Analysis, simulation, and implementation of block transform OFDM

Xiaoliang Xue
University of Wollongong

Recommended Citation
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Analysis, Simulation, and Implementation of Block Transform OFDM

A thesis submitted in partial fulfilment of the requirements for the award of the degree

Master of Engineering by Research

from

UNIVERSITY OF WOLLONGONG

by

Xiaoliang Xue

School of Electrical, Computer and Telecommunications Engineering

October 2011
Statement of Originality

I, Xiaoliang Xue, declare that this thesis, submitted in partial fulfillment of the requirements for the award of Master of Engineering - Research, in the School of Electrical, Computer and Telecommunications Engineering, University of Wollongong, is wholly my own work unless otherwise referenced or acknowledged. The document has not been submitted for qualifications at any other academic institution.

Xiaoliang Xue
28 March, 2011
<table>
<thead>
<tr>
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<th>Description</th>
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<tr>
<td>1G</td>
<td>First-generation</td>
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<tr>
<td>2G</td>
<td>Second-generation</td>
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<td>3G</td>
<td>Third-generation</td>
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<td>4G</td>
<td>Fourth-generation</td>
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<tr>
<td>A/D</td>
<td>Analog-to-digital</td>
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<td>AMPS</td>
<td>Advanced mobile phone service</td>
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<td>ASIC</td>
<td>Application specific integrated circuit</td>
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<td>AWGN</td>
<td>Additive white Gaussian noise</td>
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<tr>
<td>BER</td>
<td>Bit error rate</td>
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<td>BPSK</td>
<td>Binary phase shift keying</td>
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<td>B/S</td>
<td>Block to serial</td>
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<td>BS-OFDM</td>
<td>Block spread OFDM</td>
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<td>BT-OFDM</td>
<td>Block transform OFDM</td>
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<tr>
<td>CDMA</td>
<td>Code division multiple access</td>
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<td>COFDM</td>
<td>Coded OFDM</td>
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<tr>
<td>CP</td>
<td>Cyclic padding</td>
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<tr>
<td>CSS</td>
<td>Chirp spread spectrum</td>
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<tr>
<td>DAB</td>
<td>Digital audio broadcasting</td>
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<td>DFT</td>
<td>Discrete Fourier transform</td>
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<td>DMB</td>
<td>Digital multimedia broadcasting</td>
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<td>DQPSK</td>
<td>Differential quadrature phase shift keying</td>
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<tr>
<td>DSP</td>
<td>Digital signal processing</td>
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<tr>
<td>DSSS</td>
<td>Direct-sequence spread spectrum</td>
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<td>DVB</td>
<td>Digital video broadcasting</td>
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<tr>
<td>DVB-C</td>
<td>DVB cable</td>
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<td>DVB-H</td>
<td>DVB handheld</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>DVB-S</td>
<td>DVB satellite television and satellite Internet</td>
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<td>DVB-T</td>
<td>DVB terrestrial</td>
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<tr>
<td>E-Commerce</td>
<td>Electronic commerce</td>
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<tr>
<td>EDGE</td>
<td>Enhanced data rates for global evolution</td>
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<tr>
<td>EU</td>
<td>European Union</td>
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<tr>
<td>FDM</td>
<td>Frequency-division multiplexing</td>
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<td>FFT</td>
<td>Fast Fourier transform</td>
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<td>FHSS</td>
<td>Frequency-hopping spread spectrum</td>
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<td>FLO</td>
<td>Forward Link Only</td>
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<td>FM</td>
<td>Frequency modulation</td>
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<td>FWA</td>
<td>Fixed wireless access</td>
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<td>GPRS</td>
<td>General packet radio service</td>
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<td>GSM</td>
<td>Global system for mobile communications</td>
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<td></td>
<td>Groupe speciale mobile (Original)</td>
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<td>HAP</td>
<td>High altitude platform</td>
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<td>HIPERLAN</td>
<td>High performance local area network</td>
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<tr>
<td>HSCSD</td>
<td>High-speed circuit-switched data</td>
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<td>ICI</td>
<td>Inter-carrier interference</td>
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<tr>
<td>IDFT</td>
<td>Inverse discrete Fourier transform</td>
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<td>IFFT</td>
<td>Inverse fast Fourier transform</td>
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<td>IMT</td>
<td>International mobile telecommunications</td>
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<tr>
<td>IOFDM</td>
<td>Interleaved OFDM</td>
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<td>ITU</td>
<td>International telecommunications union</td>
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<tr>
<td>IS</td>
<td>Interim standard</td>
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<td>ISDB</td>
<td>Integrated services digital broadcasting</td>
</tr>
<tr>
<td>ISI</td>
<td>Intersymbol interference</td>
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<tr>
<td>LP-OFDM</td>
<td>Linear precoded orthogonal frequency-division multiplexing</td>
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<tr>
<td>LSI</td>
<td>Large scale integrated</td>
</tr>
<tr>
<td>MC-DS-CDMA</td>
<td>Multicarrier direct sequence CDMA</td>
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<td>MAI</td>
<td>Multiuser access interference</td>
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<tr>
<td>MAN</td>
<td>Metropolitan area network</td>
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<td>MBS</td>
<td>Mobile broadband system</td>
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<td>MC-CDMA</td>
<td>Multicarrier code division multiple access</td>
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<tr>
<td>MCM</td>
<td>Multi-carrier modulation</td>
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<tr>
<td>Acronym</td>
<td>Description</td>
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<tr>
<td>MIMO</td>
<td>Multi-input and multi-output</td>
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<td>ML</td>
<td>Maximum likelihood</td>
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<td>MMSE</td>
<td>Minimum mean squared error</td>
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<tr>
<td>M-QAM</td>
<td>M-quadrature amplitude modulation</td>
</tr>
<tr>
<td>Next-G</td>
<td>Next-generation</td>
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<td>NLOS</td>
<td>Non line of sight</td>
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<td>NMT</td>
<td>Nordic mobile telephony</td>
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<td>OFDM</td>
<td>Orthogonal frequency division multiplexing</td>
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<tr>
<td>OFDMA</td>
<td>Orthogonal frequency division multiple access</td>
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<tr>
<td>OOB</td>
<td>Out of band</td>
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<tr>
<td>PA</td>
<td>Power amplifier</td>
</tr>
<tr>
<td>PAN</td>
<td>Personal area network</td>
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<tr>
<td>PAPR</td>
<td>Peak average power ratio</td>
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<td>PDA</td>
<td>Personal digital assistant</td>
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<td>PHY</td>
<td>Physical layer</td>
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<td>PN</td>
<td>Pseudo noise</td>
</tr>
<tr>
<td>P/S</td>
<td>Parallel to Serial</td>
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<tr>
<td>PTS</td>
<td>Partial transmit sequences</td>
</tr>
<tr>
<td>PUSC</td>
<td>Partial usage of subcarrier</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of service</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature phase shift keying</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal software radio peripheral</td>
</tr>
<tr>
<td>S/B</td>
<td>Serial to block</td>
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<tr>
<td>SC</td>
<td>Single carrier</td>
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<tr>
<td>SDR</td>
<td>Software-defined radio</td>
</tr>
<tr>
<td>SLM</td>
<td>Selected mapping</td>
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<tr>
<td>SNR</td>
<td>Signal-to-noise ratio</td>
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<td>S/P</td>
<td>Serial to parallel</td>
</tr>
<tr>
<td>SS</td>
<td>Spread spectrum</td>
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<tr>
<td>STBC</td>
<td>Space-time block coding</td>
</tr>
<tr>
<td>STTC</td>
<td>Space-time trellis coding</td>
</tr>
<tr>
<td>TACS</td>
<td>Total access communications system</td>
</tr>
<tr>
<td>TDD</td>
<td>Time-division duplex</td>
</tr>
<tr>
<td>TDMA</td>
<td>Time division multiple access</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>TD-SCDMA</td>
<td>Time division synchronous CDMA</td>
</tr>
<tr>
<td>THSS</td>
<td>Time-hopping spread spectrum</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal mobile telecommunications system</td>
</tr>
<tr>
<td>USRP</td>
<td>Universal software radio peripheral</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband code division multiple access</td>
</tr>
<tr>
<td>WiMAX</td>
<td>Worldwide interoperability for microwave access</td>
</tr>
<tr>
<td>WLAN</td>
<td>Wireless local area network</td>
</tr>
<tr>
<td>WLL</td>
<td>Wireless local loop</td>
</tr>
<tr>
<td>WMAN</td>
<td>Wireless metropolitan area networking</td>
</tr>
<tr>
<td>ZF</td>
<td>Zero forcing</td>
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<tr>
<td>ZP</td>
<td>Zero padding</td>
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Abstract

The fourth generation (4G) mobile communications technology and beyond are widely in development nowadays. Among all the technologies, Orthogonal Frequency Division Multiplexing (OFDM) is the most potential candidate of the 4G system, due to the advantages it can offer in wideband wireless communications. However, it also has some disadvantages. Researchers are trying to find methods to make this scheme perform better. In other words, they are trying to overcome the disadvantages, while keeping the advantages.

In my project, a new scheme based on OFDM called Block Transform OFDM (BT-OFDM) is introduced. In this scheme, data symbols are grouped into blocks. Thus, a reduced size Inverse Fast Fourier Transform (IFFT) will be used for block transformation compared to the conventional OFDM. This scheme takes the advantages of the single-carrier system to solve some well-known problems such as high Peak-to-Average Power Ratio (PAPR), Inter-Channel Interference (ICI) caused by the frequency offset. At the same time, it still has the advantages from the OFDM compared to the single carrier systems. Hence, it is more power and bandwidth efficient and achieves higher degree frequency diversity than the conventional OFDM. Also, the BT-OFDM is robust against carrier frequency offset and timing errors, and achieves significant performance improvement over frequency-selective fading channels.

The system architecture and properties are introduced and analyzed in detail. Monte Carlo simulations on system performances such as transmit signal PAPR, bit error rate (BER) under different parameters are presented to verify the improvement of the new
system compared with the conventional OFDM system. The first step of Universal Software Radio Peripheral (USRP) hardware implementations will be performed as well.
Acknowledgements

I would like to thank my principal supervisor, Dr. Raad Raad for his guidance and helpful advice in this project and in writing the thesis.

I would also like to thank my co-supervisor, Ass/Pro. Kwan-Wu Chin, for his counsel, assistance and time devoted for my research.

A big gratitude goes out to Pro. Xiaojing Huang. This work presented in this thesis would not have been possible without his help and support.

I would like to gratefully acknowledge the staff, both academic and administrative, of the School of Electrical, Computer and Telecommunications Engineering of University of Wollongong, and the fellow Staff and students, especially Dr. Le Chung Tran.

On a personal note, undertaking a project would have been unthinkable without the support of my parents.
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7.1 Contribution

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Chapter 1

Introduction

Since the end of last century, wireless mobile communications technology has been advancing in a booming speed. Now, the technology has evolved into its third generation (3G). However, new applications such as better performance multimedia, Internet and broadband services are highly demanded in the new mobile communication systems. All of these services need higher speed and larger capacity data transmission. Thus, the fourth generation (4G) and beyond are in development.

The main purpose of 4G is to provide the users broader bandwidth, higher data rate, wider coverage, more secure communications, but with lower cost, compared to previous generations. Briefly speaking, it is expected to provide the users much better services on an ‘Anytime, Anywhere’ basis.

Because of the huge impact of the future information and communication technology on the international economy, there is plenty of related research on 4G. A number of advanced techniques are presented as potential candidates for the coming 4G wireless
communication systems. Among all the techniques, orthogonal frequency division multiplexing (OFDM) and its advanced versions, and combined with multi-input and multi-output (MIMO) antennas are considered best to meet the requirements of the 4G system, due to the advantages it can offer in wideband wireless communications. However, as other schemes, it has some disadvantages. Researchers try to find methods to balance the properties to make the schemes get better performance. In other words, they try to overcome the disadvantages, while keeping the advantages.

1.1 Research Objectives

In this thesis, a new block transform orthogonal frequency division multiplexing (BT-OFDM) system is proposed. The purpose of this system is to balance the properties between the conventional OFDM and single carriers system. In other words, from this system, the advantages of the OFDM still can be enjoyed and meanwhile, some of the disadvantages of the conventional OFDM can be conquered once the block size is properly chosen. The specific objectives are as follows:

1. Develop the BT-OFDM scheme and design system architectures for both transmitter and receiver;

2. Analyze the frequency domain representation of the BT-OFDM signal;

3. Analyze the system properties such as carrier frequency offset and timing error sensitivity;

4. Analyze the Equalizer architecture and the complexity of the BT-OFDM system;
5. Perform a simulation of a complete BT-OFDM system using Monte Carlo simulation;

6. Demonstrate a transmitter hardware performance on universal software radio peripheral (USRP) device.

1.2 Overview of This Thesis

This thesis is organised as follows:

Chapter 1 briefly introduces the research project and its objectives. The research contributions and publication are also included in this chapter.

Chapter 2 reviews the evolution of the wireless communications systems. Specific attention will be paid on the fourth generation (4G) or the next-generation (Next-G) systems.

Chapter 3 compares two extreme schemes of the wireless communications systems – the single carriers system and the conventional OFDM system. In this chapter, OFDM is introduced in more detail. Recent research in this area to improve the system performance is also involved.

Chapter 4 presents the new BT-OFDM system. The system architecture is proposed. Also, the frequency domain representation is analyzed. From this, a very good property of the BT-OFDM is revealed that the BT-OFDM system implies a precoding or block spreading of the transmitted data symbols without actually processing the precoding. Also, this chapter discusses system equalizer architecture in detail. Finally,
the system complexity and peak average power ratio (PAPR) are discussed in this chapter as well.

Chapter 5 represents some of the system performances, which include signal-to noise ratio (SNR) at decision, SNR degradation due to carrier frequency offset, and bit error rate (BER) deterioration.

Chapter 6 performs a whole system Monte Carlo simulation, and it also performs a hardware simulation for the transmitter end in universal software radio peripheral (USRP) devices.

Chapter 7 summarises the research project and proposes areas of future work.

1.3 Publications

X. Xue, and X. Huang, 'Block Transform OFDM: A Robust Power and Bandwidth Efficient System with Improved Frequency Diversity Performance'.

This is a paper in which we propose a BT-OFDM system which improves some properties of the conventional OFDM such as better power and bandwidth efficiency and better frequency diversity performance. In BT-OFDM system, block IFFT and block FFT are applied instead of IFFT and FFT in conventional OFDM. The signal and system model is presented, the properties are analyzed, and simulations are carried out to confirm the expected performance improvement. The paper has been accepted by ISICT2011 by the date when this thesis revision has been finished.
1.4 Contributions

The contributions of this thesis are listed as follows:

- A novel scheme BT-OFDM which sits in-between the conventional OFDM and single carrier system is proposed. Comparisons among the BT-OFDM, conventional OFDM and single carrier system are performed.

- System architecture of the new BT-OFDM system is designed.

- System performances of the BT-OFDM system are investigated. Carrier frequency offset and timing error sensitivity, equalization architecture, and system complexity are mainly considered.

- A Monte Carlo simulation is performed to test the BT-OFDM system. Also, a hardware simulation of the transmitter is performed as well.
Chapter 2

Overview of Next-G Systems

2.1 Introduction

The Fourth generation (4G) of cellular wireless standard is the next generation of the wireless communications network standard and also is a successor to third generation (3G) and second generation (2G) standards. It is expected to replace the current cellular networks in the near future. Currently, the 3G system is still being deployed in the world. However, in the modern telecommunications industry, communications are not limited in voice or even video, new applications are highly demanded by users; and better multimedia, Internet and broadband services need to be supported on the new mobile communication systems, all which need higher speed and larger capacity for data transmission. Thus, there has been much research in 4G and 4G systems have started to be deployed since around 2010 [1].
In this chapter, the history of mobile telephony will be briefly introduced, and this will include the evolutionary path of cellular mobile communication systems from the very first generation (1G) to 4G of the commercial mobile communication system. Emphasis will be paid to the 4G overview. The characteristics and the main technologies applied in 4G and 4G standardization trends are discussed as well.

2.2 Evolution of the Mobile Communication Systems

Mobile telephony can dates back to the 1920s, when radiotelephony was used in several police departments in the United States. In its infancy, this system was operating at a frequency of 2MHz, which is just above the present A.M. radio broadcast band. However, this system only remained in experimental level because of many different reasons, such as technology, cautiousness, and some regulations.

In the 1930s, with the development of frequency modulation (FM), further progress was made in mobile telephony, which was firstly used for military purpose during World War II, and later was brought into public use in some large cities in the 1940s [2].

2.2.1 History of Cellular Mobile Systems

Mobile communications as the cellular systems we know today actually started from the late 1970s. In May 1978, The Bahrain Telephone Company (Batelco) began to operate the first commercial cellular telephone system in the world. The
simple system only had two cell schemes with 250 subscribers, and operated on 20 channels in the 400MHz band. In July 1978, another system using Advanced Mobile Phone Service (AMPS) was deployed near two American cities – one around AT&T Labs in Newark, New Jersey, and another near Chicago, Illinois. The Chicago system was covered by ten cells covering 21,000 square miles (about 54,390 square kilometres). After six months, a trial market was deployed in Chicago using the newly allocated 800 MHz band [3].

However, for numerous reasons, including the breakup of AT&T, after a few years in 1983, in Chicago, a real commercial system in the United States was launched. Meanwhile, other countries were making progress in cellular communications as well. A commercial AMPS system was launched in Japan in 1979. The Europeans developed their own technology known as Nordic Mobile Telephony (NMT) and launched their first system in 1981 mainly in Scandinavian countries. The NMT was firstly operating in the 450 MHz band and later in the 900 MHz band named NMT900. Also, the British introduced the Total Access Communications System (TACS) - a modified version of AMPS, which operated in the 900-MHz band. All those technologies are considered as First Generation (1G) systems [2].

The 1G system was built on analog techniques and only supported speech transmissions. It established the basic structure of mobile communications, e.g. cellular architecture adopting: multiplexing frequency bands, roaming across domain, non-interrupted communication in mobile circumstances, and so on [4]. Though the 1G systems achieved far greater success than anyone had expected, they had one weakness – limited capacity. This weakness became more and more intolerable along with more subscribers. When the number of the subscribers reached millions with the subscribers tending to be densely clustered in metropolitan areas, cracks started to appear [2]. Consequently, an advanced mobile system was needed to satisfy the market demand.
The 2G system was based on digital signal processing techniques instead of analog signal processing techniques that 1G systems used. Thus, there was no backward compatibility with the old generation. Like 1G systems, various technologies had been developed in different countries and regions. Among all of those technologies, the most successful ones included the Global System for Mobile Communications (GSM) (The acronym GSM originally meant Groupe Speciale Mobile, but now its meaning has morphed to Global System for Mobile Communications), Interim Standard (IS)-54B Time Division Multiple Access (TDMA), IS-136 TDMA, IS-95 Code Division Multiple Access (CDMA). The use of digital technology brought a number of advantages compared with 1G, including increased capacity, greater security against fraud, and more advanced services. However, 2G was still not well-suited to data communications and the issue became a serious drawback especially when the Internet, Electronic Commerce (E-Commerce), and multimedia communications had fast development [5].

When talking about the history of cellular mobile systems, there is a 2.5 generation (2.5G), which is sometimes called the evolution generation, between 2G and 3G. So, what is 2.5G? Generally speaking, 2.5G is the next-generation (3G at that time) transitional technology. The purpose of the 2.5G is to extend the 2G with data services and packet switching methods like 3G can offer but still on 2G networks. Thus, 2.5G brought the Internet into mobile communications under the same networks with 2G without investing too much money before the telecommunications services providers started to deploy the 3G networks [2]. The main technologies used in 2.5G are General Packet Radio Service (GPRS), High-Speed Circuit-Switched Data (HSCSD), Enhanced Data Rates for Global Evolution (EDGE) and CDMA2000 1xRTT [4].

The 3G, therefore, was presented to provide users with high-speed data access (2 Mb/s for fixed users, 384 kb/s for low mobility users such as pedestrians and 144 kb/s for high mobility users like vehicular traffic) [6]. Due to its high transfer performance improvement and data rate increase, 3G was developed rapidly since 1990s. In
Europe, the 3G mobile system was known as Universal Mobile Telecommunications System (UMTS) when it first launched through several European Union (EU) funded research projects [7]. The UMTS is a Wideband Code Division Multiple Access (WCDMA) standard. UMTS is one of the 3G wireless mobile standards that makes up the International Mobile Telecommunications 2000 (IMT-2000). IMT2000 is a radio and network access specification defined by the International Telecommunications Union (ITU). In IMT2000, it also defined some other 3G standards. Besides WCDMA, other major representative standards include Time Division Synchronous CDMA (TD-SCDMA), and CDMA2000 [8]. Compared with previous generations of cellular systems, 3G offers better quality voice, higher capacity, access to the Internet, and high-speed packet data and multimedia applications. However, there are also several limitations. The major one is that due to excessive interference between services, there is difficulty in continuously providing a high data rate transmission to meet some multimedia services requirements. Therefore, more advanced systems are demanded to offer more reliable transmission on broadband wireless communications [6]. Table 2.1 summarizes the development of cellular mobile systems from 1G to 3G with the properties of each generation including starting time, driven technique, representative standard, radio frequency, bandwidth, multiplexing technique, cellular coverage, service type and core network.

Besides more reliable transmission with high peak data rates, which is never enough, what is next? The answer is “Convergence” [4]. Data (new Internet-related services) and circuit-switched services (traditional voice communications) will be better merged in the same network. Usually, data transmission and voice service require a different quality of service (QoS). For example, data transmission needs reliable transmission but does not care about the order of the arrival packets; with some mechanism, packets can be reassembled into the correct order in the receiver. By contrast, the voice service may not care about a little data loss but is very sensitive of the arrival sequence of the data. Meanwhile, the fixed and mobile phones, personal digital assistants (PDAs), and laptops enable multiple functions to be performed on a single platform as well. There is no formal definition for what 4G is. Generally
speaking, 4G is expected to be a fully IP-based integrated system which carries the transmission with peak data rates from 100Mb/s for high mobility applications (mobile traffic) to 1Gb/s for low mobility applications (pedestrians), high spectrum efficiency up to 10b/s/Hz, and ubiquitous services that can accommodate various radio accesses [9]. In other words, there are certain objectives which 4G systems aim to achieve. The objectives include the integrated properties we talked about above, and also high quality and security.

<table>
<thead>
<tr>
<th>Property</th>
<th>1G</th>
<th>2G</th>
<th>2.5G</th>
<th>3G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driven Technology</td>
<td>Analog signal processing</td>
<td>Digital signal processing</td>
<td>Packet switching</td>
<td>Intelligent signal processing</td>
</tr>
<tr>
<td>Representative Standard</td>
<td>AMPS, TACS, NMT</td>
<td>GSM, TDMA, CDMA</td>
<td>GPRS, HSCSD, EDGE, CDMA2000 1xRTT</td>
<td>IMT-2000(UMTS, WCDMA, CDMA2000, TD-SCDMA)</td>
</tr>
<tr>
<td>Radio Frequency(Hz)</td>
<td>400M-900M</td>
<td>800M-900M, 1800-1900M</td>
<td>2G</td>
<td></td>
</tr>
<tr>
<td>Bandwidth(bps)</td>
<td>2.4K-30K</td>
<td>9.6K-14.4K</td>
<td>171K-384K</td>
<td>2M-5M</td>
</tr>
<tr>
<td>Multiplexing</td>
<td>FDMA</td>
<td>TDMA, CDMA</td>
<td>CDMA</td>
<td></td>
</tr>
<tr>
<td>Cellular Coverage</td>
<td>Large Area</td>
<td>Medium area</td>
<td>Small area</td>
<td></td>
</tr>
<tr>
<td>Service Type</td>
<td>Voice Mono-service Person-to-person</td>
<td>Voice, SMS Mono-media Person-to-person</td>
<td>Data service</td>
<td>Voice, Data Some Multimedia Person-to-machine</td>
</tr>
<tr>
<td>Core Network</td>
<td>PSTN</td>
<td>PSTN</td>
<td>PSTN, Packet Network</td>
<td>Packet Network</td>
</tr>
</tbody>
</table>

Table 2.1 Mobile Communications History and Status [2][4]

DoCoMo [10] used the word MAGIC to introduce 4G. MAGIC stands for Mobile multimedia; Anytime, anywhere, anyone; Global mobility support; Integrated wireless solution; and Customized personal service. This is a good definition for what 4G can do for us, but is only focused on public civil systems. Because of the integrated property, the term 4G will not only be used on cellular telephone systems
like its predecessors, but also includes several types of other broadband wireless access communication systems from satellite broadband to High Altitude Platforms (HAP), to cellular 2G and 3G systems, to Mobile Broadband Systems (MBS), to Wireless Local Loop (WLL) and Fixed Wireless Access (FWA), to Wireless Local Area Network (W-LAN), Personal Area Networks (PAN) and Body-LANs. Pereira [11] also pointed out that from the service point of view, 4G will implement adaptation to multiple standards across multiple operators and service provider domains, with user-controlled Quality of Service (QoS) and ensuring data privacy and information integrity. Table 2.2 summarizes 4G perspectives with the same properties as a continuator of Table 2.1.

<table>
<thead>
<tr>
<th>Property</th>
<th>4G</th>
</tr>
</thead>
<tbody>
<tr>
<td>Starting Time</td>
<td>2010-2012</td>
</tr>
<tr>
<td>Driven Technique</td>
<td>Intelligent software auto configuration</td>
</tr>
<tr>
<td>Representative Standard</td>
<td>OFDM, UWB</td>
</tr>
<tr>
<td>Radio Frequency(Hz)</td>
<td>3G-5G</td>
</tr>
<tr>
<td>Bandwidth(bps)</td>
<td>200M</td>
</tr>
<tr>
<td>Multiplexing</td>
<td>FDMA, TDMA, CDMA</td>
</tr>
<tr>
<td>Cellular Coverage</td>
<td>Mini area</td>
</tr>
<tr>
<td>Service Type</td>
<td>Multimedia</td>
</tr>
<tr>
<td></td>
<td>Machine-to-machine</td>
</tr>
<tr>
<td>Core Network</td>
<td>All-IP networks</td>
</tr>
</tbody>
</table>

Table 2.2 4G Visions Summary [2][4]

### 2.3 4G Overview

The first section briefly introduced the evolution trend of cellular wireless communication systems. We realize 4G as the representative of the next generation wireless communication system expected to offer high data rate applications. A number of different perspectives and standardizations of 4G systems have been introduced as well. This section will present more about 4G systems. The topics will
include some enhancement techniques for 4G systems, and some standard applications, e.g. WiMAX and Mobile DTV as examples.

2.3.1 Multicarrier Systems and OFDM

As we discussed in the previous section, 4G systems are designed to support high data rate transmissions, thus large bandwidths are required. However, as the bandwidth is increased, intersymbol interference (ISI) becomes a big issue and complex equalizers are needed to compensate the channel effects [6]. This is a common drawback caused by large bandwidth system, because complex equalization reduces the power efficiency this in turn, reduces battery life, and the channel cannot be perfectly equalized in most of cases [6].

In order to avoid the complexity of equalization, most 4G systems are based on multicarrier modulation such as orthogonal frequency division multiplexing (OFDM) or multicarrier code division multiple access (MC-CDMA) [6]. In these multicarrier systems, the total bandwidth is divided into several low bandwidth groups, each of which has a subcarrier. The overall data stream is then split into each section and then transmitted in parallel. The advantage of this approach is that a large bandwidth is divided into a number of narrowband subcarriers. Thus, each subcarrier can be considered as nearly flat fading, where less ISI is experienced and therefore low complexity equalization can be utilized [6]. A narrowband system has longer symbol duration by transmitting each symbol relatively slowly [12].

The OFDM technique is one specific case of many multi-channel transmission methods in which the channel is subdivided into several subbands and each subband modulates the corresponding data symbol by employing the FFT and IFFT [13, 14]. It has been researched for decades and has been used in many current and future systems since it is able to boost high speed transmission over wireless channels.
Presently, it has already been widely used in today’s digital communications systems, such as Digital Audio Broadcasting (DAB) and Digital Video Broadcasting - Terrestrial (DVB-T) in Europe [15, 16], and also WLAN standards including 802.11a [17], and more recently 802.11g [18] and High Performance Local Area Network type 2 (HIPERLAN-II) [19]. As our proposed block transform (BT) OFDM system is based on the conventional OFDM system, the multicarrier system and OFDM are only introduced briefly here. More details about OFDM will be discussed in next chapter.

### 2.3.2 OFDMA

Orthogonal frequency-division multiple access (OFDMA) is a multi-user version of the popular OFDM modulation scheme. A typical OFDMA system architecture is showed in Fig. 2.1. From the figure, we can see that unlike an OFDM system, K users are involved in the OFDMA system to share N subcarriers. The difference arises in the forming and deforming of FFT block. The rest is the same as an OFDM system as seen in Fig. 2.1 [20]. Each user allocates a non-overlapping set of sub-carriers, depending on their QoS requirement and system loading characteristics. After the subcarrier allocation and an adaptive modulation for each subcarrier, the IDFT is applied like conventional OFDM in transmitter. A guard insertion and a parallel to serial (P/S) process are applied before sending the signal into the transmission channel. In the receiver, the received signal is firstly transformed from serial to parallel (S/P), and then the guard is removed. DFT is then processed to counteract IDFT in the transmitter. With a subcarrier extraction for each user and an adaptive demodulation, the original signal can be recovered. There are two strategies for establishing subcarriers groups, which are shown in Fig. 2.2. In the first strategy, adjacent subcarriers are grouped in the same frequency range in each subchannel, whereas in the second, the subchannels which are chosen to be grouped spread over the total bandwidth. It is obvious that the second strategy is better, especially in
frequency selective fading channels. This is because if there is a deep narrow-band fading, only a fraction of subcarriers in each subchannel can be affected [21].

![Diagram of OFDMA system](image)

Fig. 2.1 Orthogonal frequency division multiple access (OFDMA) system [20].

![Diagram of subcarrier allocation](image)

Fig. 2.2 Two possible scenarios for establishing subcarrier groups in an OFDMA system [21].
OFDMA has been already deployed in current telecommunications systems. Both UMTS [7], the European standard for the 3G cellular mobile communications, and IEEE 802.16 [22], a broadband wireless access standard for metropolitan area networks (MAN) introduced OFMDA as modulation scheme [21]. Table 2.3 shows the basic parameters used in these two standards.

<table>
<thead>
<tr>
<th></th>
<th>UMTS</th>
<th>IEEE 802.16</th>
</tr>
</thead>
<tbody>
<tr>
<td>System bandwidth</td>
<td>100kHz-1.6MHz(Flex.)</td>
<td>6Mhz</td>
</tr>
<tr>
<td>Number of subcarriers</td>
<td>240/100kHz</td>
<td>2048</td>
</tr>
<tr>
<td>Subcarrier spacing</td>
<td>4.16kHz</td>
<td>3.35kHz</td>
</tr>
<tr>
<td>N Subcarriers/Band-unit</td>
<td>24SB/Bandslot</td>
<td>53SB/Subchannel</td>
</tr>
<tr>
<td>Modulation time</td>
<td>240μs</td>
<td>298μs</td>
</tr>
<tr>
<td>Guard time</td>
<td>38 μs (pre-) and 8 μs (post-guard)</td>
<td>38 μs</td>
</tr>
<tr>
<td>Symbol time</td>
<td>288 μs</td>
<td>340 μs</td>
</tr>
<tr>
<td>Resource allocation unit</td>
<td>1 bandslot, 1 timeslot (1 symbol)</td>
<td>1 Subchannel, 1 timeslot</td>
</tr>
<tr>
<td>Modulation</td>
<td>QPSK, 8-PSK (differential &amp; coherent)</td>
<td>QPSK, 16-QAM, 64-QAM</td>
</tr>
<tr>
<td>Channel Coding</td>
<td>Convolutional (1/3, 2/3)</td>
<td>Turbo (1/2)</td>
</tr>
<tr>
<td>Max. Data throughput</td>
<td>2Mbps</td>
<td>54Mbps</td>
</tr>
</tbody>
</table>

Table 2.3 Parameters of UMTS and IEEE 802.16 standards [21].

2.3.3 Multicarrier CDMA

Code division multiple access (CDMA) is a widely used multiple access technique that has been deployed on many recent wireless communications systems like IS-95, UMTS or CDMA2000 [7]. CDMA uses spread spectrum (SS) technique. A SS [43]
system spreads the signal generated in a particular bandwidth into a signal with a wider bandwidth in the frequency domain. There are few SS techniques have been commonly used, which are frequency-hopping spread spectrum (FHSS), direct-sequence spread spectrum (DSSS), time-hopping spread spectrum (THSS), chirp spread spectrum (CSS), and combinations of these techniques. In CDMA systems, different users are identified by allocating with unique pseudo noise (PN) codes and therefore spread at the receiver by means of their characteristic individual codes. At the receiver, the incoming signal is multiplied by a synchronized version of the identical PN sequence. In this way, the signal is despread, and the original message signal can be restored [6]. A simple spread spectrum communications system with this procedure is shown in Fig. 2.3.

![Fig. 2.3 Spread spectrum modulator and demodulator [6].](image)

Multicarrier code division multiple access (MC-CDMA) is a combination of OFDM and CDMA. The OFDM brought in here can provide higher capacity multiple accesses than traditional OFDMA systems. This can be seen in Fig. 2.4. In an MC-CDMA modulator, the incoming data stream is first multiplied by a user-specific PN sequence as in a CDMA system. The length of this spreading code is identical to the number of subcarriers [6]. The resulting sequence then passes a serial to parallel (S/P) converter, an IFFT modulator, and a parallel to serial (P/S) converter. A cyclic prefix is added before the signal has been sent to the channel. These procedures are exactly the same as OFDM modulation.
In an MC-CDMA system, frequency diversity can be obtained because each bit is transmitted over several independent subcarriers. Thus, even if some subcarriers experience destructive frequency selective fading, the data can still be recovered at the receiver by means of the diversity combining feature. This improves the bit error rate (BER) performance over OFDM, and as the number of subcarriers is increased, this improvement becomes more significant. However, because each chip of the PN sequence experiences independent fading, the MC-CDMA system may experience high levels of multiuser access interference (MAI) when the channel is heavily loaded which tends to destroy the orthogonality between spreading sequences. Therefore, MC-CDMA systems perform best under low channel loads [6].

There is another alternative version of MC-CDMA. It is called multicarrier direct sequence CDMA (MC-DS-CDMA), which transmits direct sequence CDMA signals in parallel over orthogonal subcarriers [6]. Fig. 2.5 shows a typical MC-DS-CDMA modulator block diagram. Compare to the MC-CDMA, we can see that the data stream is first converted into parallel. Then each bit is multiplied by a user-specific spreading sequence with a higher chip rate. Here is where we get DS-CDMA signals. And the rest of the diagrams are the same as MC-CDMA, i.e. the IFFT is used to modulate these signals to the intended subcarriers.

As we can see, all of the PN chips are transmitted on the same subcarrier, which experiences correlated fading caused by the slow channel variance. Thus, the MC-DS-CDMA can provide multiple accesses without the excessive MAI that can occur
in MC-CDMA systems. However there is no gain from frequency diversity in this approach. The data may not be recovered at the receiver if a subcarrier experiences a destructive fading [6].

![Diagram](image)

Fig. 2.5 MC-DS-CDMA modulator [6]

### 2.3.4 Standard Applications

In this subsection, worldwide interoperability for microwave access (WiMAX) and mobile DTV are briefly introduced as examples of major standardization trends for the next generation wireless communications applications. Mainly some standards related to OFDM will be highlighted as our proposed BT-OFDM system is based on traditional OFDM system.

**a. WiMAX [23]**

Worldwide Interoperability for Microwave Access (WiMAX) is a telecommunications protocol that provides fixed and fully mobile internet access. It is
implemented as wireless metropolitan area networking (WMAN) standards developed by IEEE 802.16 group and adopted by both IEEE and the ETSI HIPERMAN group.

The WiMAX physical layer (PHY) is based on OFDM, which offers good resistance to multipath, and allows WiMAX to operate in non line of sight (NLOS) conditions. WiMAX is capable of supporting very high peak data rates. The peak PHY data rate can be as high as 74Mbps combined uplink/downlink PHY throughput when operating on 20MHz wide spectrum. But more typically, the peak PHY data rate is about 25Mbps and 6.7Mbps for the downlink and the uplink respectively with a 3:1 downlink-to-uplink ratio, when operating a 10MHz spectrum using TDD scheme. With multiple antennas and spatial multiplexing, even higher peak rates may be achieved under very good signal conditions. Also, supported by the OFDMA mode which has been introduce in previous section, WiMAX physical layer architecture offers scalability that allows for the data rate to scale easily by choosing a different FFT size such as 128-, 512-, or 1024-bit FFTs based on different available channel bandwidth 1.25MHz, 5MHz, or 10MHz, respectively. The scaling can be done dynamically to support user roaming across different networks with different bandwidth allocations. Table 2.4 shows the OFDM Parameters Used in WiMAX.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Fixed WiMAX OFDM-PHY</th>
<th>Mobile WiMAX Scalable OFDMA-PHY</th>
</tr>
</thead>
<tbody>
<tr>
<td>FFT size</td>
<td>256</td>
<td>128</td>
</tr>
<tr>
<td>Number of used data subcarriers (downlink partial usage of subcarrier (PUSC))</td>
<td>192</td>
<td>72</td>
</tr>
<tr>
<td>Number of pilot subcarriers</td>
<td>8</td>
<td>12</td>
</tr>
<tr>
<td>Number of null/guardband subcarriers</td>
<td>56</td>
<td>44</td>
</tr>
<tr>
<td>Cyclic prefix or guard time (Tg/Tb)</td>
<td>1/32, 1/16, 1/8, ¼</td>
<td></td>
</tr>
<tr>
<td>Oversampling rate (Fs/BW)</td>
<td>Depends on bandwidth: 7/6 for 256 OFDM, 8/7 for multiples of 1.75MHz, and 28/25 for multiples of 1.25MHz, 1.5MHz, 2MHz, or 2.75MHz.</td>
<td></td>
</tr>
<tr>
<td>Channel bandwidth (MHz)</td>
<td>3.5</td>
<td>1.25</td>
</tr>
<tr>
<td>Subcarrier frequency spacing (KHz)</td>
<td>15.625</td>
<td>10.94</td>
</tr>
<tr>
<td>Useful symbol time (μs)</td>
<td>64</td>
<td>91.4</td>
</tr>
<tr>
<td>Guard time assuming 12.5% (μs)</td>
<td>8</td>
<td>11.4</td>
</tr>
<tr>
<td>OFDM symbol duration (μs)</td>
<td>72</td>
<td>102.9</td>
</tr>
<tr>
<td>Number of OFDM symbols in 5 ms frame</td>
<td>69</td>
<td>48.0</td>
</tr>
</tbody>
</table>

Table 2.4 OFDM Parameters Used in WiMAX. Boldfaced values correspond to those of the initial mobile WiMAX system profiles [23].

b. Mobile Digital Television

There are several standards competing for the mobile digital television (mobile DTV), such as digital video broadcasting (DVB), integrated services digital broadcasting (ISDB), digital multimedia broadcasting (DMB), and MediaFlo [24].
DVB is a suite of internationally accepted open standards for digital television, and it is maintained by the DVB Project. There are four core standards of DVB: DVB-S (Satellite television and satellite Internet), DVB-C (Cable), DVB-T (terrestrial) and DVB-H (Handheld) [25-27]. DVB uses multiple carrier modulation system. Of all these DVB solutions for the transmission of content to the home, DVB-T has received by far the most attention. Its excellent performance has led to its adoption in large parts of the world, including Australia [28]. DVB-T uses coded orthogonal frequency division multiplexing (COFDM). Fig. 2.6 shows a block diagram of a DVB-T encoder [25, 28]. The shaded blocks are also used in DVB-C and DVB-S.

![Fig. 2.6 Block diagram of a DVB-T encoder](image)

ISDB is a Japanese standard which provides integrated and transmission of a variety of multi-program TV and other data services [29]. Like DVB, ISDB also includes a few core standards, which are ISDB-S (satellite television), ISDB-T (terrestrial) and ISDB-C (cable) [30]. ISDB-T also employs OFDM as the modulation scheme [31].

DMB is a digital radio transmission technology developed in South Korea. It can operate via satellite (S-DMB) or terrestrial (T-DMB) transmission. The T-DMB
system has adopted transmission mode 1 from Eureka 147 digital audio broadcasting (DAB) for a transmission standard where COFDM and differential quadrature phase shift keying (DQPSK) are adopted [32]. It allows leveraging on its widely installed and established network infrastructure.

MediaFLO is a unique mobile broadband approach using multiple frequency bands at the same time. It is also a CDMA/OFDM-based air interface designed specifically for high-resolution video multicasting [2]. FLO stands for “Forward Link Only” [33]. Traditionally, due to power consumption and some other issues such as multipath, analog TV and DVB-T were difficult to implement on mobile devices. MediaFLO was designed as competitor to T-DMB, DVB-H and some other mobile DTV standards. It allows mobile operators to provide live streaming video channels, in addition to supporting 50-100 national local contents channels. The FLO technology is also cost effective for mobile multimedia content distribution, because it only requires two or three broadcast towers per metropolitan area, which is 30-50 times fewer than that required by cellular network systems [24].

2.4 Summary

We started this chapter with a review of cellular mobile system history. From the evolution of the mobile systems, we can see that 1G built the basic cellular structure and set up the fundamental concepts of wireless communications systems. Between 1G and 2G there was a great leap as 2G uses digital technology instead of 1G’s analog technology, and this also gained a tremendous success in market as well? 3G was developed to provide higher data rate and broader bandwidth for different multimedia services requirements. And between 2G and 3G, there was an evolution generation e.g. 2.5G, mainly represented by GPRS, as a transitional technology to offer 3G-like data service and packet switching methods by using 2G networks. 2.5G
provided the telecommunications services providers a transitional cost saving method before they deployed the 3G networks.

Then we introduced why we need 4G and what is 4G. A number of technical perspectives are presented according to different visions. Due to the limitations of equalization of single carrier systems, 4G systems are based on multicarrier modulation schemes. As this is the core of the proposed BT-OFDM system of this thesis, more details about multicarrier systems and OFDM will be introduced in next chapter. However, some variations of OFDM are introduced in this chapter, which are OFDMA and MC-CDMA. OFDMA is a multiuser version of OFDM, where each user is assigned with a fraction of the available number of subcarriers. And MC-CDMA is a combination of OFDM and CDMA to achieve diversity improvement over OFDMA.

Last but not least, we introduced two standard trends of 4G applications. WiMAX refers to interoperable implementations of the IEEE 802.16 wireless networks standard. Mobile DTV is digital TV usually watched on a small handheld device. It includes some competing standards, such as DVB, ISDB, DMB and MediaFLO. Many of the standards in both WiMAX and Mobile DTV employ OFDM of variation versions of OFDM as modulation scheme. In next chapter, OFDM will be introduced in detail. The major drawbacks of OFDM, which are high peak-to-average power ratio, vulnerability to synchronization errors, lack of frequency diversity, and the researches on improved those issues will also be introduced.
Chapter 3

Orthogonal Frequency-Division Multiplexing (OFDM)

3.1 Introduction

As mentioned in Chapter 2, orthogonal frequency-division multiplexing (OFDM) has already been implemented in some of today’s Third Generation (3G) technologies. Also, OFDM and its variations are considered as excellent candidates for the Fourth Generation (4G) systems.

In literature, there are some comparisons between the conventional OFDM and the single-carrier system on aspects such as Peak-to-Average Power Ratio (PAPR), equalization complexity, carrier frequency offset sensitivity, and frequency diversity performance [34-37]. It is interesting to know that the conventional OFDM system and the single-carrier system are complementary and often represent the two extremes when evaluating the system performances. That is to say, when the conventional
OFDM system demonstrates advantages on some aspects, the single-carrier system will demonstrate disadvantages on these aspects, and vice versa.

In this Chapter the OFDM will be introduced. Also, the properties of OFDM, both the advantage and disadvantage will be discussed. Several techniques for improving OFDM system as the solutions for those drawbacks of the OFDM system will be included in this chapter as well.

3.2 OFDM Techniques

OFDM is one of the special cases of multi-carrier modulation (MCM) which originally dates back to 1950s and early 1960s in military high frequency radio links. However, OFDM was firstly introduced in mid 1960s by R. W. Chang [38], but it hadn’t been developed much during that time, because of the high complexity of using analogue filters to implement this system. In the year of 1971, S. B. Weinstein and P. M. Ebert addressed a method in which they used Discrete Fourier Transform (DFT) to implement multicarrier modulation [39]. This paper laid the foundation of the research in OFDM. In 1980s, L. J. Cimini [40] firstly analyzed the problems about applications of OFDM in the mobile communication systems and proposed some solutions. Since then, the research in OFDM and its application on Mobile communication systems became booming. As discussed in Chapter 2, it has already been widely used in today’s digital communication systems.
3.2.1 Multicarrier Systems

With particular given channel characteristics, there are two types of block transmission modes for communication systems to consider how to efficiently use the given system channel frequency band for reliable information transmission in a given transmitter power and limited receiver complexity - to subdivide the frequency band into the non-ideal or nearly ideal filter channels [41]. For the non-ideal filter channels, a common option is to employ a single carrier (SC) transmission system in which the data sequence is transmitted serially at some specified rate. In such mode, the inter symbol interference (ISI) is caused by the non-ideal frequency response characteristics of the channel because the time dispersion is normally much larger than the symbol rate.

Another approach to improve the efficiency of channel band utilization in the presence of channel distortion is the ideal filter channel. In this channel model, the channel is subdivided into a number of sub channels which are narrow enough to be considered nearly ideal. This model is also known as multicarrier model. Multicarrier modulation is widely used in broad bandwidth communications. It is a method of transmitting data by splitting it into a number of components, and then sending each of these components over separate carriers. In a multicarrier system, each individual carrier still has narrow bandwidth, but overall the composite signal can have broad bandwidth [41].

Comparing with single carrier systems, which are usually equalized by means of highly complex time-domain equalizers when the channel impulse response is much longer than the symbol duration, multicarrier systems can be employed by much easier equalizers. In a multicarrier system, each individual carrier can be equalized
by means of a single tap. However multicarrier systems are more sensitive than single
carrier systems to carrier frequency offsets and amplifier nonlinearities [42].

3.2.2 OFDM Architecture

OFDM is a typical multicarrier system, which subdivides the available bandwidth
into a large number of orthogonal, overlapping, narrowband subchannels or
subcarriers and these subcarriers transmit in parallel. A simplified OFDM system
block diagram is shown in Fig. 3.1. In this figure, the top half represents the
transmitter and the bottom half represents the receiver, respectively. At the
transmitter, the incoming data are firstly modulated by binary phase shift keying
(BPSK), quadrature phase shift keying (QPSK) or M-quadrature amplitude
modulation (M-QAM) [43]. After that, the serial stream is converted into parallel
format by a serial to parallel (S/P) converter. In this process, every N symbols are
grouped to be sent to the inverse fast Fourier transform (IFFT) modulator. IFFT does
the same thing as Inverse Discrete Fourier Transform (IDFT) but it is only more
efficient and low complexity [44]. In the IFFT block, these symbols are modulated
into different N subcarriers. In my project, the difference between IFFT and IDFT is
not distinguished. (3.1) depicts the IDFT process.

\[
S_k = \sum_{i=0}^{N-1} d_i \exp\left(j \frac{2\pi ik}{N}\right) \quad (0 \leq k \leq N - 1)
\]  

(3.1)

where \(d_i\) is the \(i^{th}\) symbol, and \(N\) is the number of subcarriers.
Following the IFFT and before being transmitted, the parallel symbols are converted into a serial stream again and a cyclic prefix (CP) is added in order to eliminate the effect of inter-symbol interference (ISI) and inter-carrier interference (ICI). To satisfy the condition, the CP has to be longer than the length of the channel.

Figure 3.2 shows the spectrum of an OFDM signal. From this, the orthogonality of the sub-carriers can be seen. Every subcarrier falls into other sub-channels’ zero value. Thus, there is no overlap and little interference is created, and the crosstalk between sub-channels is eliminated and this greatly simplifies the design of both the transmitter and the receiver.

The receiver performs the opposite of the transmitter. After receiving the signal, it removes the CP first, and followed by a parallel to serial process. Then it implements an N point DFT.
After a serial to parallel transform and demodulation, it gets the expected signal. (3.2) shows the DFT function.

\[ d_i = \sum_{k=0}^{N-1} S_k \exp(-j \frac{2\pi ik}{N}) \quad (0 \leq i \leq N-1) \tag{3.2} \]

Here the orthogonal property is used, because \( \frac{1}{N} \sum_{k=0}^{N-1} \exp(j \frac{2\pi}{N} (n - m)) = 1 \), only when \( n = m \); otherwise \( \frac{1}{N} \sum_{k=0}^{N-1} \exp(j \frac{2\pi}{N} (n - m)) = 0 \).
3.2.3 OFDM Properties

OFDM enjoys the benefits when offering the higher speed and capacity for the new wireless communication systems. It easily eliminates the effect of the ISI caused by channel time spread because the time duration of an OFDM symbol is much longer than that of the original data symbol. Besides, due to the orthogonal property of the subcarriers, the spectrum of the channels can be overlapped. Comparing with normal FDM, OFDM systems can maximally utilize the spectrum [45]. OFDM uses IFFT to modulate the subcarriers, so that a simple frequency domain channel equalizer can be applied at the receiver via FFT. As the development of the Application Specific Integrated Circuit (ASIC), Large Scale Integrated (LSI) circuit and Digital Signal Processing (DSP), IFFT and FFT are easy to implement.

However, the OFDM suffers from some drawbacks as well, mainly including: a high peak-to-average power ratio (PAPR) which may distort the signal when it passes through the amplifier, which finally affects the orthogonality of subcarriers [46]; the sensitivity of synchronization at the receiver which causes ICI [47][48]. Also, due to its lack of frequency diversity [49], it performs poorly in frequency-selective channels.

a. High Peak-to-Average Power Ratio (PAPR)

In OFDM systems, signals are comprised of a summation of a number of independently modulated subcarriers. The summation of subcarriers may result in a signal with large or small amplitude, depending on the input data. Thus, the peak signal power is much larger than the average power. However, in a single carrier
system, the transmission power is generally constant (with PSK modulation). With a high PAPR, a communications system may encounter two major problems. First, large changes in amplitude levels can cause out-of-band (OOB) emissions if the operating range of the power amplifier (PA) is not perfectly linear. This causes pulse distortion when the signal traverses the nonlinearities of the amplification curve. Also, OOB emissions can be caused by clipping distortion when the amplitude exceeds the saturation level of the PA as well, this, furthermore, will affect the orthogonality of subcarriers [6].

There are many algorithms proposed to reduce the PAPR and improve OFDM system performance. These methods include selected mapping (SLM) [50], clipping with filtering [51], interleaved OFDM (IOFDM) [52], partial transmit sequences (PTS) [46, 53], block coding [54], and selective scrambling [55].

b. Vulnerability to Synchronization Errors

An OFDM system is sensitive to frequency synchronization errors. This vulnerability may cause inter-carrier interference (ICI) when the frequency references of the transmitted and received signals are not perfectly matched. This is because subcarriers in OFDM systems are densely packed to maximize spectral efficiency due to the orthogonal nature of OFDM. The orthogonality is destroyed once the frequency offset occurs, and thereby interference is introduced from adjacent subcarriers. There are mainly two sources which can cause these frequency synchronization errors. First, this effect is inherent to mobile channels due to the Doppler Effect, which causes a signal to experience a frequency shift when the source is traveling at a high velocity. Also, it can be observed in the static channels because of any misalignment in the transmitter or receiver generators. ICI aggravates the error probability performance of the system [48]. There have been many solutions
proposed to solve synchronization problems, which generally acquire coarse synchronization, and perform fine tracking thereafter [56-60].

c. Lack of Frequency Diversity

The Third major disadvantage of OFDM is the lack of frequency diversity. In other words, each symbol is transmitted over a single subchannel independently, thus the uncoded OFDM system only achieves diversity order one and hence performs poorly in frequency-selective channels due to the lack of frequency diversity of the single-tap equalizer for each subcarrier. As a result, subcarriers in OFDM may experience high frequency dependent attenuations on transmission over such frequency selective fading channels. The symbols carried by the subcarriers are consequently erased by the channel attenuations and cannot be accurately recovered at the receiver [49].

In order to improve the diversity across frequency and time, channel coding has been traditionally used [61, 62], and recently linear precoding and block spreading for OFDM systems are introduced as well [40, 63-65]. The idea of precoding is that the individual symbol information is effectively distributed across a number of subcarriers rather than a single subcarrier, and this adds sufficient frequency diversity and thereby improves the system performance [66].

3.3 Improvement for OFDM

Plenty of research has been undertaken to overcome those problems discussed above. Channel coding and interleaving have been traditionally used to improve the diversity across frequency and time [40][62], and recently, linear precoding and block
spreading for OFDM systems are introduced to improve the frequency diversity performance [40, 64-68]. Meanwhile, OFDM is extended to combine with multiple accesses such as Orthogonal Frequency Division Multiple Access (OFDMA) [69], Multicarrier Code Division Multiple Access (MC-CDMA) [70], also known as OFDM-CDMA, which have been introduced in Chapter 2. The use of multiple antennas is also the most promising areas in recent research on wireless mobile communications to improve the current systems. The multiple-input multiple-output (MIMO) [71] system refers to the system in which multiple antennas are used at both transmitter and receiver.

In this section, we are going to introduce the linear precoding, block spread and MIMO which are related to our new BT-OFDM system.

### 3.3.1 Linear Precoding

A linear precoded orthogonal frequency-division multiplexing (LP-OFDM) is generally based on classical OFDM combined with a precoding component. The concept is to group together a set of subcarriers with the help of precoding sequences. Each resulting set accumulates the energies of all of its subcarriers to achieve an equivalent SNR such that the total number of bits supported is greater than the sum of the bits supported by each subcarrier individually. The main advantage of linear precoding is to improve the signal robustness against frequency selectivity and narrowband interference, since the signal bandwidth could become much larger than the coherence and interference bandwidths [64]. Furthermore, the linear precoded component can also be exploited to reduce the peak-to-average power ratio of the OFDM system [72].

The precoding is normally applied in the frequency domain. And in practice, the system is modified by simply adding a precoding block in the transmission chain;
therefore the system complexity is not significantly increased. A typical linear block diagram is showed in Fig. 3.3. From the diagram, we can see that the information bits are first convolutional encoded, bit interleaved and then mapped to complex symbols, and then applied by linear precoding. In the linear precoding process, the principle is to linearly combine the $L$ symbols of vector $x$ with a complex unitary matrix $\Theta_L$ of size $L \times L$ in order to bring diversity between each component of the resulting vector $s = \Theta_L \cdot x$ [73]. By using maximum likelihood (ML) receivers, it shows that an $L$-order diversity can be achieved. Moreover, this diversity is brought without bandwidth expansion and without any channel knowledge at the transmitter [74].

![Diagram](image)

Fig. 3.3 LP-OFDM Block Diagram [73].

### 3.3.2 Block Spread OFDM

The block spreading techniques have also been commonly used to achieve the better frequency diversity in OFDM systems over frequency selective fading channels. The block spread systems based on OFDM is termed BS-OFDM. The essential idea of these techniques is to split the subcarriers into smaller groups and spread the
information symbols across these groups by applying a unitary transformation [75]. Bury et al. [76] firstly proposed this idea and presented a design technique for developing spreading codes through column-wise rotation of the discrete Fourier transform (DFT) or Hadamard matrix. In a typical BS-OFDM system, \( N \) subcarriers are split into \( N/M \) blocks of size \( M \). Each of these blocks is then multiplied by an \( M \times M \) unitary spreading matrix \( U_M \). The resulting length output \( M \) vectors are then interleaved to separate the entries in each block as far as possible across the frequency band so that they will encounter independent fading channels before they can be sent to the traditional OFDM modulation [77]. At the receiver, after passed through an FFT processor, the data is then deinterleaved prior to block-by block processing [78]. Fig. 3.4 shows a block diagram of BS-OFDM with a block size \( M=2 \).

![Block diagram representation of the BS-OFDM channel for a block length of two [77]](image)

The spreading matrices are generally used to increase the correlation between the transmitted symbols in order to achieve diversity in frequency selective fading channels. The most common spreading matrix in use is the Hadamard matrix according to [76]. The Hadamard matrix is defined as
In the equation, $\otimes$ denotes the Kronecker product [79], and the matrix size is $M = 2^n$. Another less common spreading matrix DFT matrix is also presented in [76]. The element which combines a DFT matrix is defined as

$$U_{i,k} = \frac{1}{\sqrt{M}} \cdot \exp\left(-j2\pi \frac{(i-1)(k-1)}{M}\right), \quad 0 < i, k \leq M.$$ \hspace{1em} (3.4)

As the block spread schemes increase the correlation between the transmitted symbols by the creation of the higher order modulation, and therefore achieving frequency diversity and better system performance, there are more researches have been made in this topic. In those researches, varies of spread matrices have been introduced.

One of these matrices is the rotated Hadamard matrix [80, 81], which is based on the Hadamard matrix but rotated using the rotation equation given below,

$$U = \frac{1}{\sqrt{2}} H_{M \times M} \text{diag}\left(\exp\left(\frac{j \times \pi \times m}{C}\right)\right).$$ \hspace{1em} (3.5)

where $C$ is the rotation value which the modulation rotated back on to itself, for QPSK it is 4. $H$ is the Hadamard matrix described above and $M$ is the size of the matrix. By multiplying the rotated Hadamard matrix $U$, a higher modulation scheme than traditional Hadamard matrix is produced to result a better BER performance in BS-OFDM system.

In addition, Raad and Huang introduced another spreading matrix for BS-OFDM in [81]. This matrix can be defined as

$$U_2 = \begin{bmatrix} 1 & \tan(\alpha) \\ \tan(\alpha) & -1 \end{bmatrix}.$$ \hspace{1em} (3.6)
In this scheme, not all angles $\alpha$ can be chosen since this would not yield a better result compared with the Hadamard matrix, and also when $\alpha = \pi$ and $\frac{\pi}{2}$, the rotation of QPSK would rotate back onto itself. However, by choosing the proper $\alpha$, different modulation schemes are possible. An example is that the choice of $\tan(\alpha) = 0.5$ makes QPSK into 16QAM. Also, it is easy to figure out when $\alpha = \pi/4$, it is equivalent to the Hadamard matrix.

In order to expand the above spreading matrix into higher order spreading matrix with larger block size to improve the performance, a number of variations are also presented in their further work in [82-84].

### 3.3.3 Multiple-Antenna Systems

Time-varying multipath fading is a key factor which makes reliable wireless transmission a great challenge when compared to fibre, coaxial cable, line-of-sight microwave or even satellite transmissions. Increasing the quality or reducing the effective bit error rate (BER) in a multipath fading channel is extremely difficult. For example, in additive white Gaussian noise (AWGN), reducing the BER from $10^{-2}$ to $10^{-3}$ may require only 1 or 2 dB higher signal-to-noise ratio (SNR) by using the specific modulation and coding schemes. However, it may require up to 10dB improvement in SNR to achieve the same BER reduction in a multipath fading environment [85].

There are a few techniques to mitigate multipath fading in a wireless channel. The most effective one is transmitter power control. However, with this approach, it is not practical to reach the required transmitter dynamic range in most cases because of radiation power limitations and the size and cost of the amplifiers. Also in this
approach, the transmitter does not have any knowledge of the channel experienced by
the receiver most of the time. Thus, the channel information has to be fed back from
the receiver to the transmitter, which results in throughput degradation and
considerable extra complexity to both the transmitter and the receiver [85].

Antenna diversity is another considerable and practical effective and hence a widely
applied technique for reducing the effect of multipath fading in most scattering
environments [85]. The use of multiple antennas allows independent channels to be
created in space and is one of the most interesting and promising areas of recent
innovation in wireless communications. In order to providing spatial diversity without
using additional bandwidth that time and frequency diversity both require, antenna
arrays can be used to focus energy or create multiple parallel channels for spatial
multiplexing. Multiple input multiple output (MIMO) systems can be defined as an
arbirtary wireless communication system, in which a link multiple antenna elements
are equipped at the transmitting end as well as the receiving end. The core idea in
MIMO systems is space-time signal processing in which time is complemented with
the spatial dimension inherent in the use of multiple spatially distributed antennas.
Thus, MIMO systems can be viewed as an extension of the so-called smart antennas,
a popular technology which also uses antenna arrays for improving wireless
transmission which can date back decades ago. The most amazing feature of MIMO
systems is the ability to turn multipath propagation, traditionally a pitfall of wireless
transmission, into a benefit for the user. By using MIMO techniques, the
communications systems can achieve the incense of the system reliability (in other
words, decrease of the bit or packet error rate), achievable data rate and hence system
capacity, coverage area, and the decrease of the required transmit power. However,
these four desirable attributes usually cannot be consistent at the same time. For
example, an increase in data rate often means an increase in either the error rate or
transmit power [23, 86]. Fig. 3.5 shows an MIMO wireless transmission system
diagram.
There are a lot of approaches have been researched for antenna diversity. Wittneben [87, 88] proposed a delay diversity scheme and Seshadri and Winters [89, 90] also proposed a similar scheme for a base station in which copies of the same symbol are transmitted through multiple antennas at different times, resulting in an artificial multipath distortion. Space-time trellis coding (STTC) is also an interesting approach, where modulation and trellis coding are combined to transmit signals over multiple transmit antennas and multipath channels [91-94]. Space-time block coding (STBC) is developed due to the exponentially increscent of the STTC complexity as high diversity order is required. STBC uses simple linear processing at the receiver to decode in contrast to the complex decoding algorithm for STTC, and meantime give the same diversity gain as STTC for the same number of transmit antennas [95].

The space-time coding was originally designed for a narrowband wireless system, where only a flat fading channel is expected. Therefore, when it is used over frequency selective fading channels, a complex equalization method is required at the receiver along with the space-time decoder. However, OFDM, as described in previous sections, is an effective technique for frequency selective fading channels. By using OFDM modulation, frequency selective fading channels can be considered as multiple flat fading channels; thereby the space-time coding method can be effectively applied to improve system performance, even over channels with large delay spreads. Thus a combined system of OFDM and MIMO effectively resolves the equalization complexity problem and extends the utilization of space-time coding into
frequency selective fading channels [96]. Numerous researches have been made on the OFDM based MIMO [97-99].

3.4 Summary

In this chapter, we introduced orthogonal frequency-division multiplexing (OFDM) and its related techniques. We started this chapter by a brief introduction of the multicarrier systems. Also, a compare has been made between multicarrier systems and single carrier systems. Then, we described the OFDM system - a special multicarrier system. The core idea of the OFDM was introduced with the OFDM system architecture and the spectrum analysis. We also talked about OFDM properties, mainly the disadvantages the system may encounter, which are a high peak-to-average power ratio (PAPR), sensitivity to synchronization errors, and a lack of frequency diversity. After that, we introduced the different ways to conquer those problems in literature. We payed specific attention to linear precoding, block spread OFDM, and multiple antenna systems as these techniques will be related to our new proposed BT-OFDM system. In next chapter, we will introduce our new proposed BT-OFDM system.
Chapter 4

Block Transform OFDM System

4.1 Introduction

In Chapter 3, we reviewed the basic theory and some applications of orthogonal frequency division multiplexing (OFDM), the advantages and the disadvantages of OFDM. Also, single-carrier system was briefly reviewed as comparison, because in literature, the conventional OFDM and the single-carrier system often represent the two extremes on system performance. In the end of last chapter, a question that whether there is any transmission scheme which can bridge the two extremes is asked.

In this chapter, a block transform (BT) OFDM system is introduced to offer the solution which balances the system performance in-between the conventional OFDM and single carrier system. From the literature, it is known that the conventional OFDM perform an inverse fast Fourier transform (IFFT) modulation in transmitter
and a fast Fourier transform (FFT) demodulation at the receiver. The idea of BT-OFDM is to group the data symbols to be transmitted into blocks and use smaller size IFFT to generate the BT-OFDM symbol with the same number of subcarriers. When properly configured, the BT-OFDM is expected to remove the disadvantages of the conventional OFDM, to be specifically, reduce the PAPR thus offers higher power efficiency, increase the frequency diversity, but still enjoys the benefits offered by multicarrier transmission. We will then talk about the equalization techniques when noise and multipath involved. In the last section of this chapter, we will discuss how this BT-OFDM system is sitting in-between the conventional OFDM system and single carrier system. Also the peak average power ratio (PAPR) will be covered in that section as well.

### 4.2 BT-OFDM System Architecture

In this section, the BT-OFDM system architecture is presented. Both transmitter and receiver are explained in detail. Also, the frequency domain representation is analyzed. From the system model, the relationships among BT-OFDM, conventional OFDM, and single-carrier system are discussed.

#### 4.2.1 BT-OFDM Transmitter

In a BT-OFDM system, the bit stream is firstly modulated by binary phase shift keying (BPSK), quadrature phase shift keying (QPSK) or any other quadrature amplitude modulation (QAM). Take $MN$ data symbols ($M$ and $N$ are integer powers of 2 in the purpose of IFFT and FFT) which have already been mapped from those
constellation mapping. Then the $MN$ data symbols are grouped into $N$ blocks of size $M$.

Assume data stream $x[i], i = 0, 1, \ldots, MN - 1$, denote these $MN$ modulated data symbols. After grouping, the symbols are rearranged as an $N \times M$ matrix. The $n$th block denoted as a vector

$$x_n = (x[nM], x[nM + 1], \ldots, x[nM + M - 1]), n = 0, 1, \ldots, N - 1,$$

(4.1)

which is also the $n$th row of the matrix $x = \begin{pmatrix} x_0 \\ x_1 \\ \vdots \\ x_{N-1} \end{pmatrix}$, where the data at the $n$th row and $m$th column is $x[nM + m], n = 0, 1, \ldots, N - 1, m = 0, 1, \ldots, M - 1$.

There is a difference here in the BT-OFDM system compared with the conventional OFDM. Instead of performing one $MN$ – point inverse discrete Fourier transform (IDFT) with $MN$ subcarriers in a conventional OFDM system following the previous processes, BT-OFDM performs $M$ IDFTs of size $N$ on the data symbol matrix $x$ to produce the transmitted signal matrix

$$y = W_N^{-1}x$$

(4.2)

where

$$W_N^{-1} = \frac{1}{N} \left( e^{-\frac{2\pi j nm}{N}} \right)_{N \times N}$$

(4.3)

is the $N$-point IDFT matrix. The notation $(\cdot)_{N \times M}$ is used to represent an $N \times M$ matrix where the dot is the element at the $n$th row and the $m$th column for simplicity.

In other words, BT-OFDM performs an $N$-point IDFT of each column in the matrix $x$ respectively to form another $N \times M$ matrix $y = (y_0, y_1, \ldots, y_{M-1})$, where
\[ y_m = \begin{pmatrix} y[m] \\ y[M + m] \\ \vdots \\ y[nM + m] \end{pmatrix} \] is the IDFT form of \( m \)th column of \( x \).

(4.2) is referred to as the \( N \)-point block IDFT. Then a sequence \( y[i] \), \( i = 0,1,\ldots, MN-1 \), taking from matrix \( y \) row by row is the transmitted signal. Take the sample element at the \( n \)th row and \( m \)th column of \( y \), \( n = 0,\ldots, N-1 \), \( m = 0,1,\ldots, M-1 \), which is \( y[n'M + m] \). According to (4.2), it is easy to get

\[
y[n'M + m] = \frac{1}{N} \sum_{n=0}^{N-1} x[nM + m] e^{\frac{j2\pi nm}{N}} \tag{4.4}
\]

Before being transmitted, a pulse shaping filter \( g(t) \) is applied, and the transmitted analog BT-OFDM signal can be expresses as

\[
y_i(t) = \sum_{i=0}^{MN-1} y[i] g(t - iT) \tag{4.5}
\]

where, \( T \) represents the sampling period.

Fig. 4.1 denotes the baseband block diagram which is deployed in a BT-OFDM system transmitter. The figure shows that the signal data stream modulated from QAM or PSK first passes through a serial-to-block (S/B) transformer to produce an \( N \times M \) data symbol matrix block \( x \). Unlike performing an \( NM \) – point IFFT in conventional OFDM, an \( N \) – point block IFFT is then performed directly after S/B to generate the BT-OFDM signal matrix \( y \). The \( N \) – point block IFFT is followed by a block-to-serial (B/S) block to convert the new block back into a serial stream. The rest of the parts are similar to conventional OFDM. A cyclic padding (CP) or zero padding (ZP) of sufficient length (longer than the maximum path delay) will be inserted into the transmitted BT-OFDM data symbol. The purpose of the sufficient length is to avoid interference between adjacent BT-OFDM symbols and turn the linear convolution of the transmitted signal with channel impulse response into a
circular one. Before sending, a pulse shaping filter is used to limit the transmitted
signal bandwidth.

Fig. 4.1 BT-OFDM system model: Transmitter.

4.2.2 Block FFT

In the previous section, the BT-OFDM system architecture is proposed. As we can
see, one of the greatest differences between the conventional OFDM and our new BT-
OFDM system is instead of performing an $MN$-point FFT at the receiver side and an
$MN$-point IFFT at the transmitter side, ($MN$ is the length of the transmitted data
symbols), data symbols are first grouped into $N$ blocks of size $M$ and in each block,
$N$-point block IFFT and block FFT are then performed at transmitter and receiver,
respectively. In this section, the process of block IFFT and block FFT will be
introduced. By applying a BT-OFDM, the signal energy for each data symbol is
spread across different subcarriers, therefore increase the frequency diversity. Also, it
implicitly realizes a block spreading. We will analyze the properties of the BT-
OFDM system later.

To simplify the discussion, we use a much short vector as an example to compare to
the real stream. Assume a vector of size 8:

$$x = [x_0, x_1, x_2, x_3, x_4, x_5, x_6, x_7],$$  \hspace{1cm} (4.6)
Also, set the block size $M = 4$, then the number of blocks will be $N = MN / M = 2$.

The block looks like $\mathbf{x}' = \begin{pmatrix} x_1' \\ x_2' \end{pmatrix}$, here $x_1' = [x_0, x_1, x_2, x_3]$, $x_2' = [x_4, x_5, x_6, x_7]$.

Then $N = 2$ point IFFTs are performed. Because each block has 4 symbols, there are 4 IFFTs in this case. In other words, IFFT will be performed to the vectors $[x_0, x_4]'$, $[x_1, x_2]'$, $[x_2, x_6]'$, $[x_3, x_7]'$, where $'$ denotes the conjugate of the original vector.

After the block IFFT, we get the new matrix:

$$
\mathbf{y} = \begin{pmatrix} y_0, y_1, y_2, y_3 \\ y_4, y_5, y_6, y_7 \end{pmatrix} = \text{BlockIFFT}(\mathbf{x}),
$$

where $\begin{pmatrix} y_0 \\ y_4 \end{pmatrix} = \text{IFFT} \begin{pmatrix} x_0 \\ x_4 \end{pmatrix}$, $\begin{pmatrix} y_1 \\ y_5 \end{pmatrix} = \text{IFFT} \begin{pmatrix} x_1 \\ x_5 \end{pmatrix}$, $\begin{pmatrix} y_2 \\ y_6 \end{pmatrix} = \text{IFFT} \begin{pmatrix} x_2 \\ x_6 \end{pmatrix}$, $\begin{pmatrix} y_3 \\ y_7 \end{pmatrix} = \text{IFFT} \begin{pmatrix} x_3 \\ x_7 \end{pmatrix}$.

At the receiver side, the block FFT is similar but only changes the IFFT into FFT. We will talk about this more when we talk about the receiver later. Fig. 4.2 shows a block IFFT process of this 8-point data stream discussed above.

![Block IFFT Diagram](image)

**Fig. 4.2** An example of block IFFT to an 8-point stream with block size $M = 4$. 

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4.2.3 Frequency Domain Representation

Frequency domain is often used to analyze the characteristics of a communication system. In this section, we will analyze some characteristics of the BT-OFDM signal in the frequency domain as well.

First, an $MN$-point DFT is performed to convert $y[i]$ to frequency domain

$$Y[k] = \sum_{i=0}^{MN-1} y[i] e^{-j2\pi ki/MN}$$

$$= \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} y[nM + m] e^{-j2\pi nM/MN} e^{-j2\pi km/MN}$$

(4.8)

Substituting (4.4) into (4.8), we can get

$$Y[k] = \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} \frac{1}{N} \sum_{l=0}^{N-1} x[nM + m] e^{2\pi j(nM + m)/N} e^{-j2\pi nM/MN}$$

$$= \sum_{n=0}^{N-1} \sum_{m=0}^{M-1} x[nM + m] e^{-j2\pi km/MN} \frac{1}{N} \sum_{n=0}^{N-1} e^{2\pi j(k-n)n}/N$$

(4.9)

Since the orthogonal property, 

$$\frac{1}{N} \sum_{n=0}^{N-1} e^{-j2\pi (k-n)n}/N = \begin{cases} 1, & k - n = lN \\ 0, & \text{otherwise} \end{cases}$$

(4.9) can be expressed as

$$Y[k] = \sum_{n=0}^{k=M-1} x[nM + m] e^{-j2\pi m/M} e^{-j2\pi Mn/N} = X_n[l],$$

$$k = lN + n, \quad l = 0, 1, \ldots, M-1, \quad n = 0, 1, \ldots, N-1,$$

(4.10)
where $X_n[l]$ is the $M$-point DFT of a sequence taking from the $n$th data symbol block $x_n$ after performing a phase rotation to each element, i.e. $x[nM + m]e^{-\frac{2\pi}{MN}mn}, \ m=0,1,...,M-1$. This phase rotation will be referred to as down-shift thereafter since it corresponds to shifting a sequence’s Fourier transform downwards in the frequency domain.

From (4.10), notice that the transmitted BT-OFDM signal also has $MN$ subcarriers. However, unlike conventional OFDM where the data symbols are directly mapped onto the subcarriers, each block of data symbols in the BT-OFDM is first down-shifted and transformed into frequency domain through DFT, and the transformed data symbols are then uniformly spaced across the $MN$ subcarriers. This means that the BT-OFDM efficiently achieves the frequency diversity as the precoded or block spread OFDM system does but without explicit precoding or block spreading. As discussed in Chapter 3, precoding is a common way we use today to achieve the frequency diversity. In BT-OFDM system, we achieve a precoding without actually having a precoding process, which removes the system complexity.

From (4.5), the frequency domain representation of the transmitted analogue BT-OFDM signal $y(t)$ is

$$Y(f) = G(f)Y(e^{j2\pi fT}),$$

(4.11)

where $G(f)$ is the frequency response of the pulse shaping filter $g(t)$, $Y(e^{j\omega})$ is the Fourier transform of $y(t)$. $Y(e^{j\omega})$ can also be interpolated from $Y(k)$ by (4.12) according to the relationship between Fourier transform and discrete Fourier transform.

$$Y(e^{j\omega}) = \sum_{k=0}^{MN-1} Y[k] \Phi_{MN} (\omega - \frac{2\pi}{MN} k),$$

(4.12)

where the interpolation function is defined as

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\[ \Phi_n(\omega) = \frac{\sin(\frac{\omega n}{2})}{n \sin(\frac{\omega}{2})} e^{-\frac{\omega(n-1)}{2}}. \] (4.13)

Again, using the previous 8-point data stream as an example, Fig. 4.3 and Fig. 4.4 depict the frequency domain analysis process and the equivalent process respectively. In both processes, if the same stream \( x \) is input, we should get the same \( Y \). This proves that our new BT-OFDM system implies a precoding process. However, as we can see, we do not really have this process in our system. In other words, we achieve this precoding without really performing it.

Fig. 4.3 Frequency domain representation of an 8-point stream after block IFFT
4.2.4 BT-OFDM Receiver

In 4.2.1, the BT-OFDM transmitter model was introduced. The signal was transmitted out from the antenna. In this section, the receiver model will be discussed.

After transmitting over a frequency-selective multipath fading channel, the BT-OFDM signal is received at the receiver by an antenna. Firstly, the received BT-OFDM signal is filtered by a matched-filter (frequency response $G^*(f)$, where * denotes complex conjugation), and then sampled to yield the received baseband signal.

From Fig. 4.1, we can see that either a CP or ZP of sufficient length is added to the transmitted data stream in the transmitter. Thus, a removing of the CP process or an overlap-add operation at the receiver baseband is performed in the receiver. Then, the stream length becomes $MN$ again. In other words, $MN$-point received BT-OFDM
samples \( r(i), i = 0, 1, ..., MN - 1 \), will be produced. In frequency domain, the discrete received signal model can be expressed as

\[
R[k] = H[k]V[k] + V[k], \quad k = 0, 1, ..., MN - 1, \tag{4.14}
\]

where \( R[k] \) is the \( MN \)-point discrete Fourier transform (DFT) of \( r[i] \), \( H[k] \) is the \( MN \)-point DFT of the discrete channel impulse response \( h[i] \), and \( V[k] \) is a zero-mean Gaussian noise on subcarrier \( k \).

In a telecommunications system, at the receiver end, one process that must be performed is to recover the transmitted data symbols from the transmitter which transmit through the channel (air in a wireless telecommunications system case). To do so, in the BT-OFDM system, we group \( r[i] \) into \( N \) blocks of size \( M \) just as we did in transmitter. The \( n' \)th block is then defined as a vector

\[
r_{n'} = (r[n'M], r[n'M + 1], ..., r[n'M + M - 1]), \quad n' = 0, 1, ..., N - 1. \tag{4.15}
\]

All \( N \) vectors can form a matrix \( r = \begin{pmatrix} r_0 \\ r_1 \\ \vdots \\ r_{N-1} \end{pmatrix} \), thus, the element of which at the \( n' \)th row and the \( m \)th column is the received signal sample \( r[n'M + m] \).

Then, as a DFT is performed in a traditional OFDM receiver, an \( N \)-point block DFT is performed on \( r \). This can be represented as

\[
z = W_N r, \tag{4.16}
\]

where

\[
W_N = (e^{-j2\pi nm/N})_{N \times N} \tag{4.17}
\]

denotes the \( N \)-point DFT matrix.

According to (4.16) and (4.17), the element at the \( n \)th row and the \( m \)th column of \( z \) which obtained from \( r[i] \) is
\[ z[nM + m] = \sum_{n=0}^{N-1} r[n'M + m] e^{-j \frac{2\pi n}{MN}}. \]  

(4.18)

Because of the orthogonal property which \( \frac{1}{M} \sum_{l=0}^{M-1} e^{-j \frac{2\pi l}{M} (i-m)} = \begin{cases} 1, & i-m = n'M \\ 0, & \text{otherwise} \end{cases} \) from (4.18), we can find the relationship between \( z[nM + m] \) and \( R[k] \) can be also derived as

\[ z[nM + M]^{n'M + m-i} = \sum_{(i-m,M+m) = (N-1)M+m} r[i] e^{-j \frac{2\pi n}{MN} (i-m)} \]

\[ = \sum_{l=0}^{MN-1} r[l] \frac{1}{M} \sum_{l=0}^{M-1} e^{-j \frac{2\pi n}{MN} (i-m)} e^{j \frac{2\pi l}{M} (i-m)} \]

\[ = e^{j \frac{2\pi l}{MN} \sum_{l=0}^{M-1}} \frac{1}{M} \sum_{l=0}^{M-1} \sum_{i=0}^{M-1} r[i] e^{-j \frac{2\pi n}{MN} (N+n)} e^{j \frac{2\pi l}{M} (i-m)} \]

\[ = e^{j \frac{2\pi l}{MN} \sum_{l=0}^{M-1}} \frac{1}{M} \sum_{l=0}^{M-1} R[N + n] e^{j \frac{2\pi l}{M} (i-m)}. \]  

(4.19)

If we consider that there is no noise or multipath present, i.e., in (4.14), \( H[k] = 1 \) and \( V[k] = 0 \) for all \( k \), then (4.16) is the inverse operation of (4.14). [44] In this ideal situation, \( z \) is expected to be the recovered transmitted data symbol matrix \( x \). This can also be confirmed from (4.19). From (4.14) and (4.10), we have

\[ R[N + n] = Y[N + n] = X_n[I]. \]

Then we get

\[ z[nM + m] = e^{j \frac{2\pi n}{MN} \sum_{l=0}^{M-1} X_n[I]} e^{j \frac{2\pi n}{M} m} = e^{j \frac{2\pi n}{MN} \sum_{l=0}^{M-1} X[N + m] e^{-j \frac{2\pi n}{MN}} = x[nM + m]. \]  

(4.20)

Therefore, for the ideal case, (without considering noise and multipath), (4.16) can be used to retrieve the transmitted data stream. Once noise and multipath is considered, additional equalizer must be deployed, which will be discussed in the following sections.
After the equalization, the received data symbol sequence is finally obtained after B/S process. Fig. 4.5 shows the blocks of the BT-OFDM system receiver model.

![Fig. 4.5 BT-OFDM system model: Receiver](image)

### 4.3 Equalization

In previous sections, we discussed the BT-OFDM system architecture. However, all of these discussions are based on one assumption – there is no noise or multipath involved. In the real world, this ideal environment is impossible. Thus, at the receiver, additional equalization techniques must be employed. In this section, we will talk about the equalization architecture, the output SNR derivation, and we will also analyze the Minimum Mean Squared Error (MMSE) equalization and Zero Forcing (ZF) Equalization respectively.

#### 4.3.1 Equalization Architecture

In this chapter, we have learned that the BT-OFDM provides a simple way to achieve frequency diversity. It is expected that the BT-OFDM will offer better performance than the conventional OFDM in frequency-selective fading channels. In this section,
the BT-OFDM system performance is evaluated under different transmitter configurations, i.e. block size \( M \) and IFFT size \( N \), as well as channel diversity degrees. Due to the complexity of the optimum maximum-likelihood equalization, only the minimum mean squared error (MMSE) type equalization is considered, since it can simply use a single-tap equalizer for each subcarrier in the frequency domain.

Fig. 4.6 shows the equalization architecture of the BT-OFDM system. It can be determined by (4.19), (4.14) and (4.10). To be easy reading, here list the three equations again.

\[
\begin{align*}
   z[nM + m] &= n^M + m^i \sum_{i=m, M + m,...,(N-1)M + m} r[i] e^{-j\frac{2\pi}{MN}(i-m)} \\
   &= \sum_{i=0}^{MN-1} r[i] \frac{1}{M} \sum_{l=0}^{M-1} e^{-j\frac{2\pi}{M}l} e^{-j\frac{2\pi}{MN}(i-m)} \\
   &= e^{j\frac{2\pi}{MN}m} \frac{1}{M} \sum_{i=0}^{M-1} \sum_{l=0}^{M-1} r[i] e^{-j\frac{2\pi}{MN}(i+l)} e^{j\frac{2\pi}{M}l} \\
   &= e^{j\frac{2\pi}{MN}m} \frac{1}{M} \sum_{i=0}^{M-1} R[lN + n] e^{j\frac{2\pi}{M}l}. \\
   R[k] &= H[k]Y[k] + V[k], \quad k = 0,1,...,MN - 1, \\
   Y[k] &= \sum_{n=0}^{M-1} x[nM + m] e^{-j\frac{2\pi}{MN}n} e^{-j\frac{2\pi}{M}m} = X_n[l], \\
   k &= lN+n, l = 0,1,...,M-1, n = 0,1,...,N-1, \\
\end{align*}
\]

\[
R = \left\{ z \left( e^{-j\frac{2\pi}{MN}m} \right)_i \right\}_{nM} W_M, \quad \text{C} \cdot \text{R} \\
\text{d} = \left( (\text{C} \cdot \text{R})^{-1} \right) \left( e^{-j\frac{2\pi}{MN}m} \right)_{nM} \\
\]

Fig. 4.6 Equalization architecture for BT-OFDM
In the figure, the dot (.) in equations denotes element by element matrix multiplication. From the figure, we can see that after performing phase rotation $e^{-j\frac{2\pi}{MN} n m}$ to $z[nM + m]$ (i.e. down-shift) and $M$ -point block FFT, the discrete Fourier transform $R[IN + n]$ of the received signal is obtained. Then $R[IN + n]$ is equalized by a one-tap equalizer $C[IN + n]$ to recover the transmitted signal’s discrete Fourier transform $Y[IN + n]$. After $M$ -point block IFFT and $e^{j\frac{2\pi}{MN} n m}$ phase rotation (i.e. up-shift), the decision variable is obtained and the transmitted data symbol can be retrieved after hard decision.

4.3.2 Output SNR Derivation

We first derive the post-equalization SNR as a function of the equalizer coefficients $C[IN + n]$. According to the architecture we described above, the decision variable can be expressed as

$$d[nM + m] = \frac{1}{M} \sum_{l=0}^{M-1} C[IN + n] R[IN + n] e^{j\frac{2\pi}{M} l m} e^{j\frac{2\pi}{MN} n m}$$

$$= \frac{1}{M} \sum_{l=0}^{M-1} C[IN + n] \left\{ H[IN + n] \sum_{m'=0}^{M-1} x[nM + m'] e^{-j\frac{2\pi}{MN} n m'} e^{-j\frac{2\pi}{M} l m'} + V[IN + n] \right\} e^{j\frac{2\pi}{M} l m} e^{j\frac{2\pi}{MN} n m}$$

(4.23)

Since $x[nM + m]$ is the desired data symbol, (4.23) can be rearranged as

$$d[nM + m] = x[nM + m] \frac{1}{M} \sum_{l=0}^{M-1} C[IN + n] H[IN + n]$$

$$+ \sum_{m'=0}^{M-1} x[nM + m'] e^{-j\frac{2\pi}{MN} (m'-m)} \frac{1}{M} \sum_{l=0}^{M-1} C[IN + n] H[IN + n] e^{j\frac{2\pi}{M} l (m'-m)}$$

$$+ \frac{1}{M} \sum_{l=0}^{M-1} C[IN + n] V[IN + n] e^{j\frac{2\pi}{M} l m} e^{j\frac{2\pi}{MN} n m}.$$  

(4.24)
Assume that the average power of a data symbol is $\sigma^2_x$ and the average power of the noise before equalization is $\sigma^2_v$. From (4.24) the useful signal power after equalization is found to be

$$E\left[x[nM + m] \frac{1}{M} \sum_{l=0}^{M-1} C[lN + n]H[lN + n]\right]^2 = \frac{1}{M} \sum_{l=0}^{M-1} C[lN + n]H[lN + n] \sigma^2_x = q_0[n]$$

(4.25)

and the average power of $d[nM + m]$ is evaluated as

$$E\{d[nM + m]\}^2 = \frac{1}{M} \sum_{l=0}^{M-1} \|C[lN + n]H[lN + n]\|^2 \sigma^2_x + \frac{1}{M^2} \sum_{l=0}^{M-1} \|C[lN + n]\|^2 \sigma^2_v = q_1[n]$$

(4.26)

where $E\{\}$ denotes ensemble averaging on data and noise. The output SNR after equalization is thus expressed as

$$\gamma[n] = \frac{q_0[n]}{q_1[n] - q_0[n]}$$

$$= \frac{1}{M} \sum_{l=0}^{M-1} C[lN + n]H[lN + n] \right)^2}{\frac{1}{M} \sum_{l=0}^{M-1} \|C[lN + n]H[lN + n]\|^2 + \frac{1}{M} \sum_{l=0}^{M-1} \|C[lN + n]\|^2} - \frac{1}{M} \sum_{l=0}^{M-1} C[lN + n]H[lN + n] \right)^2 \frac{1}{\gamma_{in}} = \frac{1}{M} \sum_{l=0}^{M-1} \|C[lN + n]H[lN + n]\|^2 \frac{1}{\gamma_{in}} = \frac{M \sigma^2_x}{\sigma^2_v}$$

(4.27)

where $\gamma_{in} = \frac{M \sigma^2_x}{\sigma^2_v}$ is the input SNR before equalization.

Now, we are going to discuss a different equalization method.
4.3.3 MMSE Equalization and Zero-Forcing (ZF) Equalization

First, we consider the MMSE criterion, in other words, we use the minimizing $E\left[d[nM + m] - x[nM + m] \right]^2$ to design the equalizer coefficients, so these equalizer coefficients can be derived to be

$$C[\text{IN} + n] = \frac{H^*[\text{IN} + n]}{|H[\text{IN} + n]|^2 + \frac{1}{\gamma_{in}}}.$$ (4.28)

Substituting (4.28) into (4.27), the output SNR by MMSE equalization becomes

$$\gamma_{\text{mmse}}[n] = \frac{1}{1 - \frac{1}{M} \sum_{l=0}^{M-1} |H[\text{IN} + n]|^2 + \frac{1}{\gamma_{in}}} = \frac{1 - \frac{1}{M} \sum_{l=0}^{M-1} |H[\text{IN} + n]|^2 \gamma_{in} + 1}{1 - \frac{1}{M} \sum_{l=0}^{M-1} |H[\text{IN} + n]|^2 \gamma_{in} + 1}.$$ (4.29)

For ZF equalization, we assume that there is no noise present and select the equalization coefficients to force the ISI represented by the second term on the right-hand-side of (5.19) to be zero. We then get

$$C[\text{IN} + n] = \frac{1}{H[\text{IN} + n]}.$$ (4.30)

And the output SNR by ZF becomes
Comparing those two equalization method, since ZF equalization causes noise enhancement, MMSE equalization will be preferable. However, MMSE equalization requires the knowledge of $\gamma_{in}$ to determine the equalization coefficients, which is not practical. To solve the issue, in practice, we can design the equalization coefficients according to a predetermined (or estimated) input SNR $\gamma_0$ as

$$C[IN + n] = \frac{H^*[IN + n]}{|H[IN + n]|^2 + \frac{1}{\gamma_0}}.$$  \hfill (4.32)

Again, substituting (4.32) into (4.27), the output SNR will be

$$\gamma_{\text{prac}}[n] = \frac{\left| \frac{1}{M} \sum_{l=0}^{M-1} |H[IN + n]|^2 \right|^2}{\frac{1}{M} \sum_{l=0}^{M-1} |H[IN + n]|^2 + \frac{1}{\gamma_0}} \left( \frac{1}{\gamma_{in}} - \frac{1}{\gamma_0} \right)$$

\hfill (4.33)

We will use Matlab to simulate these performances in Chapter 6.


4.4 BT-OFDM Properties

In this section, we will talk about some properties such as PAPRs under different modulation schemes and IFFT sizes. However, we first talk about how this new BT-OFDM system is sitting in-between the single carrier system and the conventional OFDM system. We’ve already compared the two extreme schemes in Chapter 3. Also, from this chapter, we see that the difference between conventional OFDM and BT-OFDM is when we perform an $MN$-point IFFT in conventional OFDM, we perform $M \cdot N$-point IFFTs in BT-OFDM instead. By choosing different size of blocks, i.e. different $M$s or $N$s, BT-OFDM can be a very flexible scheme. Let us look at two extreme situations. When $M = 1$, the block size is 1, and $N = MN$ point IFFT is performed, which is exactly the same as conventional OFDM. When $N = 1$, 1-point IFFT will not change the data. In that case, the system is equivalent to the single carrier system. For a given subcarrier number $MN$, if the parameters $M$ and $N$ are properly chosen, the BT-OFDM can reserve the advantages of both two extremes while overcoming their disadvantages, and hence achieves better overall performance.

One of the examples is that BT-OFDM is more power and bandwidth efficient than the conventional OFDM. As we can see from Chapter 3, high PAPR is one of the major disadvantages of the conventional OFDM. But in BT-OFDM, the PAPR is greatly reduced as the IFFT size at the transmitter is $N$ instead of $MN$. How much PAPR can be reduced depends on the block size. The bigger the $M$ is, (in other words, the smaller the $N$ is compared with $MN$), the lower PAPR we can get. For binary phase shift keying (BPSK) or quadrature phase shift keying (QPSK), the PAPR is equal to $N$ and for $2^m$-ary quadrature amplitude modulation (QAM) ($m = 2, 3, 4$) the PAPR is calculated by $3N \frac{2^m - 1}{2^m + 1}$ [37]. Here we set the length of the
data symbols $MN = 128$. Table 4.1 lists the PAPRs under different modulation schemes and IFFT sizes. In this table, the leftmost column ($N = 1$) is equals to the single-carrier, and the rightmost column ($N = 128$) is equivalent to the conventional OFDM. From this table, we can find that for a given $MN$ which is not very long (128 in this example), the PAPR reduction can be as large as 21 dB when $N$ varies from 128 to 1 no matter what modulation scheme is used. This means that the BT-OFDM provides an efficient way to reduce PAPR and thus offers higher power efficiency. In addition, unlike the conventional OFDM, a guard band is no longer necessary to protect the subcarriers near the two sides of the transmitted signal band because the signal energy for each data symbol is spread across $M$ subcarriers. Therefore the bandwidth efficiency is improved because all the subcarriers in the BT-OFDM system can be used to carry data symbols.

<table>
<thead>
<tr>
<th>N</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
<th>32</th>
<th>64</th>
<th>128</th>
</tr>
</thead>
<tbody>
<tr>
<td>BPSK/QPSK</td>
<td>0</td>
<td>3.01</td>
<td>6.02</td>
<td>9.03</td>
<td>12.04</td>
<td>15.05</td>
<td>18.06</td>
<td>21.07</td>
</tr>
<tr>
<td>16-QAM</td>
<td>2.55</td>
<td>5.56</td>
<td>8.57</td>
<td>11.58</td>
<td>14.59</td>
<td>17.60</td>
<td>20.61</td>
<td>23.63</td>
</tr>
<tr>
<td>64-QAM</td>
<td>3.68</td>
<td>6.69</td>
<td>9.70</td>
<td>12.71</td>
<td>15.72</td>
<td>18.73</td>
<td>21.74</td>
<td>24.75</td>
</tr>
<tr>
<td>256-QAM</td>
<td>4.23</td>
<td>4.23</td>
<td>7.24</td>
<td>10.25</td>
<td>13.26</td>
<td>19.28</td>
<td>22.29</td>
<td>25.30</td>
</tr>
</tbody>
</table>

Table 4.1 BT-OFDM PAPRs for different module schemes (in dB)

Fig. 4.7 depicts the frequency domain representation of the BT-OFDM transmitted and received signals for $M = 8$ and $N = 4$, where the overall channel frequency response is $|G(f)|^2$ with 3dB cut-off frequency equal to half of the sampling rate $\frac{1}{T}$.

In the figure, we can see if $|G(f)|^2$ satisfies the Nyquist pulse shaping criterion [43], i.e., $|G(f)|^2 + |G(f - \frac{1}{T})|^2 = 1$ in the overlapped frequency band, the received signal spectrum will be the same as the transmitted signal spectrum. Even though a multipath channel will destroy the Nyquist condition, the protection for the subcarriers on the edges of the transmitted signal band is not necessarily as long as
the overlap band because the overlap band is only a fraction of the total transmitted signal band.

However, the size of the block in BT-OFDM have to be chosen not only based on the PAPR, but also some other factors. For example, when there are impairments such as carrier frequency offset and timing error presenting at the receiver, it has been known to us that the conventional OFDM is robust against timing error but sensitive to carrier frequency offset. On the contrary, the single-carrier system is sensitive to timing error but robust against carrier frequency offset. So by properly choosing the parameter $N$, the proposed BT-OFDM system will be expected to demonstrate a balanced robustness against these impairments. All about these will be analyzed in next chapter.

\[
|y[k]| = |X_n[l]| = lN + n \quad \Delta |X_1[l]| \quad |X_2[l]| \quad |X_3[l]|
\]

![Diagram](image_url)

(a)
Fig. 4.7 Illustration of BT-OFDM frequency domain representation with $M = 8$ and $N = 4$ for (a) transmitted signal and (b) received signal.

4.5 Summary

In this chapter, we introduced our new proposed block transform (BT) OFDM system. We talked about the system signal model in detail. From the system model, we can see that, through the block IDFT (or IFFT), the $MN$ data symbols are grouped into $N$ blocks of size $M$, and each block is precoded or block spread via phase rotation and DFT (or FFT). Meantime, the precoded or spread data symbols are distributed across $M$ equally spaced subcarriers. By exploiting this frequency diversity, we can expect that the BT-OFDM performance in frequency-selective channel will be greatly improved.
When we talked the BT-OFDM system architecture in this chapter, for the receiver end, we mentioned that we did not consider the noise and multipath delay. However in real wireless communications, it is too ideal to consider the system performance without noise and multipath present. Thus, we introduced some additional equalization techniques for our BT-OFDM system. We presented feasible equalization architecture. In the architecture, we employed down-shift, up-shift and some block FFT/IFFT. We chose one-tap equalizer because of its simplicity. We also compared MMSE and Zero-Forcing equalization, and decided to use MMSE in the simulation model because of its advantages.

We also analyzed the peak-to-average power ratio (PAPR) of our BT-OFDM system by comparing different modulate schemes such as BPSK/QPSK, and some $2^m$-ary QAMs with different block size $M$. From this part, we can conclude that by properly choosing the block size, the reduction of the PAPR can be achieved by the BT-OFDM system. After system analysis and simulation in the next two chapters, a possible better performance block size will be chosen.

Last but not least, we illustrated how the BT-OFDM improved the frequency diversity in the frequency-selective channel.
Chapter 5

System Performance of BT-OFDM

5.1 Introduction

In Chapter 4, a new BT-OFDM system has been proposed. The system architecture has been given as well. We also talked about some system properties.

In addition, from the BT-OFDM signal model, we can see that through the block IFFT, the $MN$ data symbols are grouped into $N$ blocks of size $M$, each block is preceded or block spread via phase rotation and FFT, and the precoded or spread data symbols are distributed across $M$ equally spaced subcarriers. By exploiting this frequency diversity, we can expect that the BT-OFDM performance in frequency-selective channel will be greatly improved.

When there are impairments such as carrier frequency offset and timing error present at the receiver, from literature review, we know that the conventional OFDM is robust against timing error but sensitive to carrier frequency offset. On the contrary,
the single-carrier system is sensitive to timing error but robust against carrier frequency offset. The new BT-OFDM is the one sitting in-between those two scheme. So by properly choosing the parameter $N$, the BT-OFDM can be expected to demonstrate a balanced robustness against these impairments.

In this chapter, we will talk about the BT-OFDM system performance with carrier frequency offset and timing error sensitivity, which will include signal-to-noise ratio (SNR) at decision, SNR degradation due to carrier frequency offset, and bit error rate (BER) deterioration. And finally, the system complexity will be talked about as well.

5.2 Signal-to-Noise Ratio (SNR) at Decision

First, we derive the SNRs of the decision variables when there are both carrier frequency offset and timing error considered at the receiver. For simplicity, only an additive white Gaussian noise (AWGN) channel is considered and the assumption that the combined pulse shaping and matched-filtering satisfies Nyquist criterion is made. [43]

We denote the carrier frequency offset between the transmitter and receiver as $\Delta F$, and the effective OFDM symbol duration due to timing error as $P$, $P \leq MN$, in terms of number of samples, which corresponds to a timing error of $MN - P$ samples, the received signal sequence then is modelled as

$$r[i] = y[i]w_p[i]e^{j\omega_d} + v[i],$$  \hspace{1cm} (5.1)

where

$$w_p[i] = \begin{cases} 1, & 0 \leq i \leq P - 1 \\ 0, & \text{otherwise} \end{cases}$$  \hspace{1cm} (5.2)
is a window function of width $P$, 
$$\omega_0 = 2\pi\Delta FT = \frac{2\pi}{MN} \eta \quad (\eta = \Delta FMNT \text{ is the normalized carrier frequency offset with respect to the subcarrier spacing } \frac{1}{MNT}),$$
and $\nu[i]$ is the additive zero-mean Gaussian noise.

From last chapter, we can see that to retrieve the transmitted data symbol $x[nM + m]$, an $N$-point DFT needs to be performed on decimated $r[i]$. This was indicated by (4.18). To be easy to read, we express this equation here:

$$z[nM + m] = \sum_{n'=0}^{N-1} r[n'M + m]e^{-j\frac{2\pi}{N}nM}$$

(5.3)

From (5.1) and

$$y[n'M + m] = \frac{1}{N} \sum_{n=0}^{N-1} x[nM + m]e^{-j\frac{2\pi}{N}nM},$$

(5.4)

the DFT can be expressed as

$$z(nM + m) = \sum_{n'=0}^{N-1} r[n'M + m]e^{-j\frac{2\pi}{N}nM}$$

$$= \sum_{n'=0}^{N-1} y[n'M + m]w_p[n'M + m]e^{j\phi(n'M + m)} e^{-j\frac{2\pi}{N}nM} + \sum_{n'=0}^{N-1} \nu[n'M + m]e^{-j\frac{2\pi}{N}nM}$$

$$= \sum_{n'=0}^{N-1} \frac{1}{N} \sum_{n''=0}^{N-1} x[n''M + m]e^{-j\frac{2\pi}{N}n''} w_p[n'M + m]e^{j\phi(n'M + m)} e^{-j\frac{2\pi}{N}nM} + \sum_{n'=0}^{N-1} \nu[n'M + m]e^{-j\frac{2\pi}{N}nM}$$

$$= e^{j\phi m} \sum_{n''=0}^{N-1} x[n''M + m] \frac{1}{N} \sum_{n''=0}^{N-1} w_p[n'M + m]e^{-j\frac{2\pi}{N}(n'' - n'' - \phi m)} + \sum_{n'=0}^{N-1} \nu[n'M + m]e^{-j\frac{2\pi}{N}nM}.$$ 

(5.5)

We express the window width $P$ as $P = pM + q \quad (0 \leq p \leq N, 0 \leq q \leq M - 1)$, and also define

$$\Theta_p(\omega, m) = \frac{1}{N} \sum_{n''=0}^{N-1} w_p[n'M + m]e^{-j\omega n''}$$
where $\Phi_n(\omega)$ is the normalized Fourier transform of a window function of width $n$ and defined in last chapter by (4.13). Again, we express this question here:

$$\Phi_{n}(\omega) = \frac{\sin\left(\frac{\omega n}{2}\right)}{n \sin\left(\frac{\omega}{2}\right)} e^{-j\omega(n-1)} \tag{5.7}$$

From (5.5), we can obtain the result,

$$z[nM + m] = e^{j\phi_m} \sum_{n'=0}^{N-1} \Theta_{r} \left( \frac{2\pi}{N} (n - n'' - \eta), m \right) x[n''M + m] + \sum_{n'=0}^{N-1} v[n' M + m] e^{-j\frac{2\pi n'}{N}}$$

$$= e^{j\phi_m} \Theta_{r} \left( \frac{2\pi}{N} \eta, m \right) x[nM + m] + e^{j\phi_m} \sum_{n'=0}^{N-1} \Theta_{r} \left( \frac{2\pi}{N} (n - n'' - \eta), m \right) x[n''M + m] + \sum_{n'=0}^{N-1} v[n' M + m] e^{-j\frac{2\pi n'}{N}}. \tag{5.8}$$

We further assume that the receiver can perfectly estimate the phase rotation for each data symbol to be detected. The decision variable for data symbol $x[nM + m]$ is then expressed as

$$d[nM + m] = e^{-j\phi_m} e^{-j\Psi} z[nM + m]$$

$$= \Theta_{r} \left( \frac{2\pi}{N} \eta, m \right) x[nM + m] + e^{-j\Psi} \sum_{n''=0}^{N-1} \Theta_{r} \left( \frac{2\pi}{N} (n - n'' - \eta), m \right) x[n''M + m] + e^{-j\phi_m} e^{-j\Psi} \sum_{n'=0}^{N-1} v[n' M + m] e^{-j\frac{2\pi n'}{N}}. \tag{5.9}$$

Where $\Psi$ represents the phase of $\Theta_{r} \left( \frac{2\pi}{N} \eta, m \right)$. The first on the right hand side of this equation is the useful signal component. The second term represents the ICI due
to carrier frequency offset and timing error. The third term is the noise component and can be denoted as $v'[nM + m]$. Let the signal energy for each data symbol $a[nM + m]$ be $E_s$ and the noise power spectral density be $N_o$. From (5.9), the useful signal power of $d[nM + m]$ is $\Theta_p\left(\frac{-2\pi}{N} \eta, m\right) \frac{E_s}{T}$. Assuming that the transmitted data symbols are independent, the ICI power is then found to be

$$
\sum_{n=0}^{N-1} \sum_{n'\neq n} \Theta_p\left(\frac{2\pi}{N} (n - n' - \eta), m\right) \left(\frac{E_s}{T}\right)^2 
= \sum_{n=0}^{N-1} \Theta_p\left(\frac{2\pi}{N} \eta, m\right) \left(\frac{E_s}{T}\right)^2 + \sum_{n=0}^{N-1} \sum_{n'\neq n} \Theta_p\left(\frac{2\pi}{N} (n - n' - \eta), m\right) \left(\frac{E_s}{T}\right)^2, m = 0, 1, \ldots, q - 1
$$

Both the signal power and ICI power are independent of $n$, and thus the SNR for the decision variable $d[nM + m]$ is finally evaluated as

$$
\gamma_m = \frac{\Theta_p\left(\frac{-2\pi}{N} \eta, m\right) \left(\frac{E_s}{T}\right)^2}{\Theta_p\left(\frac{2\pi}{N} \eta, m\right) \left(\frac{E_s}{T}\right)^2 + \frac{N_o}{T}} 
= \left\{ \begin{array}{ll}
\frac{p + 1}{N} \Phi_{p+1}\left(\frac{-2\pi}{N} \eta\right)^2, & m = 0, 1, \ldots, q - 1 \\
\frac{p}{N} \Phi_p\left(\frac{-2\pi}{N} \eta\right)^2 + \frac{N_o}{E_s}, & m = q, q + 1, \ldots, M - 1
\end{array} \right. 
$$


5.3 SNR Degradation due to Carrier Frequency Offset

In this section, we first consider a special case: when there is no timing error, i.e. $P = MN$. In this case, the SNR in presence of only carrier frequency offset is the same for every decision variable $d[nM + m]$. From the discussion in last section, we get $p = N$ and $q = 0$. Thus, the frequency offset is derived from (5.11) as

$$\gamma = \frac{\Phi_N\left(-\frac{2\pi}{N}\eta\right)^2}{1 - \Phi_N\left(-\frac{2\pi}{N}\eta\right)^2 + \frac{N_0}{E_s}}.$$  \hspace{1cm} (5.12)

Compared with the SNR without carrier frequency offset $\frac{E_s}{N_0}$, the SNR degradation due to carrier frequency offset is defined in dB as

$$D = -10\log\left(\frac{\gamma}{\frac{E_s}{N_0}}\right) = 10\log\left(\frac{1 - \Phi_N\left(-\frac{2\pi}{N}\eta\right)^2}{\Phi_N\left(-\frac{2\pi}{N}\eta\right)^2}\frac{E_s}{N_0} + 1\right).$$  \hspace{1cm} (5.13)

If we set $\frac{E_s}{N_0}$ to 10 dB, the D curves as functions of the transmitter IDFT size $N$ for different normalized carrier frequency offsets are showed in Fig. 5.1. From that, we see that the degradation is always zero for $N = 1$ (corresponding to the single-carrier system) but it increases as $N$ becomes larger. This confirms that the single-carrier system is superior to the conventional OFDM system in terms of SNR.
degradation due to carrier frequency offset. Also, if we choose the proper $N$, such as 2, 4, 8, we still can get improve the degradation compared with the conventional OFDM.

![SNR Degradation vs Transmitter IDFT Size](image)

Fig. 5.1 SNR degradation due to carrier frequency offset as a function of transmitter IDFT size $N$ when $\frac{E_s}{N_0} = 10$ dB.

### 5.4 Bit Error Rate (BER) deterioration

Now, let’s analyse a more complicated situation: when there is also timing error at the receiver, i.e., $P < MN$. Thus $p < N$, and the SNRs of the decision variables will be not only degraded but also unevenly distributed among a block of $M$ decisions.
variables if \( q \neq 0 \). In this case, instead of using the performance measure of SNR degradation, we can evaluate the average BER for all received data symbols to show how the performance is deteriorated against the one without carrier frequency offset or timing error.

Assuming a QPSK modulation at the transmitter, the BER for decision variable \( d[nM + m] \) with SNR \( \gamma_m \) can be evaluated as \( Q(\sqrt{\gamma_m}) \), where the Q-function is defined as

\[
Q(x) = \frac{1}{\sqrt{2\pi}} \int_{x}^{\infty} e^{-\frac{t^2}{2}} dt. \tag{43}
\]

The average BER is then

\[
P_e = \frac{1}{M} \sum_{m=0}^{M-1} Q(\sqrt{\gamma_m}). \tag{5.14}
\]

Fig. 5.2 shows the \( P_e \) curves as functions of the transmitter IDFT size \( N \) under different normalized carrier frequency offsets as well as timing offsets defined as \( MN - P \) for \( \frac{E_s}{N_0} = 10 \text{ dB} \) and \( MN = 128 \). From this figure, we can see that when there is no carrier frequency offset or timing error, i.e., \( \eta = 0 \) and timing offset = 0, the curve in solid line near the bottom represents the baseline BER. Other curves above the baseline mean that there are BER deteriorations. The curves with \( \eta = 0 \) represent the BER deteriorations due to the timing error only, for which the BER is the worst when \( N = 1 \) (corresponding to the single-carrier system) but it gets better as \( N \) increases. Thus, it is confirmed that the conventional OFDM system is superior to the single-carrier system in terms of BER deterioration due to timing error. However, when both carrier frequency offset and timing error are present, i.e. \( \eta \neq 0 \) and offset \( \neq 0 \), better BER performance is achieved when a suitable \( N \) is chosen. For example, when \( \eta = 0.08 \) and the timing offset = 1 or 2, \( N = 2 \) is the most suitable IDFT size.
Fig. 5.2 Average BER due to carrier frequency offset and timing error as a function of transmitter IDFT size $N$ ($\frac{E_s}{N_0} = 10$ dB and $MN = 128$).

5.5 System Complexity

Finally, we evaluate the BT-OFDM system complexity in terms of the number of complex multiplications required for performing FFT/IFFT and up/down shifts under different $M$ and $N$ configurations when the product of $MN$ is given. However, the complexity necessary for frequency domain equalization is not considered since it is the same for a given $MN$ product.
At both the transmitter and receiver, the $N$-point block IFFT/FFT of block size $M$ requires $\frac{1}{2} MN \log_2(N)$ complex multiplications each end for $N>2$ and no multiplications are needed for $N=1$ and 2. Also, for the equalizer model at the receiver, additional complex multiplications are required. For $M$-point block FFT and IFFT of block size $N$, the number of complex multiplications is $MN \log_2(M)$, and $2(M-1)(N-1)$ other multiplications for up and down shifts. Fig. 5.3 shows the complexity as functions of $N$ for transmitter, receiver, and both transmitter and receiver end respectively for a given $MN=128$. From the figure, we see that for small $N$ the complexity is mainly on the receiver side. As $N$ becomes larger, the transmitter complexity is gradually increased. Interestingly, we find that the single-carrier system and the conventional OFDM have the same total complexity with the number of complex multiplications $MN \log_2(MN)$, whereas the BT-OFDM with $N=2$ has the lowest total complexity $MN \log_2(MN) - 2$. 
5.6 Summary

In this chapter, we have discussed BT-OFDM system performance, with carrier frequency offset and timing error presented. We have analyzed SNR at decision, SNR degradation, and BER deterioration. Finally we ended up this chapter by analyzing the system complexity in terms of number of complex multiplications after the whole system including the equalizer was introduced. The complexity was calculated under different block size. Table 5.1 summarizes some of the properties we have discussed in this chapter. When \( N=1 \), the BT-OFDM system is equivalent to single carrier...
system, and when $N=128$, which is also the length of total signal in our analysis, the
BT-OFDM system is the same as conventional OFDM system. From the table, we
can see that BT-OFDM system balances the properties between single carrier system
and conventional OFDM system. We will use Matlab to simulate some other
properties such as PAPR in next chapter. Considering the analysis from this chapter
and next chapter, a possible best block size will be chosen as well.
### Table 5.1: Summary of BT-OFDM Properties Introduced in This Chapter

<table>
<thead>
<tr>
<th>$\eta$</th>
<th>1</th>
<th>2</th>
<th>4</th>
<th>8</th>
<th>16</th>
<th>32</th>
<th>64</th>
<th>128</th>
</tr>
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<tbody>
<tr>
<td>0.02</td>
<td>0.0469</td>
<td>0.0586</td>
<td>0.0615</td>
<td>0.0622</td>
<td>0.0624</td>
<td>0.0624</td>
<td>0.0625</td>
<td></td>
</tr>
<tr>
<td>0.04</td>
<td>0.1851</td>
<td>0.2302</td>
<td>0.2415</td>
<td>0.2443</td>
<td>0.245</td>
<td>0.2451</td>
<td>0.2452</td>
<td></td>
</tr>
<tr>
<td>0.06</td>
<td>0.4072</td>
<td>0.5037</td>
<td>0.5275</td>
<td>0.5335</td>
<td>0.5349</td>
<td>0.5353</td>
<td>0.5354</td>
<td></td>
</tr>
<tr>
<td>0.08</td>
<td>0.7024</td>
<td>0.8628</td>
<td>0.9021</td>
<td>0.9119</td>
<td>0.9143</td>
<td>0.9149</td>
<td>0.9151</td>
<td></td>
</tr>
</tbody>
</table>

**SNR Degradation (dB) Due to Carrier Frequency Offset, $E_s / N_0 = 10$ dB**

**BER Deterioration Due to Carrier Frequency Offset and Timing Error**

<table>
<thead>
<tr>
<th>Timing Offset</th>
<th>$\eta$=0</th>
<th>$\eta$=0.08</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.0078/27</td>
<td>0.00078/27</td>
</tr>
<tr>
<td>1</td>
<td>0.0047/685</td>
<td>0.00086/234</td>
</tr>
<tr>
<td>2</td>
<td>0.0086/659</td>
<td>0.00092/198</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.0012</td>
</tr>
</tbody>
</table>

**Complexity**

|     | 896 | 894 | 1082 | 1106 | 1106 | 1082 | 1022 | 896 |

Table 5.1 Summarizes of BT-OFDM Properties Introduced in This Chapter.
Chapter 6

System Simulation and Implementation

6.1 Introduction

In previous chapters, we have proposed a new Block Transform OFDM scheme. We introduced the BT-OFDM system model, both transmitter and receiver. We also analyzed the system performance, and explained how the BT-OFDM system sit in-between conventional OFDM system and single carrier system. Considering the noise and multipath, equalization method was also proposed. We have predicted that the BT-OFDM system can balance between conventional OFDM system and single carrier system thus improves some of the conventional OFDM system’s well-known drawbacks.

In this chapter, we will demonstrate some Monte Carlo simulations in Matlab to confirm those advantages and demonstrate different estimated performance properties
by comparisons with different block sizes. The system models we use to simulate have been discussed in Chapter 4. And also we will apply the very first step of implementing of a BT-OFDM system over the universal software radio peripheral (USRP) hardware.

This chapter is organized as follows. First, we are going to analyze the peak to average power ratio (PAPR). Then we will provide the BER performance comparisons among different block size with different equalization scheme – zero force (ZF) and minimum mean squared error (MMSE), and different multipath. Last but not least, we will transmit a BT-OFDM signal using the USRP hardware.

### 6.2 Peak to Average Power Ratio

OFDM technique has attracted significant attention due to its simple implementation by employing the IFFT operation and its extended symbol duration to combat ISI. However, one of the major disadvantages is the high peak-to-average, which makes the system implementation costly and inefficient.

The cause of a high PAPR in conventional OFDM system is partially related to how the OFDM signal is formed. We’ve already analyzed this issue in Chapter 3. However, when compared to the single carrier system, PAPR is not a problem at all in single carrier system. Recall Chapter 4, Table 4.1 listed the different block size BT-OFDM PAPR. We can find that the closer to the single carrier, meaning the smaller the $N$ is, the lower PAPR the system gets. In this section, we are going to confirm this by simulating an $MN=128$ length of QPSK mapped data stream. The PAPR can be obtained as:

$$\xi = \frac{\max|y(t)|^2}{E|y(t)|^2},$$  \hspace{1cm} (6.1)
where \( y(t) \) is time domain samples of the transmitted signal, in our scenario, the modulated BT-OFDM signal, \( \max |y(t)|^2 \) is the maximum instantaneous power and \( E|y(t)|^2 \) is the average power. We choose different block size \( N = 1, 2, 4, 8, 16, 32, 64, \) and 128. As the total length of the signal is 128, based on the definition of BT-OFDM, \( N = 1 \) is equivalent to the single carrier system, and \( N = MN = 128 \) is equivalent to the conventional OFDM. Fig. 6.1 shows the PAPR performance of the BT-OFDM transmitted signal when PAPR exceeds a certain threshold \( \text{PAPR}_0 \) with the different block size \( N \) from 1 to 128.

![PAPR performance](image)

**Fig. 6.1 PAPR performance for BT-OFDM signals with different block size**

It can be seen from the figure that the smaller the block size \( N \) is, the better PAPR performance is achieved. The extreme case \( N = 1 \) (the most-left-side curve, same as single carrier system) has the best performance and \( N = 128 \) (the most right-hand-side
curve, same as conventional OFDM) has the worst performance. By choosing smaller block size $N$, the PAPR is significantly decreased.

### 6.3 Bit Error Rate Performance

No matter what equalization method is used, the output SNR is determined by the channel frequency response $H[k]$. In all our simulations, we are going to use the QPSK modulation for data symbols. When we make a Gaussian distribution approximation for ISI, the bit error probability of the equalizer for a realization of the channel impulse response can be evaluated as $\sum_{n=0}^{N-1} Q(\sqrt{\gamma[n]})$ [43], where the output SNR $\gamma[n]$ can be $\gamma_{\text{mmse}}[n]$ or $\gamma_{\text{prac}}[n]$ depending on what equalization method is used. $\gamma_{\text{mmse}}[n]$ and $\gamma_{\text{prac}}[n]$ have been shown in (5.24) and (5.28) in last chapter respectively. Also we assume that the channel impulse response has $L$ independent paths, each of which is modelled as an independent complex Gaussian process, the average BER for such frequency-selective fading channels then can be evaluated as

$$P_e = E_{h} \left\{ \frac{1}{N} \sum_{n=0}^{N-1} Q(\sqrt{\gamma[n]}) \right\}, \quad (6.2)$$

where $E_{h}(\{\})$ denotes the ensemble averaging over all possible $h[i]$. 

To show the BT-OFDM performance potential, we work out three sets of simulations. The first set represents the performance for a given block size $M$ using MMSE equalizer. We consider the same number of channel multipath $L = 32$ for all different block size $M$.

Table 6.1 gives out all the parameters used in this simulation. The results are shown in Fig. 6.2. From the figure, we can easily see that the performance improves as $M$ increases. Also we notice that when $M = 1$, $N = MN/M = 128$ is equal to the
conventional OFDM system; and $M = 128$, $N = MN/M$ is equivalent to single carrier system. In the figure, apparently the conventional OFDM system shows the worst BER performance and the single carrier system shows the best. However, when $M = 64$, in other words, $N = 2$, the performance is very close to best performance.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapping Method</td>
<td>QPSK</td>
</tr>
<tr>
<td>Channel Diversity Degree</td>
<td>$L = 32$</td>
</tr>
<tr>
<td>Block Size</td>
<td>$M = 1, 2, 4, 8, 16, 32, 64, 128$</td>
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<tr>
<td>Number of Data Length</td>
<td>$MN = 128$</td>
</tr>
<tr>
<td>Number of Simulation Runs</td>
<td>100000</td>
</tr>
<tr>
<td>Equalization Method</td>
<td>MMSE</td>
</tr>
</tbody>
</table>

Table 6.1 Parameters used for BER simulation using MMSE equalization with given block size $M$ under a fixed channel diversity degree $L = 32$. 
Fig. 6.2 BER simulation using MMSE equalization with given block size $M$ under a fixed channel diversity degree $L = 32$.

As a comparison, in the second simulation set, we simulate a ZF equalization performance with all other parameters the same as above. Table 6.2 shows all the parameters. The simulation results are shown in Fig. 6.3.
<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mapping Method</td>
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<tr>
<td>Channel Diversity Degree</td>
<td>$L = 32$</td>
</tr>
<tr>
<td>Block Size</td>
<td>$M = 1, 2, 4, 8, 16, 32, 64, 128$</td>
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<td>100000</td>
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<tr>
<td>Equalization Method</td>
<td>ZF</td>
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Table 6.2 Parameters used for BER simulation using ZF equalization with given block size $M$ under a fixed channel diversity degree $L = 32$.

We’ve already discussed why we choose MMSE equalization but not ZF equalization in Chapter 5. Comparing with Fig. 6.2 and Fig. 6.3, we also can find out that with ZF equalization, the BT-OFDM system achieves much worse BER performance compared with MMSE equalization. However, the trends that the system achieves better BER performance with the increase of the block size $M$ are the same.

The third set we are going to simulate represents the performance for different channel diversity degrees $L = 1, 2, 4, 8, 16, 32, 64, 128$ using MMSE equalizer. The length of symbols is still $MN = 128$ as other two sets. This time we set a fixed block size $M = 64$, e.g. $N = MN/M = 2$. The parameters used in this set are shown in Table 6.3 and the performance results are presented in Fig. 6.4.
Fig. 6.3 BER simulation using ZF equalization with given block size $M$ under a fixed channel diversity degree $L = 32$.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Mapping Method</td>
<td>QPSK</td>
</tr>
<tr>
<td>Channel Diversity Degree</td>
<td>$L = 1, 2, 4, 8, 16, 32, 64, 128$</td>
</tr>
<tr>
<td>Block Size</td>
<td>$M = 64$</td>
</tr>
<tr>
<td>Number of Data Length</td>
<td>$MN = 128$</td>
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<tr>
<td>Number of Simulation Runs</td>
<td>100000</td>
</tr>
<tr>
<td>Equalization Method</td>
<td>MMSE</td>
</tr>
</tbody>
</table>

Table 6.3 Parameters used for BER simulation using MMSE equalization with given channel diversity degree $L$ under a fixed block size $M = 64$.  

85
From this figure, we can see that the BER performance is getting better along with the increase of the channel diversity degree. And the yellow curve (the third from left) is the same as the black curve (the second from left) in Fig. 6.2 because they have exactly all the same parameters.
6.4 USRP Implementation

6.4.1 Introduction

The Universal Software Radio Peripheral (USRP) is a high-speed USB based board for making software radios developed by team led by Matt Ettus [100]. A photo of USRP hardware is shown in Fig. 6.5. Software-defined radio (SDR) refers to reconfigurability at any level of the radio protocol stack by software either by over-the-air (OTA) download or by other means, together with an acknowledgement that some signal processing, including analog-to-digital (A/D) conversion at the antenna, will continue to be done in RF circuitry [101]. There are various daughter boards can be used for USRP firmware, even including own-designed ones. However, we are going to use the RFX2400 daughter board in this project because it works on 2.4 GHz ISM band which shares the same characteristics with the widely popular 802.11(b/g), Bluetooth and WiMAX systems.

In this section, we are going to use USRP to transmit some test signals along with our BT-OFDM modulated signal. However, there are a lot of further research can be done in the receiver, which are very complicated and not included in my project. Thus, we only transmit a BT-OFDM, and show the received signal from the receiver, and give out some possible future study on this topic.
6.4.2 Implementation

Using the BT-OFDM scheme, first the signal is generated. The input data was firstly mapped by QPSK. No matter how long the data stream is, it is divided into the size of 1024. The size can be any $2^n$ ($n$ is any positive integer) to make it easier to group and apply block IFFT and block FFT without add any zeroes. In each sub stream of size 1024, the data stream is then grouped into smaller blocks for BT-OFDM depending on the block size been chosen. Fig. 6.6 depicts the base band modulated signal for the same QPSK mapped data stream under different block size. In other words, different block IFFTs are applied. $N=1$ is equivalent to the original stream and for all other $N$s, a cycle prefix of $\frac{1}{4}$ length has be added respectively as well. From the figure we can
see that once the \( N \) increases the waveforms look more like conventional OFDM. When \( N = 1024 \), which is the length of the signal, it is the same as applying a conventional OFDM.

![Graphs showing waveforms for different values of \( N \)]

- a. \( N=1 \)
- b. \( N=2 \)
- c. \( N=4 \)
- d. \( N=8 \)
- e. \( N=16 \)
- f. \( N=32 \)
g. $N=64$.

h. $N=128$.

i. $N=256$.

j. $N=512$.

k. $N=1024$

Fig. 6.6 The baseband waveforms of BT-OFDM signal under different block sizes

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By choosing any of the block size, for example, $N = 2$, as our BT-OFDM modulating method, a long QPSK mapped data stream (102400 symbols) is firstly divided into smaller groups of size 1024. After a block IFFT modulation as discussed in Chapter 4, a cycle prefix of $\frac{1}{4}$ lengths, e.g. 256 in this case is added in front of each group. The transmitted signal is formed by all the groups together and an example of the transmitted signal is shown in Fig. 6.7. The zoomed-in of this data stream is similar to Fig. 6.6 (b). The whole stream is then added with a stream of zeros and repeats for a few times. This is because it is not real-time signal processing when I implement the transmission, and we handle the receiver manually, thus it is unknown when exactly the receiver starts to receive data. By repeating the bursts a few times, we can easily choose a period in which the whole stream is captured. Also, another benefit to deploy a silence space (zeros) is that the noise energy estimation for signal-to-noise ratio calculations can be evaluated. In our case, it does not matter much because we use a cable to connect with the transmitter and the receiver as an ‘ideal’ channel. The real transmitted stream and received signals are shown in Fig. 6.8 and Fig. 6.9, respectively.

![Fig. 6.7 A BT-OFDM transmitted signal waveform of $N = 2$](image-url)
In the received signal, each block represents one whole stream from Fig. 6.7. We end the implementation part here and leave the rest for further study. As we can see from the Fig. 6.7, even with a cable transmission, there are still a lot of distortions on the
received signal. This can be seen clearer in our test implementation which is shown in Fig. 6.10 with a stairs waveform. These distortions will affect the decision of the receiver once the received signal spreads into different levels instead of the constant steps in this stair waveform. Another issue we encounter is that there is periodic phase shift in the receiver which makes the signal combined with both real and image parts hard to decide. In our test, we simply transmit the real part and image part separately, and apply an absolute calculation to get the power at the receiver and reconsider the polarity. Then, plus the real part and the image part back together. Other improvements worth further research can be studied but not limited to include synchronization for real-time signal process, equalization design for wireless channels using antenna, combined with MIMO.

Fig. 6.10 A test transmission of a stair waveform for USRP.

6.5 Summary

In this Chapter, we have investigated system performance with the Monte Carlo simulations. All the simulations are presented in detail in terms of introducing the useful parameters. We have discussed the transmission signal PAPR, system BER performance with different environment such as different equalizers (ZF and MMSE)
and under different diversity. All these simulations have been performed with different block size, from one extreme (single carrier system) to another extreme (conventional OFDM). Together with other performance measures we have discussed in previous chapters, such as system complexity, sensitivity for carrier frequency offset and timing error, and so on, we can see that the transmitter block IFFT size $N = 2$ (e.g. Block size $M = 64$ for a given $MN = 128$ in our simulations) seems to be the best option for the BT-OFDM system. This is also the reason why we choose $N = 2$ for BT-OFDM in hardware implementations.

We end up this chapter and also this thesis by implementing the very first step of a BT-OFDM signal transmission over a USRP hardware system. This can be the start of the further research on the BT-OFDM. We presented the transmitted and received signal waveforms, and the issues we encountered during the implementation and also the possible improvements which can be developed on further work. Those improvements include but not limit to the synchronization of real time transmission for continual signal (both real and image parts), eliminate of distortion and phase shift, equalization design, MIMO application for BT-OFDM and so on.
Chapter 7

Contribution and Future Work

7.1 Contribution

The contribution of this thesis is to propose a new block transform OFDM (BT-OFDM) system design. The conventional OFDM is a multicarrier modulation technique of delivering high data rates with strong resistance to ISI. Thus, it has been widely used in today’s digital communication systems. However, it also suffers from some well-known disadvantages. Comparing with conventional OFDM and single carrier system, we find that those two systems are complementary and often represent two extremes when evaluating the system performance on aspects such as PAPR, equalization complexity, carrier frequency offset sensitivity, and frequency diversity. The idea of the BT-OFDM is to find a new transmission scheme which sits in-between the conventional OFDM and single carrier system and optimizes the system
performance. The BT-OFDM achieves this goal by grouping the original data symbol into \( N \) blocks. Instead of applying an \( MN \) (the length of the data symbol) point IFFT/FFT to the whole data stream, the BT-OFDM applies \( M \ (M = MN/N) \) \( N \)-point IFFT/FFTs. As analyzed and simulated, the BT-OFDM system has bridged the two extreme transmission – the conventional OFDM and single carrier system. It removes the disadvantages of the conventional OFDM but still enjoys the benefits offered by multicarrier transmission. The BT-OFDM has advantages over the conventional OFDM systems by properly choosing the block size. They are described as follows.

1. PAPR in the BT-OFDM system is greatly reduced. Since the IFFT size at the transmitter is \( N \) instead of \( MN \). A lower PAPR means more energy efficiency. However, the BT-OFDM has another advantage to achieve energy efficiency as well. Considering the way the block transmission symbols are formed, the signal energy for each data symbol is spread across \( M \) subcarriers. Thus, a guard band is no longer necessary to protect the subcarriers near the two sides of the transmitted signal band. Therefore, all the subcarriers in the BT-OFDM system can be used to carry data symbols.

2. When both carrier frequency offset and timing error are present, by choosing a suitable \( N \), (in our analysis, 2, 4, or 8) better BER performance is achieved in BT-OFDM.

3. The BT-OFDM performance in frequency-selective channel is greatly improved. This can be achieved because the BT-OFDM system implicitly achieves the effect of data symbol spreading across subcarriers in frequency domain. Through the block IFFT, after \( MN \) data symbols are grouped into \( N \) blocks of size \( M \), each block is precoded or block spread via phase rotation and DFT, and the precoded or spread data symbols are distributed across \( M \) equally spaced subcarriers.
Monte Carlo simulations have been performed to simulate the whole BT-OFDM system performance. These simulations prove our expectation from the new system. Considering all the performance measures and analysis, we find that \( N = 2 \) is the best choice when we decide the block size.

In the end, we have applied the first stage of the BT-OFDM system implementation in USRP hardware. A long BT-OFDM symbol stream have been generated and transmitted through a cable which connects the transmitting and the receiving hardware.

### 7.2 Future Work

The work presented in this thesis has opened up some possible areas for ongoing research. In this section, a brief discussion about some of these topics is presented.

1. Higher order modulation schemes such as 16QAM and 64QAM can be conducted to demonstrate the performance of the proposed scheme comprehensively. Coded systems can also be considered as frequency diversity for OFDM systems is obtained via coding and decoding.

2. The BT-OFDM can be applied with MIMO. When grouping the data symbols into small blocks and applied block IFFT, MIMO can be considered for the transmission.

3. In hardware implementation, the synchronization for real-time signal process needs to be considered. Also the decision method and a sound equalization method need to be designed for wireless channels. The comparisons with conventional systems can also be simulated in USRP hardware.
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