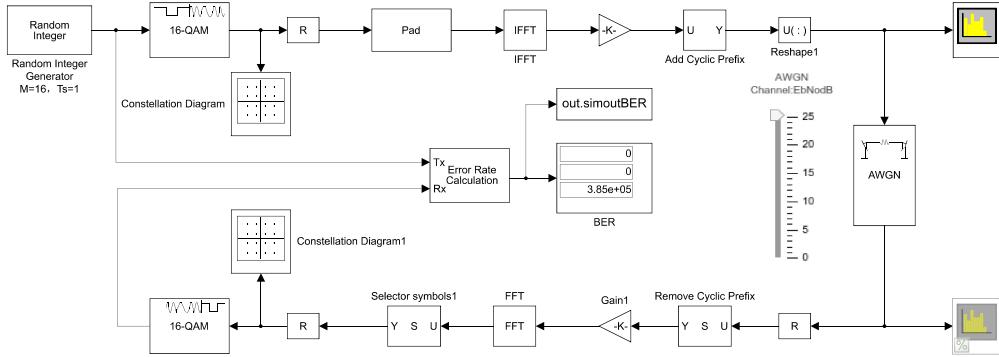


Figure 4.1: Schematic of 16-QAM-based OFDM transceiver

- Reshape + Padding: This block can reshape the data into a matrix and add some zeros to the end of the data to make the length of the data can be divided by 64. They are designed to generate OFDM symbols.
- IFFT: This block can map the OFDM symbols into time domain signals. The subcarrier signals are then modulated using the appropriate phase and amplitude information, and then combined using the IFFT to create the time-domain OFDM signal. The IFFT is used because it can efficiently compute the inverse transform of the Discrete DFT, which is used to convert the subcarrier signals from the frequency domain to the time domain. The use of the IFFT also ensures that the subcarriers are orthogonal to each other in the time domain, which is necessary for reliable transmission of data.
- Cyclic Prefix: One of the main challenges in OFDM is the effect of multi-path fading, which can cause *Inter-Symbol Interference* (ISI) between adjacent OFDM symbols. This can lead to errors in the received signal and can limit the achievable data rate. To mitigate the effect of ISI, a *Cyclic Prefix* (CP) is added to each OFDM symbol. CP is to extend the OFDM symbol by copying the last samples of the OFDM symbol into its front [7].

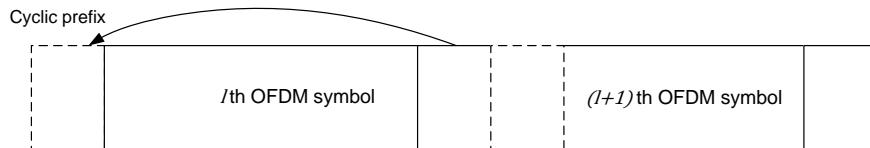


Figure 4.2: OFDM symbols with CP

- Reshape: Group the data for OFDM symbols using.
- AWGN Channel: *Additive White Gaussian Noise* (AWGN) Channel can add noise to the signal. The noise is generated by a Gaussian distribution with a mean of zero and a standard deviation of 1. The noise power is controlled by the *Eb/No* parameter.

As for the receiver, we only need to reverse the process of transmission and do some small modifications. In addition to the transceiver, I have added some blocks for testing.

- Constellation Diagram: It can reveal modulation error rates, BER, phase noise, amplitude noise and other issues.

- Spectrum Analyzer: Observation of the signal spectrum using the FFT technique.
- Error Rate Calculation: This block can calculate the error rate and provide three groups of result which are the error rate, number of errors and the number of samples compared.
- Slider: This block can adjust the Eb/No parameter in the AWGN Channel block very conveniently.

5 BER Analysis

5.1 Constellation Diagram

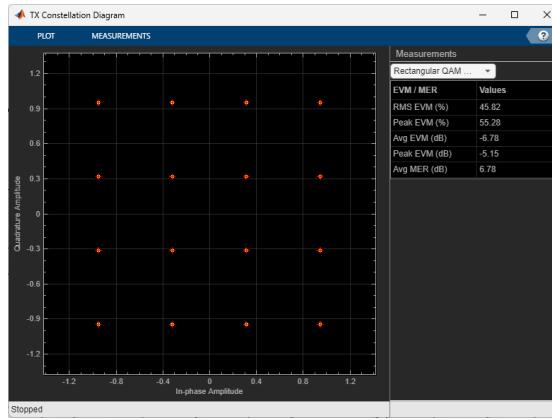


Figure 5.1: Constellation Diagram of Transmitter

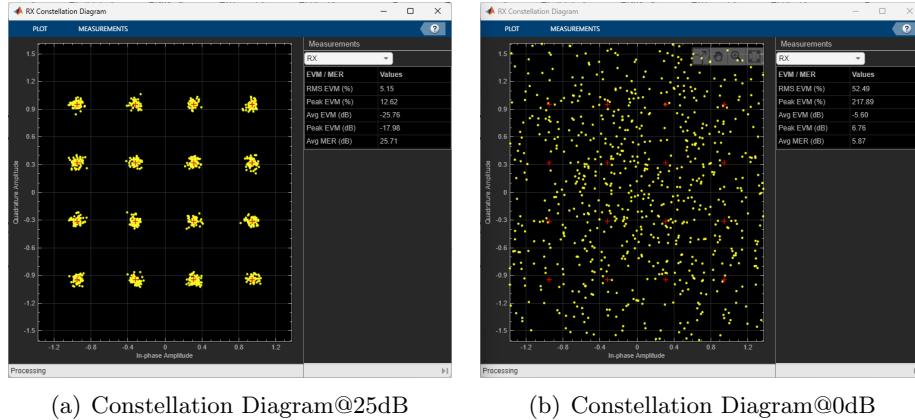
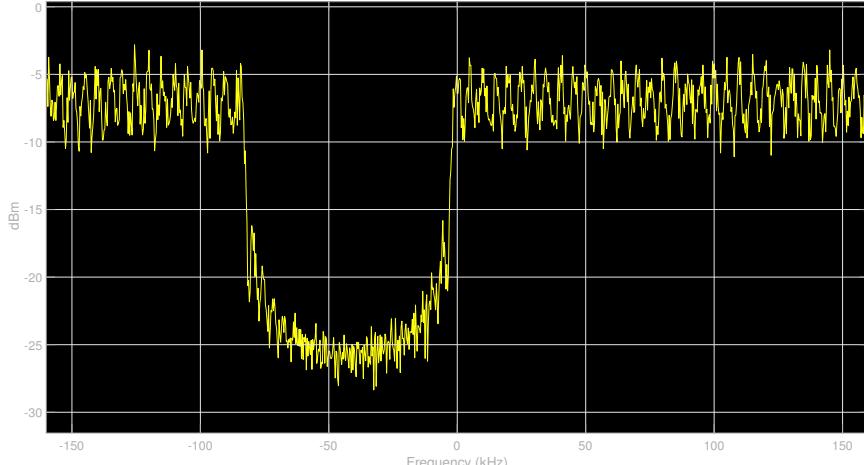


Figure 5.2: Constellation Diagram of Receiver

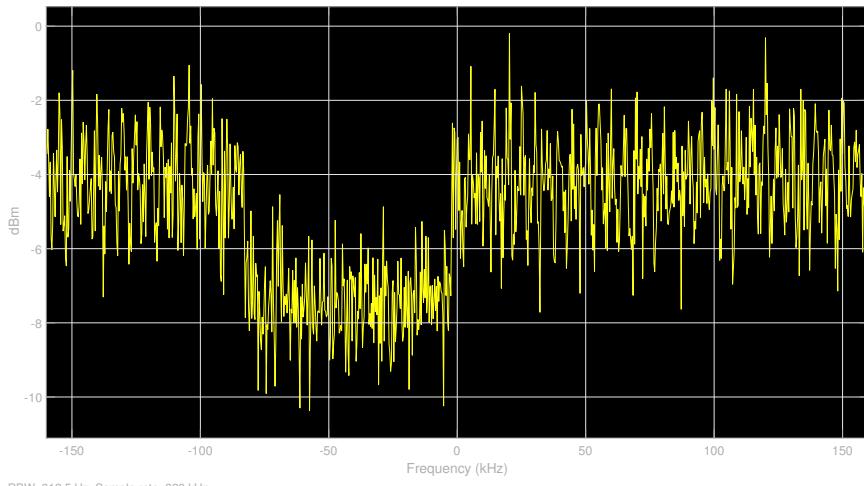
The constellation diagrams are shown in Figure 5.1 and Figure 5.2. In the figure we can clearly see that the *Root Mean Square (RMS) Error Vector Magnitude (EVM)* and Peak EVM are declined due to the reduced channel quality. The symbols have also become more dispersed.

5.2 Power Spectrum

By decreasing the SNR from $25dB$ to $0dB$, the power spectrum of the signal after AWGN channel is shown in Figure 5.3. The power spectrum of the signal is reduced due to the



(a) Power Spectrum@25dB



(b) Power Spectrum@0dB

Figure 5.3: Power Spectrum

reduced channel quality. The frequency spectrum of the signal also starts to become irregular.

5.3 BER Curve

Since I used the gain block in the OFDM model, the signal power of the AWGN input needs to be modified to 1 in the QAM only model so that the BER can be measured correctly.

In the model, I will use “To Workspace” block to save the result from the “Error Rate Calculation” block and plot the BER vs. E_b/N_o .

In addition to setting E_b/N_o to values of 0, 5, 10, 15, 20, 25 dB, I have additionally set E_b/N_o to values in steps of 1 from 0 to 20 db. The BER corresponding to these values is recorded and plotted.

From the Figure 5.4, however, we can see that the BER of 16-QAM-based OFDM is worse than that of QAM-only after signal power normalization because the OFDM model has more blocks than the QAM-only model. The more blocks there are, the more errors there will be. In addition, the OFDM model has a cyclic prefix, which will cause the BER to increase.

Comparing the channel between the AWGN channel and the Rayleigh fading channel, we can see that these two models will have a very low BER when they were transmitted under Rayleigh fading channel. The curves are almost indistinguishable and have no reference value. I believe it is caused by the wrong parameter setting of the Rayleigh fading block. I will try to fix it in the future.

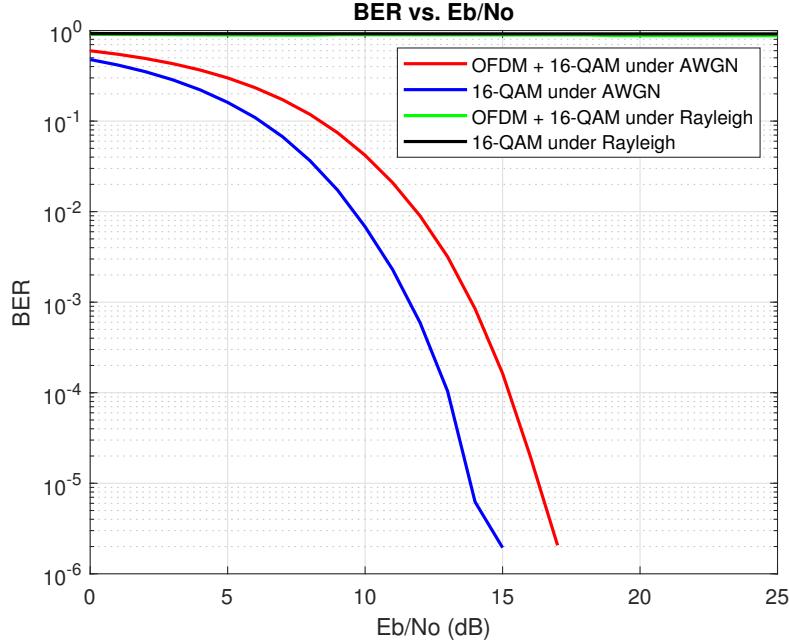


Figure 5.4: BER vs. Eb/No

Part III Conclusion

In this report, I introduced the basic OFDM introduction and implementation, and also described the process of implementing 16-QAM based OFDM from Simulink®, and performed many tests including constellation diagram, power spectrum, and BER. The tests were carried out under different channel conditions. Theoretically, the BER should not be so low in the Rayleigh channel, probably due to the wrong parameter settings. This project allowed us to build a good body of knowledge on OFDM and QAM and to exercise our Simulink® simulation skills. We learned about the various factors that judge the quality of communication and the method of judging the quality. In the future, the areas I need to improve are

- Adjusting the parameters of Rayleigh fading channel
- Familiarize me with the correspondence between the module and the actual circuit

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