Title: MIMO block spread OFDMA system for next generation mobile communications

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# MIMO block spread OFDMA system for next generation mobile communications

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# MIMO Block Spread OFDMA System for Next Generation Mobile Communications

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

Master of Engineering by Research

from

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by

Yiwei Yu
Master of Engineering Studies

School of Electrical, Computer and Telecommunications Engineering

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# Statement of Originality

I, Yiwei Yu, declare that this thesis, submitted in partial fulfilment 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.

Yiwei Yu

March 26, 2008

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# Acronyms

**1G** First-generation

**2G** Second-generation

**3G** Third-generation

**4G** Fourth-generation

**AWGN** Additive white Gaussian noise

**BER** Bit error rate

**BPSK** Binary phase shift keying

**BS-OFDM** Block spread OFDM

**BS-OFDMA** Block spread orthogonal frequency division multiple access

**CDMA** Code division multiple access

**CP** Cyclic prefix

**DFE** Decision feedback equalizer

**DFT** Discrete Fourier transform

**DMB** Digital multi media broadcasting

**DVB** Digital video broadcasting

**DVB-C** DVB-cable

**DVB-H** DVB-handheld

**DVB-S** DVB-satellite television and satellite Internet

**DVB-T** DVB-terrestrial

**EC** Eurppean Commission

**FFT** Fast Fourier transform

**FWA** Fixed wireless access

**GSM** Global system for mobile communications

**HAP** High altitude platforms

**ICI** Inter-carrier interference

**IFFT** Inverse fast Fourier transform

**ISDB** Integrated services ditial broadcasting

**ISDB-C** ISDB-cable

**ISDB-S** ISDB-satellite television

**ISI** Intersymbol interference

**M2M** Machine-to-machine

**MAC** Media access control

**MAGIC** Mobile multimedia; Anytime, anywhere, anyone; Global mobility support; Integrated wireless solution; and Customized personal service

**MC-CDMA** Multicarrier CDMA

**MC-DS-CDMA** multicarrier direct sequence CDMA

**MIMO** Multi-input and multi-out

**MISO** Multiple input and single output

**MLSE** Maximum likelihood sequence estimator

**MMSE** Minimum mean square error

**M-PSK** M phase shift keying

**M-QAM** M quadrature amplitude modulation

**NLOS** non-line-of-sight

**OFDM** Orthogonal frequency division multiplexing

**OOB** Out of band

**PAN** Personal area network

**PAPR** Peak to average power ratio

**PHY** Physical layer

**PN** Pesudo-noise

**P/S** Parallel to serial

**QoS** Quality of service

**QPSK** Quadrature phase shift keying

**SNR** Signal to noise ratio

**S/P** Serial to parallel

**SS** Spread spectrum

**STBC** Space-time block coding

**STC-MIMO** Space-time coded MIMO

**STTC** Space-time trellis coding

**TCM** Trellis-coded modulation

**TD-SCDMA** Time division synchronous CDMA

**UMTS** Universal Mobile Telecommunication system

**WCDMA** Wideband CDMA

**W-CPN** Wireless customer premise network

**WiMAX** Worldwide interoperability for microwave access

**W-LAN** Wireless local area network

**WLL** Wireless local loop

**ZF** Zero-forcing

# Abstract

Wireless communications are developing at a booming speed, with plenty of research emerging on the next generation wireless communications. This thesis presents an advanced system for the next generation wireless communications. The proposed system is called block spread OFDMA combined with STC-MIMO (STC-MIMO BS-OFDMA). The system is based on OFDM, which is able to deliver high data rates in highly dispersive channels and is thereby considered as a good candidate of modulation techniques for 4G. The block spreading technique and STC-MIMO scheme are used to provide the system with frequency and spatial diversity, therefore significantly improving system performance.

In this system, there are two stages to combine block spreading and STC-MIMO with OFDMA. Firstly, a novel block spreading approach is applied to effectively achieve frequency diversity in the OFDMA system without any explicit precoding process. The STC-MIMO using Alamouti code is then incorporated on block basis and performs in space and frequency. Accordingly, the signal model and architectures of the proposed system are presented. Two receiver architectures are designed for different STC-MIMO schemes: the receiver with one antenna and receiver with two antennas.

Simulations are carried out to demonstrate the expected performance improvement. The BER performance comparisons indicate that the proposed system can achieve significant performance improvement. The research project also investigates the system performance when different parameters are used. Our results show that using a larger block spreading size and more receive antennas can further improve system performance because of higher order of diversity advantages. In terms of linear equalizations, the MMSE equalization achieves better performance than the ZF equalization.

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# Chapter 1

# Introduction

Wireless communications are developing at an outstanding speed, with novel techniques emerging in all the fields of mobile communications and wireless networks. Currently, we are near the end of third-generation (3G) standardization phase and the beginning of 3G deployment. Compared to second-generation (2G), 3G is better but not sufficient as many problems are only partly solved. Therefore, the limitations of 3G drive for the start of the research on fourth-generation (4G), which is also considered as the next generation wireless communications.

Briefly speaking, the main idea of 4G is to provide broader bandwidth, higher data rate, wider coverage, and lower cost, etc. The 4G topics are becoming hotter and there is plenty of related research on 4G wireless communications. Many advanced techniques are presented to be possible candidates for use in the 4G wireless communication systems. For example, orthogonal frequency division multiplexing (OFDM) and multi-input and multi-output (MIMO) antennas are two powerful techniques that have been considered to best meet the requirements of 4G.

OFDM is chosen over a single carrier solution due to lower complexity of equalizers for high delay spread channels or high data rates [1]. MIMO takes advantage of the multipath diversity obtained by spatially separated antennas. The combination of OFDM and MIMO is very attractive because MIMO channel becomes frequency selective for high data rate transmission and OFDM can transform such a frequency selective MIMO channel into a set of parallel frequency flat MIMO channels, therefore decreasing receiver complexity [1, 2].

Although MIMO-OFDM is considered as a fundamental structure for 4G systems, there are other advanced techniques that can be corporately used to further improve system performance. For example, in order to minimize the effect of frequency selective fading channels for OFDM systems, block spreading technique is introduced and consequently an advanced system named block spread OFDM (BS-OFDM) system is proposed. Our research primarily focuses on proposing an advanced multiple access system based on MIMO-OFDM and block spreading, where unique system transceiver architectures are designed and correspondingly related theories and signal processing algorithms are developed as well.

## 1.1 Research objectives

The aim of this research is to develop a block spread orthogonal frequency division multiple access (BS-OFDMA) system with MIMO for next generation wireless communications. The specific objectives are as follows:

1. Design system architectures for signal generation and reception;
2. Develop transmitter algorithms for block spreading, OFDMA modulation and MIMO implementation;
3. Develop receiver algorithms for channel equalization, diversity combining and

despreading;

4. Analyse signal's spectral and temporal characteristics;

5. Build a multiuser communication simulation system, including the frequency selective multipath fading channel modelling; and

6. Conduct a comprehensive performance evaluation and comparison to demonstrate the anticipated improvement of the proposed system.

As we may realize, the idea of incorporating block spread and MIMO with OFDM to improve system performance is attractive and there are many related research works on this topic. However, most approaches use explicit precoding processes to address such a combination between block spread, MIMO and OFDM. For those approaches, performance improvement is obtained at the cost of increased system complexity. In our project, we aim to explore approaches to efficiently combine block spread and MIMO with OFDM without any explicit precoding processes required. Therefore, our proposed MIMO BS-OFDMA system involves two major aspects: (i) improving system performance; (ii) reducing system complexity. First, we develop an approach to effectively combine the block spread with OFDMA modulation to lower system complexity. Second, the space time encoding for MIMO is incorporated to exploit spatial diversity. Then a corresponding receiver model and decoding algorithms are developed, including channel equalization, space time decoding and block despreading. Finally, simulations are carried out to confirm the expected performance improvement.

In our project, we plan to address the following research questions:

1. What modifications can we make to improve OFDM system's performance?

2. How to implement the proposed MIMO BS-OFDMA system?
3. What is the advantage of the proposed system over other OFDM systems with block spread and/or MIMO?
4. What improvement can the proposed system provide?

## 1.2 Thesis organization

This thesis consists of six chapters. Most chapters contain an introduction section and a summary section. Brief contents of the chapters are as follows.

- **Chapter 1** introduces the research project and its objectives. The research contributions and publication are also included in this chapter.
- **Chapter 2** presents an overview of the next generation wireless communications. In this chapter, we discuss the evolution road on wireless communications with the emphasis on the background information that is related to 4G.
- **Chapter 3** discusses some techniques to improve OFDM systems. OFDM is considered as an excellent candidate for 4G, although it has some drawbacks. In this chapter, we first briefly review the drawbacks of OFDM and then introduce some techniques that are used popularly for the improvement of OFDM systems.
- **Chapter 4** proposes a block spread OFDMA system with a combined space-time coded MIMO scheme for transmission over frequency selective fading channels. The system is called STC-MIMO BS-OFDMA system. In this chapter, a transmitter model is presented, which includes the implementation of

block spreading, OFDMA modulation and STC-MIMO encoding. A corresponding receiver model and decoding algorithms are then presented, which includes channel equalizations, STC-MIMO decoding and block despreading.

- **Chapter 5** describes the system performance simulations and consequently provides the simulation results. We assess the system performance on numerous simulation comparisons between the proposed system and other schemes. Comparison experiments of the proposed system with different parameters are also conducted.

- **Chapter 6** summarises the research activities and gives the concluding remarks.

## 1.3 Contributions

The main contributions of this thesis can be listed as follows:

- We propose a new system for the next generation wireless communications. The system involves the currently hottest techniques such as OFDM and MIMO.

- We develop an approach to effectively combine block spreading technique with OFDMA modulation. This approach uses a complex spreading sequence to simultaneously implement block spreading and OFDMA modulation instead of separately using spreading matrices for block spread and inverse fast Fourier transform (IFFT) for OFDMA. Thus, the system does not require any explicit precoding processes and IFFT, which greatly reduces the computation complexity.

- We incorporate the Alamouti code with block spread OFDMA modulation to perform STC-MIMO characteristics in the frequency domain. The system with two transmit antennas and one receive antenna is emphasized as a simple demonstration example.

- We extend the MIMO scheme from two transmitters and one receiver to two transmitters and two receivers. In addition, a general model for MIMO with two transmitters and multiple receivers is also derived.

- We compare the proposed system to OFDMA system, OFDMA system with block spread and OFDMA system with MIMO. The proposed system achieves the best bit error performance.

- We investigate the system performance when different linear equalizations are used. The minimum mean square error (MMSE) equalization is more preferable than the zero-forcing (ZF) equalization.

## 1.4 Publication

One publication arises from the work in this research project, which took place from August 2006 to March 2008.

- Y. Yu, X. Huang and E. Dutkiewicz, 'Block spread OFDMA system with space-time coded MIMO over frequency selective fading channels', *The Third International Conference on Communications and Networking in China*, Hangzhou, 2008. Submitted on February 15, 2008 and accepted on May 12, 2008.

  This paper proposes a BS-OFDMA system with a combined space-time coded MIMO (STC-MIMO) scheme called STC-MIMO BS-OFDMA for transmission over frequency selective fading channels. In this system, a novel block spreading approach is firstly applied to effectively achieve precoding in the OFDMA system with lower complexity for improving the frequency diversity performance. The STC-MIMO is then incorporated to take advantage of the spatial diversity. The signal model and architecture of the proposed system are presented, and simulations are carried out to confirm the expected performance improvement.

# Chapter 2

# Overview of 4G

4G is the next generation of wireless communication networks that will replace the current core cellular networks in the future. The principal objectives of 4G are the delivery of high speed, large capacity, low cost and efficient bandwidth usage. But since 3G has not completely developed in practice yet, 4G, at present, exists only in plenty of conceptual research works and may become operational by around 2010 [3]. This chapter gives an overview of 4G, including the evolution history from 1G to 4G, the characteristics and key technologies for 4G and its standardization trends.

This chapter is organized as follows. The evolution of wireless communications from 1G towards 4G is introduced to start this chapter. Several technologies are then described to modulation technologies for 4G systems. At last, two examples of standardization trends of 4G applications are presented.

## 2.1 Evolution towards 4G

Wireless communication has been noticed currently as one of the hottest areas that are developing at a booming speed. Numerous advanced technologies have emerged in this field to meet the continuously increased demand of users, with an evidence of significant growth of services and applications on mobile and wireless access networks. While the 3G wireless communication system is beginning to be widely deployed around the world at current time as a main standardization of high-speed data communications, research on the 4G system are emerging and becoming more and more attractive. It has received a great amount of attention from both research communities and industry vendors in the field of telecommunications [4]. The goal of the 4G wireless communication is to provide higher data rate and more reliable services including video, audio, data and voice signals with worldwide compatibility [5]. In other words, the ultimate goal of 4G is to communicate any type of information with anyone, at anytime, from anywhere. Before we introduce the 4G as a future system, we will first take a brief review on the development history of wireless communcations from the first-generation system to the current 3G system.

### 2.1.1 History of wireless communications

The 1G radio system was using analogue technology to transmit voice signals in the 1980s [6]. The speech transmission was the only service of 1G. Though it is not a promisng wireless communication system in terms of efficiency and capacity, 1G developed the principles and established the basic structure of wireless communications, e.g. cellular architecture adopting, multiplexing frequency band, roaming across domain, non-interrupted communication in mobile circumstances, etc [6].

The 2G system was built in the 1980s and 1990s, and based on digital signal processing techniques [6]. The global system for mobile communications (GSM) is the most successful representative of 2G systems, which is widely used even in today's wireless communcations market. The 2G system works well for voice transmission, however, it cannot support the further demanding of services for higher data rate and more bandwidth, such as multimedia, massive file transfer and streaming video.

The 3G wireless system, therefore, was presented to provide users with high data rate wireless access of 2 Mb/s for fixed users, 384 kb/s for low mobility users and 144 kb/s for high mobility users [7]. Due to its contributions of data rate increase and transfer performance improvement, 3G has developed rapidly in the 1990s and is still developing today. The three major representative standards for 3G are wideband code division multiple access (WCDMA), time division synchronous CDMA (TD-SCDMA), and CDMA2000 [8]. However, there are several limitations with 3G. The major one is the difficulty in continuously providing a high data rate transmission to meet multimedia services requirements due to excessive interference between services. Therefore, the future wireless communication system is expected with respect to the development trend that higher data rate, extended coverage and more reliable transmission are demanded on broadband wireless communcations.

Table 2.1 summarizes the entire development of wireless communications from the first generation to 3G with the properties of each generation including starting time, driven technique, representative standard, radio frequency, bandwidth, multi-address technique, cellular coverage, core networks, and service type.

### 2.1.2 4G features

The key objective of 4G is to provide reliable transmission with high peak data rates ranging from 100 Mb/s for high mobility applications to 1 Gb/s for low mobility applications, high spectrum efficiency up to 10 b/s/Hz, and ubiquitous services that can accommodate various radio accesses [2]. Different 4G feature frameworks have been defined from the different perspectives of service providers, researchers and

Table 2.1: Mobile communication history and status [6].

Please see print copy for Table 2.1

engineers. In the following some representatives are given.

DoCoMo introduced the concept of MAGIC for the vision of 4G [6, 9]: Mobile multimedia; Anytime, anywhere, anyone; Global mobility support; Integrated wireless solution; and Customized personal service. It mostly focused on public systems and treated 4G as the extension of 3G cellular service.

European Commission (EC) presented a different 4G perspective [10]. Besides the need for meeting the rapid growth in the demand for broadband wireless connectivity, it focused on ensuring seamless service across a multitude of wireless systems and network, from private to public, from indoor to wide area, and providing a optimum delivery via the most efficient network available. The proposed system is particularlly to deal with the expected growth in machine-to-machine (M2M) internet based communications: wireless low power sensors and actuators, internet applications, and myriad of smart devices, capable of monitoring and interacting with the physical world. On [10–14], further discussions were presented around 4G concepts on private systems and ad-hoc networks, optimal resource utilization, multiple radio interfaces, wireless local area network (W-LAN) use, standards for interoperability, etc.

Another perspective of 4G comes from the German VDE [15]. In their vision, focus is not only on public systems, but also on private W-LANs and wireless customer premise networks (W-CPN). Self-organizing ad hoc networks are specifically identified as the portable radio systems of the fourth generation, and with them embedded systems are expected to explode.

A broader, all encompassing perspective of 4G was proposed by M. Pereira, according to whom the focus of 4G is particullarly on the user rather than on the operators of network providers. The integrated 4G system was illustrated in [16] that the broad range of systems was encompassed, from satellite broadband to High Altitude Platforms (HAP), to cellular 2G and 3G systems, to MBS, to Wireless Local Loop (WLL) and Fixed Wireless Access (FWA), to W-LAN, Personal Area Networks (PAN) and Body-LANs. 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.

Table 2.2 is presented as a summary of 4G perspectives, which is a continuum of Table 2.1 with visions of 4G features.

Table 2.2: 4G visions summary [6].

| |
|---|
| Please see print copy for Table 2.2 |

## 2.2 Modulation techniques for 4G

The first section starts with a generic overview of the wireless communication development. We describe the evolution trend and realize 4G as the representative of the next generation wireless communication system expected to offer high data rate applications. Several standardizations of 4G systems based on different perspectives have been introduced as well. Yet there are lots of technical issues that we have not taken into account. To be successfully implementing 4G systems on practise, only generic standardizations or concepts are fairly not enough, but, more importantly, the new technologies of advanced communication methods are desired to be proposed and developed fast. This section will present an introduction on some key modulation techniques which are of interests in 4G systems, with the emphasis on how those techniques can be used for the more efficient 4G multiple access.

### 2.2.1 Multicarrier systems

Since 4G systems are designed to support the high data rate transmission, a large bandwidth is of necessity in 4G systems. As the bandwidth is increased, intersymbol interference (ISI) becomes problematic and complex equalizers are required to compensate the channel effects [7]. This is a disadvantage caused by large bandwidth systems, because the complex equalization reduces battery life, and in most cases, the channel cannot be perfectly equalized.

As a result, in order to avoid complexity of equalization, 4G systems is intended to be based on multicarrier systems such as OFDM or multicarrier code division multiple access (MC-CDMA) [7]. In these systems, the total large bandwidth is divided into several groups of subcarriers, each of which has a smaller bandwidth. The overall data stream is split into each subcarrier and then transmitted in parallel. The advantage of this approach is that a large bandwidth is divided into a number of narrowband subcarriers, resulting in nearly flat fading on each subcarrier where less ISI is experienced and therefore low complexity equalization can be utilized [7]. This can also be viewed from the time domain. A narrowband system has a longer symbol duration by transmitting each symbol relatively slowly [7, 17]. In a single carrier system, for example, to transmit 1 Mbit per second, a system can only tolerate less than a microsecond delay, otherwise it will suffer ISI caused by the overlapping of the next bit. However, if a system is able to transmit $1,000$ bits in parallel over its $1,000$ subcarriers, one bit can be transmitted per millisecond and still yield aggregate 1 Mbit per second data rate, thereby reducing ISI.

Therefore, multicarrier modulation are considered as one of the most preferable techniques for 4G systems due to its ability of reduction in ISI and equalization complexity.

### 2.2.2 OFDM

OFDM is one of many multicarrier transmission methods. OFDM has been introduced by many previous literatures [17–21] as one of the most important modulation techniques for future 4G systems since it is able to boost high speed transmission over wireless channels.

OFDM is implemented by transmitting data-bearing signals over a number of parallel subcarriers spaced orthogonally in frequency. Because adjacent subchannels are orthogonal to one another, there is no overlapping and thus little interference created. Figure 2.1 shows the spectrum of an OFDM system with four subcarriers. Each of subcarriers is spaced by a frequency of $1/T$, where $T$ is the OFDM symbol duration. The orthogonality is maintained between subcarriers as the peak of each subcarrier corresponds to nulls of all adjacent subcarriers.

Please see print copy for Figure 2.1

Figure 2.1: OFDM specturm with four subcarriers [22].

Figure 2.2 shows the block diagram for a typical OFDM modulator and demodulator. The incoming data bits are first modulated with a complex modulator, such as M phase shift keying (M-PSK) or M quadrature amplitude modulation (M-QAM). Each N symbols are grouped into parallel format via a serial to parallel converter (S/P), where N is the number of subcarriers. The inverse fast Fourier transform

(IFFT) is then used to modulate these symbols to their respective subcarrier frequencies. Equation 2.1 [18]shows the baseband signal $s(t)$ after the IFFT operation on the sequence $d_k$

$$s(t) = \sum_{k=0}^{N-1} d_k e^{j2\pi \frac{k}{T} t} = N \cdot \mathrm{IFFT}(d_k), \tag{2.1}$$

where $N$ is the number of subcarriers and $T$ is the OFDM symbol duration. After the IFFT modulation, the outcoming sets of parallel symbols are converted into a serial stream and a cyclic prefix (CP)is added. The length of CP is selected to be larger than the length of the channel in order to eliminate ISI. After the CP is added, the signal is transmitted over the wireless channels.

Please see print copy for Figure 2.2

Figure 2.2: OFDM modulator and demodulator [7].

At the receiver, the signal is restored to the baseband and the CP is removed. The signal is then converted into parallel format and demodulated to complex symbols via the fast Fourier transform (FFT) operation, which is demonstrated in Eq. 2.2 [18]

$$r(t) = \mathrm{FFT}(N \cdot \mathrm{IFFT}(d_k)) = \sum_{k=0}^{N-1} d_k e^{j2\pi \frac{k}{T} t} e^{-j2\pi \frac{k}{T} t} = d_k. \tag{2.2}$$

We assume that there is no noise or fading on the channel. Therefore, the expected data bits are recovered from the complex symbols $d_k$ after being converted from parallel to serial sequences and demodulated with the appropriate demodulator.

### 2.2.3 OFDMA

There are several methods of providing multiple access in multicarrier systems. OFDMA is one of these methods and perhaps is the most straightforward one as OFDM can be easily utilized for the multiple access purpose [19, 23].

Please see print copy for Figure 2.3

Figure 2.3: Two possible strategies for allocating subcarrier groups in an OFDMA system [23].

OFDMA is implemented, based on OFDM, by dividing the total FFT bandwidth into a number of subchannels, each of which is a set of available subcarriers. Users may occupy one or more than one subchannel for data transmission, depending on their QoS requirement and system loading characteristics. There are two possible strategies for allocating subcarriers groups to users, which are shown in Figure 2.3. The first strategy groups adjacent subcarriers in the same frequency range in each subchannel, whereas in the second, subchannels are spread over the total bandwidth

Table 2.3: Parameters in the UMTS and IEEE 802.16 standards [23].

Please see print copy for Table 2.3

[23, 24]. It is obvious that the second strategy is more advantageous, especially in frequency selective fading channels where only a fraction of subcarriers in each subchannel can be affected by a deep narrow band fading.

OFDMA has been applied in the current telecommunication industries. Universal Mobile Telecommunication system (UMTS), the European standard for the 3G cellular mobile couumincations, and IEEE 802.16, a broadband wireless access standard for metropolitan area networks, are two live examples for industrial usage of OFDMA. Table 2.3 shows the basic parameters of these two systems.

### 2.2.4 Multicarrier CDMA

CDMA is a multiple access technique that has been widely used on recent wireless communication systems like IS-95, UMTS or CDMA2000 [22, 25]. CDMA is based on the spread spectrum (SS) technique, which high rate spreading sequences are assigned on data symbols to enlarge the signal bandwidth. These sequences are called pesudonoise (PN) code. In CDMA systems, different users are allocated with unique PN codes thus they can be identified and sperated at the receiver by means of their characteristic individual codes. At the receiver, the incoming signal is multipled by a synchronized version of the identical PN code for each user, which causes the signal to be despread and the orignal data signal is recovered. Figure 2.4 shows the transmitter and the receiver of a basic SS communication system.

MC-CDMA is a modulation scheme that combines OFDM and CDMA, where OFDM can be employed for multiple access to provide higher capacity than traditional OFDMA systems [7]. In MC-CDMA systems, the incoming data signal is first multiplied by a user-specific PN sequence. The length of this spreading code is identical to the number of subcarriers. The resulting sequence is then converted into parallel format, modulated by IFFT and CP added, which is exactly like the OFDM modulation. Figure 2.5 shows the block diagram for a typical MC-CDMA modulator.

Please see print copy for Figure 2.4

Figure 2.4: Spread spectrum modulator and demodulator [7].

Please see print copy for Figure 2.5

Figure 2.5: MC-CDMA modulator [7].

The benefit of MC-CDMA is that a frequency diversity is obtained because each bit is transmitted over several independent subcarriers. Even if some subcarriers are degraded due to destructive frequency selective fadings, the data signal can still be recovered at the receiver by means of the diversity combining feature. This improves the bit error rate (BER) performance over OFDM. The drawback of MC-CDMA is that it may experience high multiuser access interference (MAI) when the channel is heavily loaded. Therefore, MC-CDMA systems are preferable under low channel loads.

Another alternative of multicarrier CDMA systems is multicarrier direct sequence CDMA (MC-DS-CDMA). The basic concept of MC-DS-CDMA is to transmit direct sequence CDMA signals in parallel over orthogonal subcarriers [7]. Figure 2.6 shows the block diagram for a typical MC-DS-CDMA modulator. The data stream is first converted into parallel format. Each bit is then multiplied by a user-specific spreading sequence with a higher data rate. The following IFFT is used to modulate the DS-CDMA signals to the orthogonal subcarriers.

Please see print copy for Figure 2.6

Figure 2.6: MC-DS-CDMA modulator [7].

The benefit of MC-DS-CDMA is that it can provide multiple access without the excessive MAI that can occur in MC-CDMA systems. This is because all of the PN chips are transmitted on the same subcarrier, which experiences correlated fading caused by the slow channel variance. However, the drawback of this appraoch is that there is no gain from frequency diversity. The data may not be recovered at the receiver, if a subcarrier experiences a destructive fade.

Some adaptive multicarrier systems have been proposed to overcome the problems of traditional OFDM, MC-CDMA, and MC-DS-CDMA systems, thus improving system performance and providing additional robustness. We will discuss those systems later in the next chapter.

## 2.3 Standard applications of 4G

In this section, we introduce WiMAX and Mobile DTV as two examples of major standardization trends for the next generation wireless communication applications.

### 2.3.1 WiMAX

WiMAX is an acronym for Worldwide Interoperability for Microwave Access and is based on the IEEE 802.16 standard [26, 27].It is considered as a solution for future wireless broadband communications that offers a lot of improvements in terms of higher data rates, more scalability, broader coverage and lower latency.

The WiMAX physical layer (PHY) is based on orthogonal frequency division multiplexing, a scheme that offers good resistance to multipath, and allows WiMAX to operate in non-line-of-sight (NLOS) conditions. This OFDM-based physical layer architecture offers scalability that allows the data rate to scale easily by choosing a different FFT size based on the available channel badnwidth. For example, a WiMAX system may use 128-, 512-, or 1048-bit FFTs based on whether the channel bandwidth is 1.25MHz, 5MHz, or 10MHz, respectively. This scaling is intended to be done dynamically to support user roaming across different networks with different bandwidth allocations.

WiMAX is able to support very high peak data rates. The peak PHY data rate can be as high as 74 Mbps when operating using a 20 MHz wide spectrum. More typically, using a 10 MHz spectrum operating using TDD scheme with a $3:1$ downlink-to-uplink ratio, the peak PHY data rate is about 25 Mbps and 6.7 Mbps for the downlink and uplink, respectively. Higher peak data rates can be achieved in cases that adaptive modulation coding or multiple antennas technique is used.

The WiMAX media access control (MAC) layer has a connection-oriented architecture that is designed to support a variety of applications, including voice and multimedia services. The system offers support for constant bit rate, variable bit rate, real-time, and non-real-time traffic flows. WiMAX MAC is designed to support a large number of users, with multiple connections per terminal, each with its own QoS requirement.

### 2.3.2 Mobile DTV

There are several standards for the mobile DTV, which are DVB, ISDB, DMB and MediaFLO [26, 28].

DVB (Digital Video Broadcasting) is a set of internationally accepted, open standards for digital television protocols maintained and devised by the Digital Video Broadcasting Project. DVB uses multiple carrier modulation system to easily resolve any transmission problems, return path functions or mobile reception. There are four core standards of DVB: DVB-S (Satellite television and satellite Internet), DVB-C (Cable), DVB-T (Terrestrial) and DVB-H (Handheld) [29–31].

ISDB (Integrated Services Digital Broadcasting) is the Japanese standard for digital television. ISDB is capable of combining various services and transmitting them in an integrated form regardless of their transmission capacities, speeds and other characteristics that may differ from one service to another [32]. The core standards of ISDB are ISDB-S (satellite television), ISDB-T (terrestrial) and ISDB-C (cable) [33–35].

DMB (Digital Multi media Broadcasting) system requires some modifications to the DAB. Thus it allows to leverage on its widely installed and established network infrastructure. Currently, the main DMB market is in South Korea [26].

MediaFLO is an OFDM-based air interface designed specifically for multicasting. It allows mobile operators to provide live straming video channels, in addition to supporting national local channels. It requires only two or three broadcast towers per metropolitan area, which is $30 - 50$ times fewer than that required by cellular network systems. The FLO technology might be cost effective for mobile multimedia content distribution than competing broadcast technologies such as DVB-H.

## 2.4 Chapter summary

In this chapter, we presents an overview of 4G, which represents the next development stage of wireless communication evolution beyond 3G. We start from the introduction of development history on wireless communications. 1G built the basic structure of wireless communications and addressed many fundamental problems. 2G realized the revolution from analogy to digital technology, which has gained tremendous success with GSM as the representative. 3G was developed to provide higher data rate and broader bandwidth. After a brief review of the history, we propose 4G feature frameworks, in which several technical perspectives are presented according to different visions.

As a result of the limitations of equalization, 4G systems are considered to be based on multicarrier modulation such as OFDM, OFDMA and MC-CDMA. OFDM has attracted a great interest as a modulation technique of delivering high data rates with strong resistance to ISI because of orthogonal subcarriers. OFDMA is a variation of OFDM for multiple access purpose, where each user is assigned with a fraction of the available number of subcarriers. MC-CDMA is a modulation technique that combines OFDM and CDMA, and therefore achieves diversity improvement over OFDMA.

At last, we introduce two standardization trends as examples of 4G applications. WiMAX is based on the IEEE 802.16 to provide higher data rates, more scalability, broader coverage and lower latency. Mobile DTV includes several standards, such as DVB, ISDB, DMB and MediaFLO.

# Chapter 3

# OFDM Enhancements to Improve Performance

As mentioned in Chapter 2, OFDM has been fairly considered as an excellent candidate for 4G systems because of the high data rate applications that it can provide in highly dispersive channels. The primary benefit of OFDM systems is that complex equalizers are not necessary because OFDM is able to mitigate the ISI in large bandwidth channels, thus greatly reducing the complexity of system design.

However, like any other techniques, OFDM also has weaknesses that need to be addressed. In this Chapter, we first discuss problems that OFDM systems have in Section 1. Several techniques for improving OFDM systems, based on previous work, are then provided in next sections as solutions to those problems, therefore new OFDM systems are generated with the performance significantly improved.

## 3.1 Drawbacks of OFDM

Although OFDM provides various advantages to boost speed and capacity for wireless systems, there are drawbacks for OFDM as well. The main issues of OFDM systems include a high peak-to-average power ratio (PAPR), sensitivity to synchronization errors and lack of frequency diversity[2, 7, 23, 36].

### 3.1.1 High peak-to-average power ratio

OFDM signals are comprised of the summation of a number of independently modulated subcarriers, which result in signals having large amplitude, or small amplitude. Therefore, the peak signal power is much larger than the average power. This is different from single carrier systems, where the transmission power is generally constant.

A high PAPR introduces problems on D/A and A/D converters and power amplifiers. Large changes in amplitude can cause out-of-band (OOB) emmisions if signals pass through the power amplifier that is not perfectly linear [7]. Furthermore, high peak signals may be clipped when the amplitude exceeds the saturation level of the power amplifier. The distortion caused by this clipping effect will affect the orthogonality of subcarriers [37].

Therefore, it is really important to reduce the PAPR in OFDM systems. There are many methods proposed to deal with this problem, each of which has its advantages and disvantages. For more detail, see [38–40].

### 3.1.2 Interference by frequency synchronization errors

Another major drawback of OFDM is its relatively high sensitivity to frequency synchronization errors [41]. Due to the orthogonal nature of OFDM, subcarriers in OFDM are allowed to be densely packed to maximize spectral efficiency. Consequently, systems may experience inter-carrier interference (ICI) if the frequency references of the transmitted and received signals are not perfectly matched. These frequency synchronization errors are mainly caused by two factors. One is from the misalignment in subcarrier frequencies because of fluctuations in receiver RF oscillators. Another factor is the Doppler effect, which causes a signal to experience a frequency shift while moving at a high velocity.

When frequency synchronization errors occur,orthogonality is destroyed by the frequency offset, and thereby interference is introduced from adjacent subcarriers. ICI degrades the BER performance of the system. There have been many solutions proposed to solve frequency synchronization errors in [42–44].

### 3.1.3 Lack of frequency diversity

Another disadvantage of OFDM is the lack of frequency diversity [45]. For the ordinary uncoded OFDM, each symbol is transmitted over a single subcarrier independently. The frequency selective interference exists in many environments and systems which use OFDM, such as WiMax and 4G systems [36]. As a result, subcarriers in OFDM may experience high frequency dependent attenuations (e.g. channel nulls) on transmission over such frequency selective fading channels. The symbols carried by the subcarriers are consequently erased by the channel attenuations and can not be accurately recovered at the receiver. This phenomena results in a poor system performance.

In order to combat the bad subcarriers in OFDM some notion of frequency diversity should be introduced. Adaptive precoding is proposed as one of the solutions where the individual symbol information is effectively distributed across number of subcarriers rather than a single subcarrier [46]. This adds sufficient frequency diversity and thereby improves the system performance. There are many approaches proposed to provide frequency diversity for OFDM systems. More detailed information can be found in [47–50].

## 3.2 Achieving diversity for OFDM systems

In order to achieve diversity, the transmitted bits must experience independent or uncorrelated fadings, which can be realized by a physical separation of signals corresponding to the different bits. For multicarrier transmission, such as OFDM systems, two methods are provided to separate the bitstream in the physical transmission channel, and they are called time interleaving and frequency interleaving. Time and frequency interleavings are powerful techniques for OFDM systems to achieve diversity due to the physical separation that causes decorrelation in time and frequency dimension [22].

### 3.2.1 Time and frequency interleavers

Interleaving can be implemented by different techniques. In this section, we introduce two basic interleaving methods according to [22]: block interleaver and convolutional interleaver. The block interleaver is a typical example of frequency interleavers as there is a block structure involved by a number of subcarriers. The convolutional interleaver is always regarded as a time interleaver as it concerns decoding delay, which is the most important property of time interleavers.

The basic idea of a block interleaver is to take a block $K$ coded symbols of the data stream and change the order of symbols within this block. The simplest way to implement a block interleaver is to apply a pseudorandom permutation to each block of $K$ encoded symbols [22]. However, a randomly chosen permutation can not guarantee any minimum separation of symbols on the channel.

A matrix block interleaver offers a more effective approach. We take a block of $K = N \cdot B$ symbols and write them row-wise into an $N \times B$ matrix. Then we read them out column-wise and send them to the channel. Take $N = 12$, $B = 4$ and $K = 48$ as an example. We write 48 symbols $a_0, a_1, a_2, \cdots, a_{48}$ row-wise into a $12 \times 4$ matrix as

$$\begin{bmatrix} a_0 & a_1 & a_2 & a_3 \\ a_4 & a_5 & a_6 & a_7 \\ \vdots & \vdots & \vdots & \vdots \\ a_{44} & a_{45} & a_{46} & a_{47} \end{bmatrix}$$

and read them out column-wise. The output bitstream is then given by

$$(a_0, a_4, \cdots a_{44}, a_1, a_5, \cdots a_{45}, a_2, a_6, \cdots a_{39}, a_{43}, a_{47}) \, .$$

At the receiver, the deinterleaver writes column-wise into the same matrix and reads out row-wise.

Let us apply this example on OFDM transmission. We think of $K = 48$ subcarriers with carrier spacing $T^{-1}$. Then we choose an appropriate modulation, binary phase shift keying (BPSK) or quadrature phase shift keying (QPSK), and map the symbols in the above order on these carriers. Thus this matrix block interleaver guarantees a separation for each two adjacent symbols in frequency dimension by $12/T$.

Compared to the block interleaver, the convolutional interleaver is more preferred in practical systems as it concerns decoding delay, which is a critical issue for most communication systems [22].

We consider a serial symbol stream $a_0, a_1, a_2, \cdots, a_{B-1}$. We do a S/P conversion with this symbol stream, which results in a block of $B$ parallel symbols. Let $i = 0, 2, \cdots, B-1$ denote the position of each symbol in a block. As shown in Figure 3.1, the symbol with position $i$ in a block is delayed by $i \cdot M$ parallel symbol clocks, where $M$ is a certain integer number that must be chosen to adjust the interleaver properties [22]. After that, the block of symbols is converted by P/S from parallel to serial symbol stream and then transmitted.

Please see print copy for Figure 3.1

Figure 3.1: Block diagram for the convolutional interleaver [22].

Please see print copy for Figure 3.2

Figure 3.2: Block diagram for the convolutional deinterleaver [22].

The deinterleaver at the receiver has the same structure as the interleaver, but the order of delay is reversed. As shown in Figure 3.2, the symbol with position $i = 0, 1, 2, \cdots, B-1$ in a block is delayed by $(B-i-1) \cdot M$ parallel symbol clocks [22].

In addition to gain diversity, interleavers are used to improve the performance of OFDM systems by reducing the PAPR. Some methods have been proposed in the literature, and more detail can be found in papers [51–54].

### 3.2.2 Block spread OFDM

Another approach to gain frequency diversity in OFDM systems over frequency selective fading channels is to employ the block spreading technique. The block spreading for OFDM based systems has been studied by many researchers because of the greatly improved performance it is able to provide. The new systems have been called BS-OFDM. Numerous methods for BS-OFDM were proposed previously, and here we only discuss several of the most important ones.

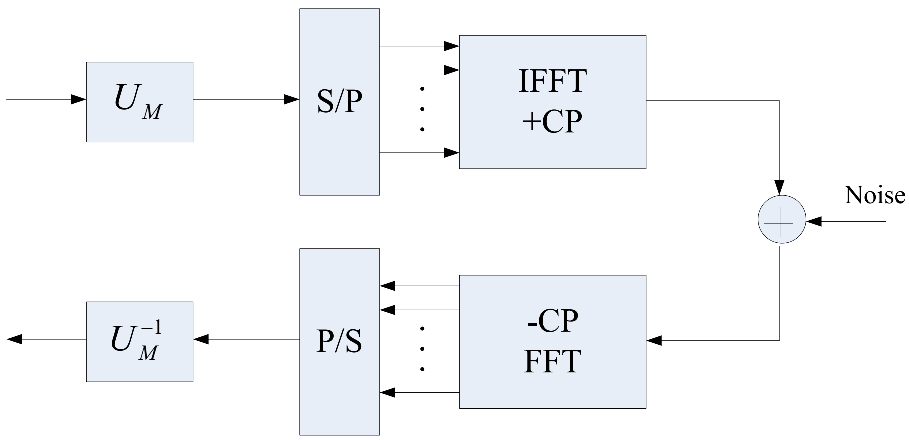


Figure 3.3: Block diagram of a block spread OFDM system model.

The basic idea of the block spread OFDM is to split the subcarriers into smaller groups and spread the informantion symbols across these groups using spreading matrices so as to achieve frequency diversity at the receiver [55, 56]. This idea was firstly introduced by Bury et al in [57], where a method for designing spreading codes through column-wise rotation of the discrete Fourier transform (DFT) or Hadamard matrix was proposed. The BS-OFDM system model is shown in Figure 3.3. As shown in Figure 3.3, a block of information bits are first multiplied with a unitary spreading matrix $U_M$ before they are sent to the OFDM modulation. The spreading matrices are generally used to increase the correlation between the transmitted symbols in order to achieve diversity in frequency selective fading channels. According to [57], the most common spreading matrix is the Hadamard matrix which is defined as

$$U_M^{(1)} = \frac{1}{\sqrt{2}} \cdot \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix}, U_M^{(n)} = U_M^{(n-1)} \otimes U_M^{(1)}, \tag{3.1}$$

where $\otimes$ denotes the Kronecker product, and the matrix size is $M = 2^n$. Another, less common, spreading matrix is the DFT matrix [57, 58]. A DFT matrix of order $M$ is defined by its elements as

$$U_{i,k} = \frac{1}{\sqrt{M}} \cdot exp(-j2\pi \frac{(i-1)(k-1)}{M}), 0 < i, k \leq M. \tag{3.2}$$

After the modulated data are multiplied by the Hadamard matrix or DFT matrix, a higher order modulation scheme is created which increases the correlation between the transmitted symbols, therefore achieving frequency diversity and better system performance.

Based on the Hadamard matrix, the rotated Hadamard matrix is further proposed. The rotated Hadamard matrix is same as the Hadmard matrix that described above with the exception it is rotated using the rotation equation given below,

$$U = \frac{1}{\sqrt{2}} H_{M\times M} diag(exp(\frac{j \times \pi \times m}{C})) \tag{3.3}$$

where $H_{M\times M}$ is the Hadamard matrix of order $M$ and $diag$ denotes the diagonal matrix [59, 60]. Here $C$ is chosen to insure that $\frac{2\pi}{C}$ is the smallest angle which rotates the signal constellation back to itself. For instance, we have $C = 2^b$ for the signal constellation $2^b$-PSK ($b$ is an integer), while for QAM constellations such as 16-QAM or 64-QAM, we have $C = 4$ [61]. The modulated data is multiplied by the matrix $U$, where the rotation takes place to produce a higher modulation scheme than traditional Hadamard. Therefore, the rotated Hadamard matrix is able to produce a better BER performance in BS-OFDM system over Hadamard.

In addition to the above three traditional spreading matrices, a new spreading matrix for BS-OFDM is presented by Raad and Huang. This new spreading matrix was first proposed in [60] and number of variations and studies carried out in [59, 62–64]. Its structure is shown as follows $U = 2 \times 2$,

$$U_2 = \begin{bmatrix} 1 & \tan(\alpha) \\ \tan(\alpha) & -1 \end{bmatrix}. \tag{3.4}$$

This spreading matrix allows a system of BS-OFDM to become more flexible by achieving different modulation schemes, say from QPSK to 64QAM. This can be done depending on the choice of angle $\alpha$. For example the choice of $\tan(\alpha) = 0.5$ makes QPSK into 16QAM. However, in order to yeild a better result than the Hadamard and Rotated Hadamard matrix, not all angles can be chosen. For example, an angle of $\alpha = \frac{\pi}{4}$ would result in one, which means that the matrix is a Hadamard matrix. Other angles which cannot be used when using QPSK are $\alpha = \pi$ and $\frac{\pi}{2}$ since the rotation of QPSK would rotate back onto itself and the new rotation would be the same as the rotated, that is QPSK [60, 63].

In [62], a method was proposed to expand the above new spreading matrix into higher order spreading matrix used for BS-OFDM with larger block size, where a higher order modulation scheme, say 64QAM for block size $M = 4$, can be achieved. The structure of this higher order rotation spreading matrix can be described as follows,

$$U_{2N} = \begin{bmatrix} U_N & \tilde{U}_N \\ U_N & -\tilde{U}_N \end{bmatrix}. \tag{3.5}$$

$\tilde{U_N} = P_N U_N Q_N$ denotes an equivalent rotation matrix obtained by permuting the rows and columns of $U_N$. $P_N$ and $Q_N$ are arbitrary monomial permutation matrices, and have exactly one non-zero entry in every row and column, therefore satisfying the conditions,

$$P_N P_N^T = P_N^T P_N = Q_N Q_N^T = Q_N^T Q_N = I_N, \tag{3.6}$$

where $P_N = \begin{bmatrix} 0 & I_{\frac{N}{2}} \\ I_{\frac{N}{2}} & 0 \end{bmatrix}$ and $Q_N = I_N$. That means $\tilde{U_N}$ is obtained by exchanging the upper and lower half of $U_N$ and it was shown to have good complementary properties.

So the $4 \times 4$ rotation matrix $U$ based on expansion method described above can be shown as follows,

$$U_4 = \begin{bmatrix} 1 & \tan(\alpha) & \tan(\alpha) & -1 \\ \tan(\alpha) & -1 & 1 & \tan(\alpha) \\ 1 & \tan(\alpha) & -\tan(\alpha) & 1 \\ \tan(\alpha) & -1 & -1 & -\tan(\alpha) \end{bmatrix} \tag{3.7}$$

For a $8 \times 8$ rotation matrix $U$, the rotation spreading matrix will have following structure, where $t = \tan(\alpha)$

$$U_8 = \begin{bmatrix} 1 & t & t & -1 & 1 & t & -t & 1 \\ t & -1 & 1 & t & t & -1 & -1 & -t \\ 1 & t & -t & 1 & 1 & t & t & -1 \\ t & -1 & -1 & -t & t & -1 & 1 & t \\ 1 & t & t & -1 & -1 & -t & t & -1 \\ t & -1 & 1 & t & -t & 1 & 1 & t \\ 1 & t & -t & 1 & -1 & -t & -t & 1 \\ t & -1 & -1 & -t & -t & 1 & -1 & -t \end{bmatrix}. \tag{3.8}$$

Higher order $M \times M$ rotation spreading matrices can be achieved when the method described in Eq. 3.5 is used. This ensures that the higher order matrix maintains orthogonality for a larger block size.

## 3.3 Multiple-antenna techniques

The use of multiple antennas has become one of the most promising areas in recent wireless communications. When multiple antennas are used at both transmitters and receivers, as shown in Figure 3.4, it is generally referred to as the MIMO system. The focus of MIMO systems is that the signals on the transmit antennas at one end and the receive antennas at the other end are combined in such a way that the quality (bit error rate) or the data rate of the communication for each user will be improved [65]. The most amazing advantage of MIMO systems is the ability to turn multipath propagation, traditionally a negative effect for wireless transmission, into a benefit for the user.

This section begins with an overview of MIMO systems, which introduces the basic idea of developing MIMO techniques, and highlights the unique benefits that MIMO can offer. Next, we look at the practical design of MIMO systems that involves the development of transmission signal processing algorithms, where different space time coding schemes are applied. We conclude with a discussion of an effective combination between OFDM and MIMO techniques, which brings a significant beneifts and may play a critical role in future wireless communications.

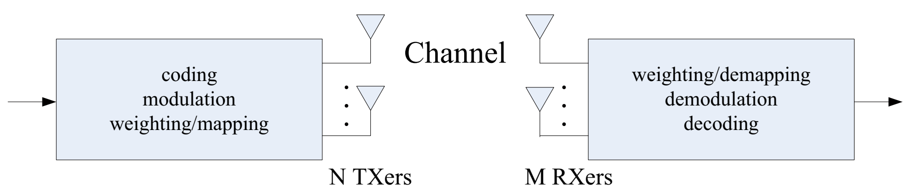


Figure 3.4: Diagram of a MIMO wireless transmission system.

### 3.3.1 Overview of MIMO systems

The phenomenon of time-varying multipath fading is a key factor that makes wireless transmission a challenge when compared to fiber, cable, microwave or even statellite transmissions. Increasing the quality or reducing the BER in a multipath fading channel is extremely difficult [66]. For instance, 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 specific modulation and coding schemes. Achieving the same BER reduction in a multipath fading environment, however, may require up to 10 dB improvement in SNR [66].

There are several techniques that can be used to mitigate multipath fading in a wireless channel. Theoretically, the most effective one is transmitter power control [66]. But there are two fundamental problems with this approach. The major problem is the required dynamic power change at the transmitter, which in most cases is impractical. The second problem is that the channel information has to be fed back from the receiver to the transmitter, which results in considerable additional complexity to both the transmitter and the receiver. Another effective technique is antenna diversity, which has been widely applied in most scattering environment for reducing the effect of multipah fading [67]. The common approach is to install multiple antennas at the receiver to perform combining and switching in order to improve the quality of the received signal. Recently multiple antennas have been exclusively equipped to base stations to improve their reception quality as a base station often covers hundreds to thousands of square kilometers, which is more economical than adding multiple antennas at the remote units. Some interesting approaches for antenna diversity have been suggested. A delay diversity scheme was proposed by Wittneben [68, 69] and a similar scheme was suggested by Seshadri and Winters [70, 71] for a base station in which copies of the same symbol are transmitted through multiple antennas at different times, resulting in an artifical multipath distortion. A maximum likelihood (ML) sequence estimator or a MMSE equalizer is then used to resolve multipath distortion and obtain diversity gain.

Another interesting approach is space-time trellis coding (STTC), discussed in [72–75], where modulation and trellis coding are combined to transmit signals over multiple transmit antennas and multipath channels. This scheme is effective since it combines the benefits of trellis-coded modulation (TCM) [72] and diversity transmission to achieve a higher coding gain and better performance. In addition to obtain diversity gains, however, low complexity encoding and decoding is crucial for MIMO systems as higher complexity consumes more battery power, which is limited for recent mobile units. Due to the fact that the complexity of STTC increases exponentially as high diversity order is required, it is not cost-effective for some applications and becomes less popular especially when another scheme, so-called space-time block coding (STBC), is developed. In contrast to the complex decoding algorithm for STTC, STBC can be decoded using simple linear processing at the receiver and meanwhile gives the same diversity gain as the STTC for the same number of TX antennas. As a result, below, we will mainly focus our attention on the design of STBC rather than on trellis-based approaches. As the reader should note, in spite of the difference between STTC and STBC, both of them belong to the STC scheme, where the multiple antennas are only used as a source of spatial diversity and not to increase data rate.

### 3.3.2 Model of STBC-MIMO systems

As introduced above, the decoding complexity of STTC increases exponentially with the diversity level and transmission rate [74]. In addressing this issue of decoding complexity, Alamouti [66] frist proposed the idea of STBC for transmission with two antennas, which improves the transmit diversity at the receiver by only using a simple linear processing scheme. The simple structure and linear processing of the Alamouti construction make STBC a very attractive scheme that is currently applied on both the W-CDMA and CDMA-2000 standards [65]. This scheme was later generalized in [76] to an arbitrary number of antennas. Next we will briefly discuss the basics of STBC by exploiting a simple example.

Figure 3.5 shows the baseband modelling for Alamouti STBC with two antennas at the transmitter. Before STBC encoder, a modulation scheme is used to map information bits to symbols from a constellation. The constellation can be any real or complex constellation, for example, PSK, QAM, and so on. The input symbols to the STBC encoder are then divided into groups of two symbols. At a given symbol period, the two symbols in each group $[c_1, c_2]$ are transmitted simultaneously from the two antennas. The signal transmitted from antenna 1 is $c_1$ and the signaltransmitted from antenna 2 is $c_2$. In the next symbol period, the signal $-c_2^*$ is transmitted from antenna 1 and the signal $c_1^*$ is transmitted from antenna 2. Therefore, the transmitted codeword is

$$C = \begin{bmatrix} c_1 & -c_2^* \\ c_2 & c_1^* \end{bmatrix}. \tag{3.9}$$

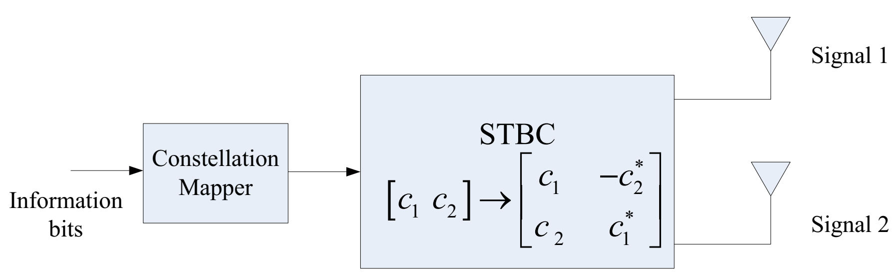


Figure 3.5: Transmitter block diagram for Alamouti STBC.

For the design of the receiver end, we assume that a single RX antenna is used.

Let $h_1$ and $h_2$ be the channels from the first and second TX antennas to the RX antenna, respectively. The major assumption here is that $h_1$ and $h_2$ are scalar and constant over two consecutive symbol periods, that is

$$h_i(2nT) = h_i((2n+1)T), i = 1, 2. \tag{3.10}$$

We denote the received signal over two consecutive symbol periods as $r_1$ and $r_2$. The received signals then can be expressed as

$$r_1 = h_1 c_1 + h_2 c_2 + n_1 \tag{3.11}$$

$$r_2 = -h_1 c_2^* + h_2 c_1^* + n_2 \tag{3.12}$$

where $n_1$ and $n_2$ represent the AWGN and are modeled as i.i.d. complex Gaussian random variables with zero mean and power spectral density $N_0/2$ per dimension. For simplicity of expression, we define the received signal vector $\mathbf{r} = [r_1\ r_2^*]^T$, the code symbol vector $\mathbf{c} = [c_1\ c_2]^T$, and the noise vector $\mathbf{n} = [n_1\ n_2^*]^T$. Thus, equations 3.11 and 3.12 can be written in a matrix form as

$$\mathbf{r} = \mathbf{H} \cdot \mathbf{c} + \mathbf{n} \tag{3.13}$$

where the channel matrix $\mathbf{H}$ is defined as

$$\mathbf{H} = \begin{bmatrix} h_1 & h_2 \\ h_2^* & -h_1^* \end{bmatrix}. \tag{3.14}$$

$\mathbf{H}$ is now a virtual MIMO matrix with space (columns) and time (rows) dimensions. It is realized that the channel matrix $\mathbf{H}$ is always orthogonal regardless of the channel coefficients, which means $\mathbf{H}^* \cdot \mathbf{H} = \alpha \cdot \mathbf{I}_2$ where $\alpha = |h_1|^2 + |h_2|^2$. Hence, the equation 3.13 can be further modified as follows

$$\tilde{\mathbf{r}} = \mathbf{H}^* \cdot \mathbf{r} = \alpha \cdot \mathbf{c} + \tilde{\mathbf{n}} \tag{3.15}$$

where $\tilde{\mathbf{n}} = \mathbf{H}^* \cdot \mathbf{n}$, which is a complex Gaussian random vector with zero mean and covariance $\alpha N_0 \cdot \mathbf{I}_2$. Therefore, in this case, the optimum ML decoding rule is

$$\hat{\mathbf{c}} = arg \min_{\hat{\mathbf{c}} \in \mathbf{c}} \|\tilde{\mathbf{r}} - \alpha \cdot \hat{\mathbf{c}}\|^2 . \tag{3.16}$$

It is obvious that for the above $2 \times 1$ STBC, only two complex multiplications and one complex addition per symbol are required for decoding. It is also straightforward to verify that the SNR for $c_1$ and $c_2$ will be

$$SNR = \frac{\alpha \cdot E_s}{N_0} \tag{3.17}$$

and hence, a diversity gain of order two is obtained at the receiver. Figure 3.6 shows a simplified block diagram of STBC receiver with one RX antenna.

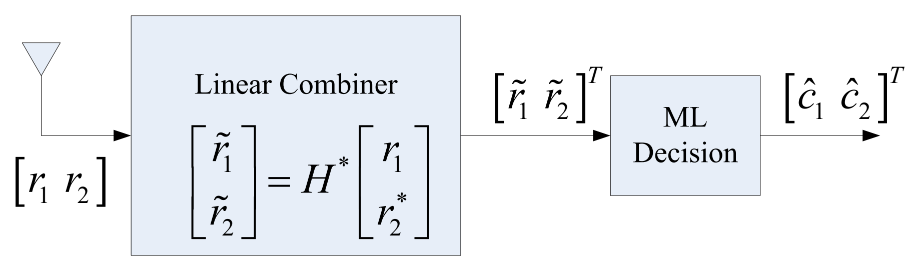


Figure 3.6: Receiver block diagram for Alamouti STBC.

Though the simple Alamouti STBC scheme, as described above, was initially developed to provide transmit diversity in the multiple-input-single-output (MISO) case, it is readily extended to the MIMO case when the receiver uses multiple RX antennas. The extension of the STBC to more than one RX antenna was later studied in many literatures, and see [77–79] for details.

### 3.3.3 OFDM with MIMO systems

The space-time coding was originally designed for a narrowband wireless system, where only a flat fading channel is experienced. Different from the flat fading channel, the large delay spreads in frequency selective fading channels destroy the orthogonality of the received signal, which is crucial for STC to gain diversity. Therefore, when used over frequency selective fading channels a complex equalization method is required at the receiver along with the space-time decoder. However, the nonlinear and noncausal nature of the space-time code makes the use of traditional equalization methods, such as MMSE linear equalizer, decision feedback equalizer (DFE), and MLSE, a challenging problem.

OFDM, as described in Chapter 2, is an effective technique for eliminating or at least mitigating the effects of delay spreads in frequency selective fading channels. According to [80], by using OFDM modulation, frequency selective fading channels can be transformed into 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. Hence, the OFDM based MIMO system effecitvely resolves the equalization complexity problem and extends the utilization of space-time coding into frequency selective fading channels. Due to the great advantage of the combination between OFDM and STC, numerous investigations have been made on this topic and various MIMO-OFDM schemes have appeared in previous work, such as [81–84]. As following, we only presents a simple example to demonstrate the scheme that combines the Alamouti STBC with OFDM.

In the present example, we implement Alamouti's transmit diversity scheme in time direction on each subcarrier for a pair of subsequent OFDM symbols. Let $s_l[k] = s_{lk}$ denote the complex PSK or QAM symbols with time index $l = 1, 2$ and frequency index $k = 1, \cdots, N$, $N$ is the total number of OFDM subcarriers. For each frequency index $k$, the symbols will be multiplexed to the two transmit antennas

Table 3.1: Alamouti transmit diversity in the frequency domain[22].

Please see print copy for Table 3.1

Table 3.2: Alamouti transmit diversity implemented in the time domain[22]

Please see print copy for Table 3.2

TX1 and TX2 according to Table 3.1. In principle, the OFDM signal generation by IFFT will then have to be done for both antennas and for the two time slots, that is, four IFFTs of length $N$ have to be performed. However, becuase of well known Fourier transform relations, only two transforms are necessary. Let us write $x_l[n]$ for the time domain signal corresponding to the frequency domain signal values $s_l[k]$. Then the transmit diversity implementation in the time domain can be written as shown in Talbe 3.2. Thus, only two IFFTs must be performed during two time slots and the Alamouti STBC scheme combined with OFDM does not require additional IFFT computation complexity.

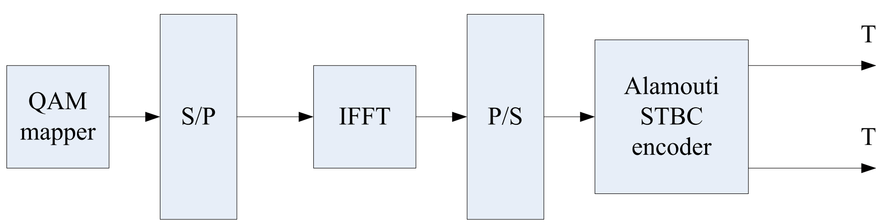


Figure 3.7: Block diagram for Alamouti STBC with OFDM system.

After multiplexing, the guard interval has to be inserted to the four signals of Table 3.2. After digital-to-analog conversion, the signals of the two branches will be sent to the respective antennas. The complete system setup is shown in Figure 3.7. The data bits are first mapped by QAM constellation. The complex

QAM symbols are then processed blockwise by an IFFT device of FFT length $N$, resulting in a stream of complex time domain samples that are grouped into vectors $x_i[n], n = 0, 1, \cdots, N-1$ of length $N$, each corresponding to one OFDM symbol numbered by $i$. These vectors are grouped into pairs, and each pair is processed by the Alamouti STBC encoder according to Table 3.2. After this, the guard interval is inserted separately to the resulting OFDM symbols for the respective antennas.

The above example briefly summarizes the approach that the Alamouti STBC is applied to two OFDM consecutive subcarriers. In previous work, the Alamouti STBC shceme is imposed on a block basis rather than the original scheme that a symbol basis is emphasized. Several approaches were proposed in [85–87], where the Alamouti STBC is applied to two OFDM consecutive block vectors in the time domain or frequency domain.

## 3.4 Chapter summary

In this chapter, we first describe several drawbacks of conventional OFDM systems. OFDM systems may experience a large distortion due to nonlinearity as a result of high PAPR. OFDM systems are also sensitive to frequency synchronization. Since subcarriers in OFDM systems are densely overlapped because of orthogonality, systems may suffer from serious ICI when frequency synchronization errors occur. Lack of frequency diversity is another common disadvantage of OFDM systems, which results in a poor performance especially on transmission over frequency selective fading channels.

Achieving diversity for OFDM systems has become attractive and has received much attention in recent research. The core idea of diversity gain is to combat the effect of frequency selective fading channels, thus improving system performance. There are many methods proposed in previous work to provide diversity for OFDM systems. The time and frequency interleaving is one of them. We introduce the interleaving method with an emphasis on two basic interleavers: block interleaver and convolutional interleaver. Another approach to gain diversity in OFDM systems is block spreading. The main idea of block spreading with OFDM is to use spreading matrices to spread symbols accross subcarriers, and as a result the frequency diversity is obtained. We introduce several spreading matrices that are well developed by previous researchers, such as the DFT matrix, the Hadamard matrix, and the rotated spreading matrix, etc.

The MIMO scheme is another important technique for OFDM systems. The most significant property of MIMO is its ability to achieve spatial diversity by taking advantage of multipath propagation, which has traditionally been an impairment in wireless transmission systems. There are many approaches to implement MIMO, but here we mainly focus on the the STBC-MIMO. We present an example model of STBC-OFDM systems with two transmitters and one receiver, and accordingly, algorithms for coding and decoding are described as well. The MIMO-OFDM systems have received considerable attention as a suitable candidate for next generation wireless communications.

# Chapter 4

# Block spread OFDMA system with STC-MIMO

In this project, we propose a block spread orthogonal frequency division multiple access (BS-OFDMA) system with a combined STC-MIMO scheme for transmission over frequency selective fading channels. We refer to the system as a STC-MIMO BS-OFDMA system. In this system, first, a novel approach is developed to effectively combine the block spreading technique and OFDMA modulation to obtain improved bit error performance and greatly lower system complexity. The STC-MIMO encoding is then skillfully incorporated to take advantage of multipath channels, resulting in a spatial diversity achieved for the proposed system.

In this chapter, we first explore the basic idea of the proposed system and describe its resultant novel contributions in order to distinguish from other similar systems presented in the literature. Next, a transmitter model for our proposed system is given in detail, including the implementation of block spreading, OFDMA modulation and STC-MIMO encoding. A corresponding receiver model and decoding algorithms are then presented. We use linear channel equalization which is simpler in practice. Finally, simulations are carried out to confirm the expected performance improvement by a comparison with an existing OFDMA system with or without block spreading.

## 4.1 Overview of the proposed system

As we have learnt from Chapter 3, the combination of block spreading technique with the OFDM systems can offer significant system improvement by achieving frequency diversity over frequency selective channels at the cost of more complicated transmitter and receiver structures. On the other hand, MIMO systems have received considerable attention as MIMO effectively takes advantage of multipath channels. Such an advantage can be used to greatly increase the quality of service for wireless communications systems. The STC is one of prominent canditates of MIMO encoding design that can be used in conjunction with OFDM.

In this project, we aim to extend the idea of block spread OFDM and STC-MIMO to a combined STC-MIMO BS-OFDMA system for multiuser application. In a conventional OFDMA system, each user transmits an OFDM signal over a number of subcarriers. Each subcarrier represents a narrowband signal and is orthogonal to other subcarriers assigned to the same user as well as other users. Therefore, the transmitted signals from different users reside in different frequency bands which are much narrower than the total available system bandwidth, and experience different channel fading effects. In our proposed BS-OFDMA scheme, however, the block spread signal is no longer a narrowband signal but spreads over all frequency band allocated for the system. All users share the same bandwidth even though they have complex exponentials with different discrete frequencies. Moreover, the transmitted information bits are combined and spread across the whole frequency band where variety of channel fadings occur. The frequency diversity is therefore achieved. As a result, the BS-OFDMA scheme will offer much better performance over frequency selective fading channels than conventional OFDMA systems.

In contrast to other block spreading techniques with OFDM, the proposed system has much simpler structures for the transmitter and reciever design. According to[58, 59, 61], at the transmitter, the combination of block spreading with OFDM is usually implemented by a precoding process of assigning a spreading matrix followed by the IFFT; and then both a de-precoding process to remove the spreading matrix and FFT are required at the receiver. In our system, however, we discard both the precoding for block spreading and the IFFT modulation. Instead we use a complex exponential sequence to effectively implement BS-OFDMA scheme, thus greatly reducing the system complexity particularly for the transmitter end.

The STC-MIMO using Alamouti code is further applied to gain an additional diversity. The encoding is theoretically performed in space and frequency, however, it is actually done in space and time to effectively incorporate with the previous block spread OFDMA modulation. Instead of the symbol basis, the Alamouti scheme is imposed on a block basis because after block spreading, symbols are no longer independently taken by each subcarrier but spread over all frequency band allocated to the system.

The relevant receiver and decoding algorithms are developed for block despreading, MIMO decoding and channel equalization. Since the ML detection is highly computationally complicated, especially when the block size is large, a linear equalization, such as the MMSE equalization and the ZF equalization, followed by a hard decision is preferable. Here we choose the MMSE equalization as it offers a tradeoff between the high complexity of ML detection and the poor performance of ZF equalization. At last, performance evaluation and comparisons are conducted to demonstrate the anticipated improvement.

The novel contributions of this project therefore include 1) the application of a new scheme to effectively combine the block spreading technique with OFDMA modulation to obtain improved performance and greatly reduce system complexity as well; 2) the implementation of STC-MIMO using Alamouti code in the frequency domain to gain multipath diversity over frequency selective fading channels; 3) the design of MMSE equalization as a decoding method for the proposed block spread STC-MIMO OFDMA system.

## 4.2 Signal model for transmitter

In this section, the structure of the block spread STC-MIMO OFDMA transmitter is shown in Figure 4.1. We first explore the method that effectively combines block spread with OFDMA without using any spreading matrices and IFFT processors. The output signals from BS-OFDMA module are then encoded by the STC-MIMO encoder to implement the Alamouti code in the frequency domain.

### 4.2.1 BS-OFDMA design

As shown in Figure 4.1, we group two vectors $\mathbf{x}_1$ and $\mathbf{x}_2$, where $\mathbf{x}_1 = (x_1[0], \cdots, x_1[M-1])$ and $\mathbf{x}_2 = (x_2[0], \cdots, x_2[M-1])$ are two consecutive block modulated symbol vectors after a Quadrature Phase Shift Keying (QPSK) modulation. The length of each symbol vector is $M$, which is an integer power of 2. The symbol vector $\mathbf{x}_1$ and $\mathbf{x}_2$ are first sent to a block extension module, where each vector is extended to $MN$ length by simply duplicating itself for $N$ times. Then a complex exponential

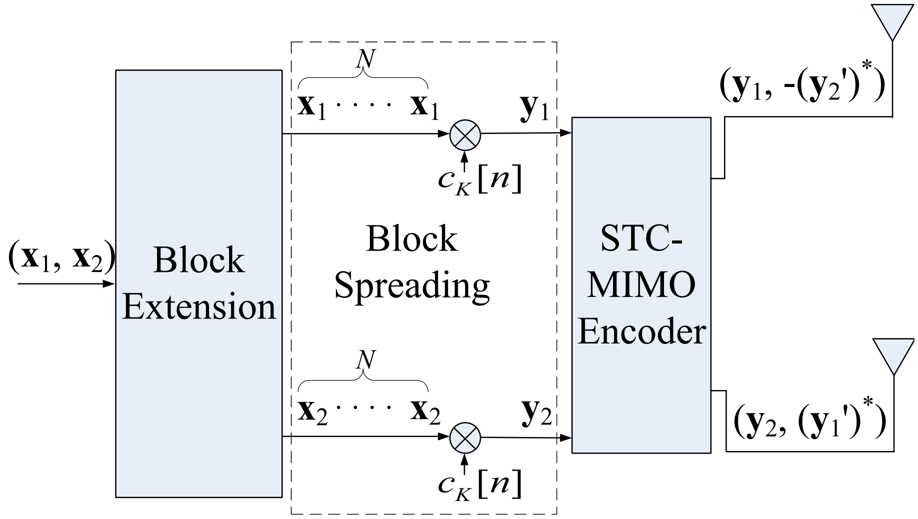


Figure 4.1: Block spread STC-MIMO OFDMA transmitter model.

sequence $c_K[n]$ is assigned to those extended vectors to implement block spreading. It is expressed as

$$c_K[n] = exp(j\frac{2\pi Kn}{N}), n = 0, 1, \cdots, N-1, K = 0, 1, \cdots, N-1, \tag{4.1}$$

where $K$ is the user index to identify a specific user and $N$ denotes the number of users in the system. In addition to block spreading, $c_K[n]$ is also used to generate OFDMA signals as it constitues a set of orthogonal functions with each user differentiated by a distinct frequency. Therefore, the block spreading technique and OFDMA modulation are effectively combined in our system without any additional precoding processes and IFFT application, and thus the system computational complexity is greatly reduced. The elements of the output symbol vector $\mathbf{y}_1 = (y_1[0], \cdots, y_1[MN-1])$ and $\mathbf{y}_2 = (y_2[0], \cdots, y_2[MN-1])$ after the block spread OFDMA modulation are expressed as

$$\begin{aligned} &y_1[i] = x_1[m]c_K[n] \\ &y_2[i] = x_2[m]c_K[n] \\ &i = nM + m, \\ &m = 0, 1, \cdots, M-1, n = 0, 1, \cdots, N-1. \end{aligned} \tag{4.2}$$

Rather than the mathematical expression, this process can also be illustrated in Figure 4.2, which is much more straightforward to explain the approach of using the proposed sequence to implement BS-OFDMA modulation.

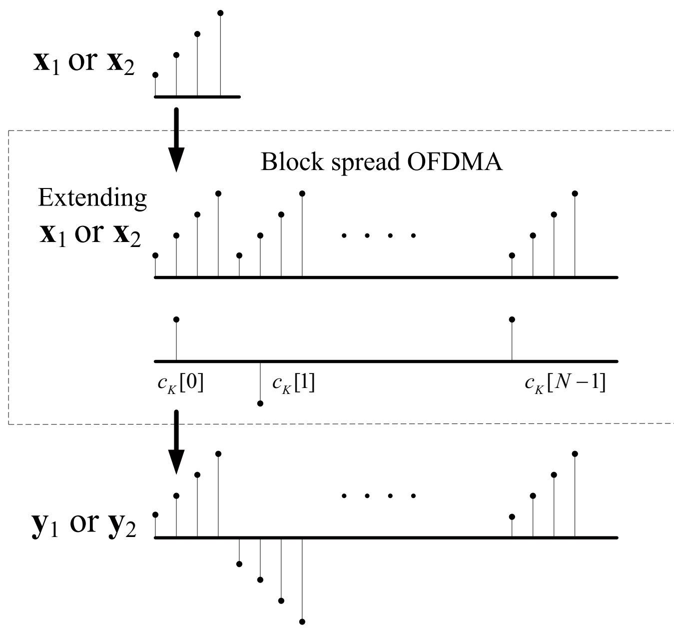


Figure 4.2: Process of BS-OFDMA implementation.

The most siginficant advantage of BS-OFDMA is that it is able to improve system performance by achieving frequency diversity to combat frequency selective fading channels. This can be easily derived by investigating the signal model in the frequency domain. After performing a $MN$-point DFT of $y_t[i], t = 1$ or $2$, we can find out

$$\begin{aligned}
Y_t[k] &= \sum_{i=0}^{MN-1} y_t[i] e^{-j\frac{2\pi}{MN}ki} \\
&\overset{i=nM+m}{=} \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} y_t[nM+m] e^{-j\frac{2\pi}{N}kn} e^{-j\frac{2\pi}{MN}km} \\
&= \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} x_t[m] c_K[n] e^{-j\frac{2\pi}{N}kn} e^{-j\frac{2\pi}{MN}km} \\
&= \sum_{n=0}^{N-1}\sum_{m=0}^{M-1} x_t[m] e^{j\frac{2\pi K}{N}n} e^{-j\frac{2\pi}{N}kn} e^{-j\frac{2\pi}{MN}km} \\
&= \sum_{m=0}^{M-1} x_t[m] e^{-j\frac{2\pi}{MN}km} \sum_{n=0}^{N-1} e^{-j\frac{2\pi}{N}(k-K)n} \\
&= \begin{cases} X_{K,t}[l], & k = lN+K, l = 0, 1, \cdots, M-1 \\ 0, & \text{otherwise} \end{cases}
\end{aligned} \tag{4.3}$$

where

$$X_{K,t}[l] = N\sum_{m=0}^{M-1} x_t[m]e^{-j\frac{2\pi}{MN}(lN+K)m},$$
$$l = 0, 1, \cdots, M-1. \tag{4.4}$$

For simplicity of the expression, we create a vector $\mathbf{Y}_t$ that only contains nonzero elements of $Y_t[k]$. It is expressed as $\mathbf{Y}_t = (Y_t[K], Y_t[N+K], \cdots, Y_t[(M-1)N+K])$. Therefore, we can write a new equation as

$$\mathbf{Y}_t = N\mathbf{x}_t\mathbf{W}_M, \tag{4.5}$$

where

$$\mathbf{W}_M = \begin{bmatrix} e^{\alpha K\times 0} & e^{\alpha(K+N)\times 0} & \cdots & e^{\alpha[K+(M-1)N]\times 0} \\ e^{\alpha K\times 1} & e^{\alpha(K+N)\times 1} & \cdots & e^{\alpha[K+(M-1)N]\times 1} \\ \vdots & \vdots & \ddots & \vdots \\ e^{\alpha K\times(M-1)} & e^{\alpha(K+N)\times(M-1)} & \cdots & e^{\alpha[K+(M-1)N]\times(M-1)} \end{bmatrix} \tag{4.6}$$

denotes the phase rotation matrix with order $M$ and $\alpha = -j\frac{2\pi}{MN}$. Eq. 4.3 and Eq. 4.5 imply that, through the block spread OFDMA modulation, the $M$ data symbols for the $K$th user are mixed via phase rotation and then spread across $M$ equally spaced subcarriers.

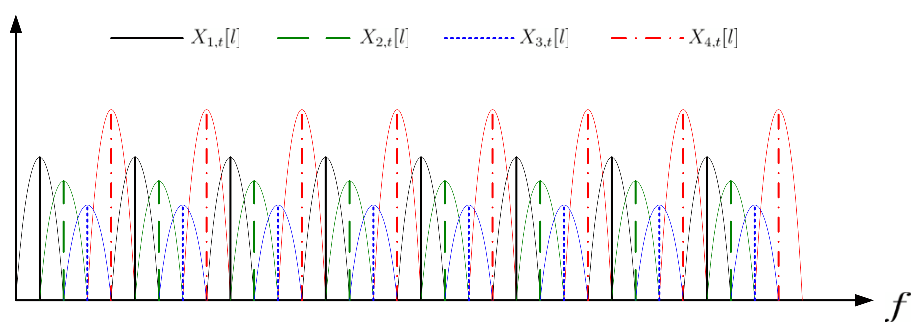


Figure 4.3: Block spread OFDMA signal model in the frequency domain.

An example of the OFDMA signal model in the frequency domain after block spreading is illustrated in Figure 4.3, where the number of users is $N = 4$ and each user carries $M = 8$ data symbols. As indicated in Figure 4.3, multiple users can share the same frequency channel like other multiple access systems (CDMA or

OFDMA). The receiver can extract any user's data signal without interference from any other user after performing correlation with the complex exponential sequence assigned to the user. However, in contrast to conventional OFDMA system without block spreading, each subcarrier for a specific user in the block spreading OFDMA system no longer takes a single data symbol but a set of all data symbols combined together. Therefore, the frequency diversity is achieved, and a significant improved performance over frequency selective fading channels is thus expected.

### 4.2.2 STC-MIMO encoding

We consider two transmit antennas for the STC-MIMO design following the BS-OFDMA module. We propose an approach that applies the Alamouti code in the frequency domain to implement space-time encoding. It is different from the STC-MIMO described in Chapter 3, where the Alamouti code is applied to the time domain. However, based on the conjugation property of Fourier transform relations between time domain and frequency domain, the STC-MIMO encoding is actually performed in the time domain in our system so that the block spreading can be easily incorporated. This process is shown in Figure 4.4.

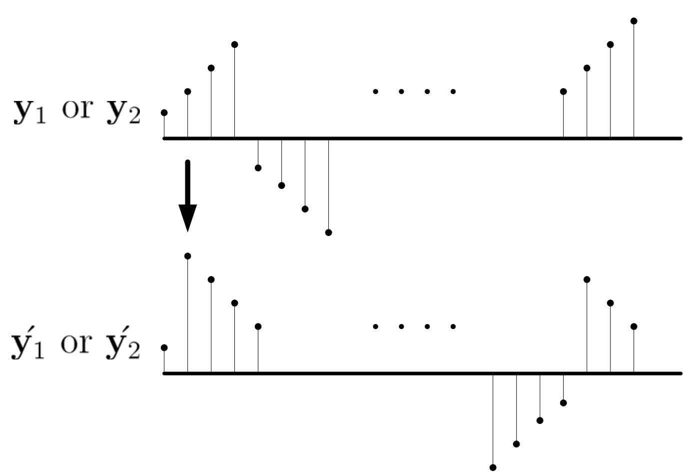


Figure 4.4: Process in the time domain to implement STC-MIMO.

Table 4.1: STC-MIMO in the time domain

| Antenna | TX1 | TX2 |
|---|---|---|
| Time slot 1 | $\mathbf{y}_1$ | $\mathbf{y}_2$ |
| Time slot 2 | $-(\acute{\mathbf{y}}_2)^*$ | $(\acute{\mathbf{y}}_1)^*$ |

Table 4.2: STC-MIMO in the frequency domain

| Antenna | TX1 | TX2 |
|---|---|---|
| Time slot 1 | $\mathbf{Y}_1$ | $\mathbf{Y}_2$ |
| Time slot 2 | $-\mathbf{Y}_2^*$ | $\mathbf{Y}_1^*$ |

In order to obtain a conjugation of the signal in the frequency domain, we maintain the first symbol and reverse the remaining symbols of the input vectors $\mathbf{y}_1$ and $\mathbf{y}_2$ respectively to generate $\acute{\mathbf{y}}_1$ and $\acute{\mathbf{y}}_2$ in the time domain. Theoretically, this is equivalent to periodically extending $\mathbf{y}_1$ and $\mathbf{y}_2$, then reversing all symbols and taking one period. At given time slot, $\mathbf{y}_1$ is transmitted from transmitter one and $\mathbf{y}_2$ is transmitted from transmitter two. During the next time slot, $-(\acute{\mathbf{y}}_2)^*$ and $(\acute{\mathbf{y}}_1)^*$ are transmitted from transmitter one and two, respectively, where $*$ denotes the complex conjugation. As a result, the Alamouti code can be accordingly realized in the frequency domain. Table 4.1 and Table 4.2 show the relationship between the STC-MIMO encoding in the time domain and the frequency domain.

To deal with the effect of multipath channels between transmitters and receivers, a CP of length $L$, which is a copy of the last $L$ symbols of each STC-MIMO BS-OFDMA vector, will be added in front of that vector before transmission. The length of CP should be longer than the maximum channel multipath delay spread in order to turn the linear convolution of the transmitted signal with the channel impulse response into a circular one. Thus, the transmitted signal block has $MN+L$ symbols in total after CP is added.

## 4.3 Signal model for receiver

For simplicity, we consider a structure with one receive antenna to explain the receiver algorithms for STC-MIMO decoding, block despreading and channel equalization in detail. In order to achieve a higher order of diversity, we extend the reciever structure to the case of two receive antennas. In such a case, it attempts to double the diversity order by simply adding an extra antenna, and thus a further performance improvement is obtained.

### 4.3.1 MIMO channel model for one receiver

Figure 4.5 shows the baseband representation of the block spread STC-MIMO OFDMA receiver structure with one antenna. The received signals are first transformed from the time domain to the frequency domain, which is done by an FFT processing. It is much more insightful to consider the decoding process in the frequency domain, although the time domain model is straightforward. The frequency domain signals are then sent to the STC-MIMO decoder, where a decoding algorithm is developed for one receiver.

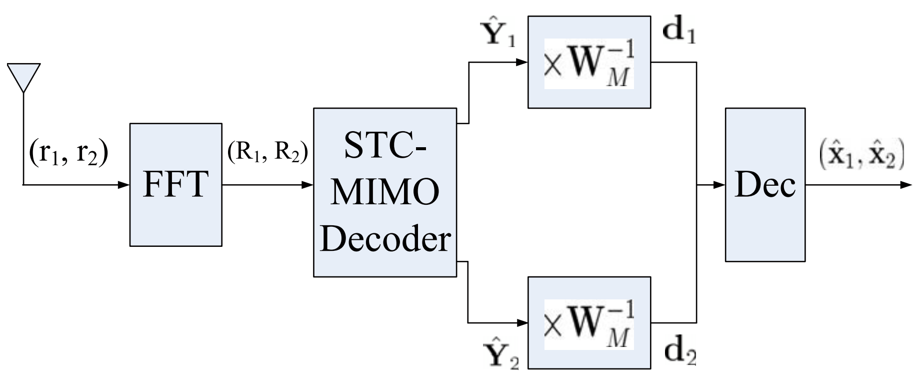


Figure 4.5: Block spread STC-MIMO OFDMA receiver model with one antenna.

Let $H_1[k]$ and $H_2[k]$ be the channel frequency responses for the $k$-th subcarrier corresponding to two transmitters and one reciever. We assume that those channel responses are constant during periods of two consecutive block data vectors and known to the receiver. After removing the CP, the $MN$-point FFT and $N$ factor down-sampling are implemented to generate frequency domain signals. Thus, the received signals in the frequency domain can be expressed by $R_1[k]$ and $R_2[k], k = 0, 1, \cdots, M-1$, as

$$R_1[k] = Y_1[k]H_1[k] + Y_2[k]H_2[k] + V_1[k] \tag{4.7}$$

$$R_2[k] = -Y_2^*[k]H_1[k] + Y_1^*[k]H_2[k] + V_2[k], \tag{4.8}$$

where $V_1[k]$ and $V_2[k]$ are noise samples for $k$-th subcarrier on each channel that can be modeled as complex Gaussian random variables with zero mean and power $N_0/2$ per dimension. To group the received symbols to be a vector format, the above equations can be equivalently expressed as follows,

$$\mathbf{R}_1 = \mathbf{Y}_1\mathbf{H}_1 + \mathbf{Y}_2\mathbf{H}_2 + \mathbf{V}_1 \tag{4.9}$$

$$\mathbf{R}_2 = -\mathbf{Y}_2^*\mathbf{H}_1 + \mathbf{Y}_1^*\mathbf{H}_2 + \mathbf{V}_2, \tag{4.10}$$

where we denote

$$\begin{aligned}
\mathbf{R}_1 &= (R_1[0], R_1[1], \cdots, R_1[M-1]), \\
\mathbf{R}_2 &= (R_2[0], R_2[1], \cdots, R_2[M-1]), \\
\mathbf{Y}_1 &= (Y_1[0], Y_1[1], \cdots, Y_1[M-1]), \\
\mathbf{Y}_2 &= (Y_2[0], Y_2[1], \cdots, Y_2[M-1]), \\
\mathbf{H}_1 &= diag(H_1[0], H_1[1], \cdots, H_1[M-1]), \\
\mathbf{H}_2 &= diag(H_2[0], H_2[1], \cdots, H_2[M-1]), \\
\mathbf{V}_1 &= (V_1[0], V_1[1], \cdots, V_1[M-1]), \\
\mathbf{V}_2 &= (V_2[0], V_2[1], \cdots, V_2[M-1]).
\end{aligned} \tag{4.11}$$

Note that $\mathbf{H}_1$ and $\mathbf{H}_2$ are $M \times M$ matrices with diagonal elements decimated from the channel discrete frequency responses $H_1[k]$, and $H_2[k], k = 0, 1, \cdots, M-1$, respectively.

For simplicity of expression, we define $\mathbf{R} = (\mathbf{R}_1,\ \mathbf{R}_2^*)$, $\mathbf{Y} = (\mathbf{Y}_1,\ \mathbf{Y}_2)$, $\mathbf{H} = \begin{pmatrix} \mathbf{H}_1 & \mathbf{H}_2^* \\ \mathbf{H}_2 & -\mathbf{H}_1^* \end{pmatrix}$ and $\mathbf{V} = (\mathbf{V}_1,\ \mathbf{V}_2^*)$. Thus, Eq. 4.9 and Eq. 4.10 can be rewritten in a matrix form as

$$\mathbf{R} = \mathbf{Y}\mathbf{H} + \mathbf{V}. \tag{4.12}$$

### 4.3.2 MIMO channel model for two receivers

The receiver model can be easily generalized to multiple receive antennas to provide a higher order of diversity. For illustration, we discuss an another example in detail, where the receiver is equipped with two antennas. Figure 4.6 shows the baseband representation of the receiver with two antennas.

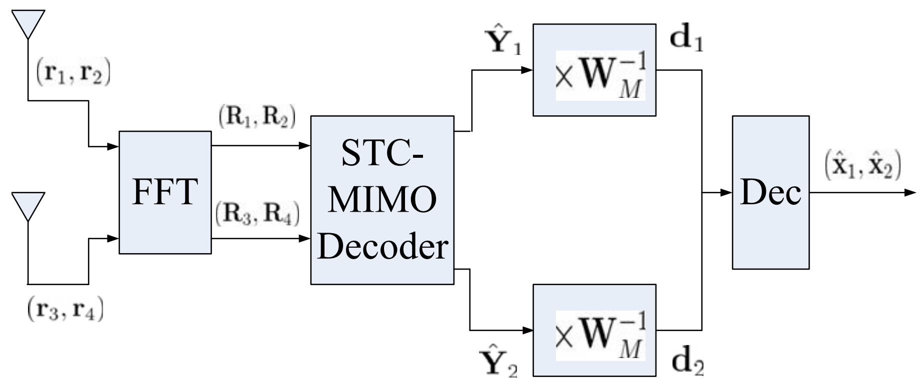


Figure 4.6: Block spread STC-MIMO OFDMA receiver model with two antenna.

The transmitter structure and encoding algorithms of the information symbols for this example is identical to the case of a single receiver, shown in Figure 4.1. Instead of two channels in the single receiver, we have four independent channels corresponding to two transmitter and two receiver. Table 4.3 defines the channel frequency responses at $k$-th subcarrier between the transmit and receive antennas. Table 4.4 defines the notation of the received signals at the $k$-th subcarrier in the frequency domain at the two receive antennas.

Like the channel model for one receiver, the same assumption is made to two receivers that channel responses are constant during periods of two consecutive symbol vectors and known to the receivers. Therefore, the received signals are similarly

Table 4.3: Channels between the transmit and receive antennas

| | RX antenna1 | RX antenna2 |
|---|---|---|
| TX antenna1 | $H_1[k]$ | $H_3[k]$ |
| TX antenna2 | $H_2[k]$ | $H_4[k]$ |

Table 4.4: Received signals at the two receive antennas

| | RX antenna1 | RX antenna2 |
|---|---|---|
| Time slot 1 | $R_1[k]$ | $R_3[k]$ |
| Time slot 2 | $R_2[k]$ | $R_4[k]$ |

expressed as

$$\begin{aligned}
&R_1[k] = Y_1[k]H_1[k] + Y_2[k]H_2[k] + V_1[k] \\
&R_2[k] = -Y_2^*[k]H_1[k] + Y_1^*[k]H_2[k] + V_2[k] \\
&R_3[k] = Y_1[k]H_3[k] + Y_2[k]H_4[k] + V_3[k] \\
&R_4[k] = -Y_2^*[k]H_3[k] + Y_1^*[k]H_4[k] + V_4[k] \\
&k = 0, 1, \cdots, M-1,
\end{aligned} \tag{4.13}$$

where $V_1[k]$, $V_2[k]$, $V_3[k]$ and $V_4[k]$ are complex Gaussian random variables representing noise samples for $k$-th subcarrier on each channel. For clearness, the above equation can be transformed to a vector expression as

$$\begin{aligned}
\mathbf{R}_1 &= \mathbf{Y}_1\mathbf{H}_1 + \mathbf{Y}_2\mathbf{H}_2 + \mathbf{V}_1 \\
\mathbf{R}_2 &= -\mathbf{Y}_2^*\mathbf{H}_1 + \mathbf{Y}_1^*\mathbf{H}_2 + \mathbf{V}_2 \\
\mathbf{R}_3 &= \mathbf{Y}_1\mathbf{H}_3 + \mathbf{Y}_2\mathbf{H}_4 + \mathbf{V}_3 \\
\mathbf{R}_4 &= -\mathbf{Y}_2^*\mathbf{H}_3 + \mathbf{Y}_1^*\mathbf{H}_4 + \mathbf{V}_4
\end{aligned} \tag{4.14}$$

if we denote

$$\begin{aligned}
\mathbf{R}_1 &= (R_1[0], R_1[1], \cdots, R_1[M-1]), \\
\mathbf{R}_2 &= (R_2[0], R_2[1], \cdots, R_2[M-1]), \\
\mathbf{R}_3 &= (R_3[0], R_3[1], \cdots, R_3[M-1]), \\
\mathbf{R}_4 &= (R_4[0], R_4[1], \cdots, R_4[M-1]), \\
\mathbf{Y}_1 &= (Y_1[0], Y_1[1], \cdots, Y_1[M-1]), \\
\mathbf{Y}_2 &= (Y_2[0], Y_2[1], \cdots, Y_2[M-1]), \\
\mathbf{H}_1 &= diag(H_1[0], H_1[1], \cdots, H_1[M-1]), \\
\mathbf{H}_2 &= diag(H_2[0], H_2[1], \cdots, H_2[M-1]), \\
\mathbf{H}_3 &= diag(H_3[0], H_3[1], \cdots, H_3[M-1]), \\
\mathbf{H}_4 &= diag(H_4[0], H_4[1], \cdots, H_4[M-1]), \\
\mathbf{V}_1 &= (V_1[0], V_1[1], \cdots, V_1[M-1]), \\
\mathbf{V}_2 &= (V_2[0], V_2[1], \cdots, V_2[M-1]), \\
\mathbf{V}_3 &= (V_3[0], V_3[1], \cdots, V_3[M-1]), \\
\mathbf{V}_4 &= (V_4[0], V_4[1], \cdots, V_4[M-1]).
\end{aligned} \tag{4.15}$$

Similarly, in order to derive a general expression, we can further define $\mathbf{R} = (\mathbf{R}_1,$ $\mathbf{R}_2^*,$ $\mathbf{R}_3,$ $\mathbf{R}_4^*)$, $\mathbf{Y} = (\mathbf{Y}_1,\ \mathbf{Y}_2)$, $\mathbf{H} = \begin{pmatrix} \mathbf{H}_1 & \mathbf{H}_2^* & \mathbf{H}_3 & \mathbf{H}_4^* \\ \mathbf{H}_2 & -\mathbf{H}_1^* & \mathbf{H}_4 & -\mathbf{H}_3^* \end{pmatrix}$ and $\mathbf{V} = (\mathbf{V}_1,\ \mathbf{V}_2^*,$

$\mathbf{V}_3$, $\mathbf{V}_4^*$). Therefore, Eq. 4.14 can be also rewritten to Eq. 4.12.

It is interesting to note that the channel models for the receiver with one antenna and two antennas can be represented by the same general expression as shown in Eq. 4.12, although the definitions of the $\mathbf{R}$, $\mathbf{H}$ and $\mathbf{V}$ are different in each equation. We may hence conclude that, the MIMO scheme can be feasiblely extended from the special cases of one receiver and two receiver to a general environment where multiple antennas, say $Q$ antennas, are applied on the receiver. We can use the same expression as shown in Eq. 4.12 to represent the channel model for $Q$ receiver, where

$$\begin{aligned}
&\mathbf{R} = (\mathbf{R}_1, \mathbf{R}_2^*, \cdots, \mathbf{R}_{2Q-1}, \mathbf{R}_{2Q}^*), \\
&\mathbf{Y} = (\mathbf{Y}_1, \mathbf{Y}_2), \\
&\mathbf{H} = \begin{pmatrix} \mathbf{H}_1 & \mathbf{H}_2^* & \cdots & \mathbf{H}_{2Q-1} & \mathbf{H}_{2Q}^* \\ \mathbf{H}_2 & -\mathbf{H}_1^* & \cdots & \mathbf{H}_{2Q} & -\mathbf{H}_{2Q-1}^* \end{pmatrix}, \\
&\mathbf{V} = (\mathbf{V}_1, \mathbf{V}_2^*, \cdots, \mathbf{V}_{2Q-1}, \mathbf{V}_{2Q}^*).
\end{aligned} \tag{4.16}$$

Therefore, the STC-MIMO scheme for the proposed system can be easily generalized to two transmit antennas and $Q$ receive antennas to provide a higher diversity order of with only small computation complexity.

### 4.3.3 Linear equalization

In contrast to ML detection, the linear equalization is preferable in practice since it simply uses a one-tap equalizer for each subcarrier in the frequency domain. Let $\mathbf{C}$ denote the one-tap equalizer coefficient to be applied to $\mathbf{R}$ that is expressed as $\mathbf{R} = \mathbf{YH} + \mathbf{V}$ as shown in above equations. For simplicity, here we only consider the example of using one receive antenna, where $\mathbf{R} = (\mathbf{R}_1, \mathbf{R}_2^*)$. The process of linear equalization can be described as that $\mathbf{C}$ is applied to $\mathbf{R}$ to produce an equalized vector $\hat{\mathbf{Y}} = \mathbf{RC}$. In order to be related to $\mathbf{Y} = (\mathbf{Y}_1, \mathbf{Y}_2)$, the equalized vector $\hat{\mathbf{Y}}$ can also be written as $\hat{\mathbf{Y}} = (\hat{\mathbf{Y}}_1, \hat{\mathbf{Y}}_2)$.

When the MMSE criterion is used to design $\mathbf{C}$, the mean squared error (MSE) between $\hat{\mathbf{Y}}$ and $\mathbf{Y}$ that ban be expressed as

$$\varepsilon^2 = E\left\{(\hat{\mathbf{Y}} - \mathbf{Y})^\dagger(\hat{\mathbf{Y}} - \mathbf{Y})\right\} \tag{4.17}$$

is minimized, where $(\cdot)^\dagger$ denotes the matrix transposition and complex conjugation operation. Since $\hat{\mathbf{Y}} = \mathbf{RC}$, the MSE express in 4.17 can be rewritten as

$$\varepsilon^2 = E\left\{(\mathbf{RC} - \mathbf{Y})^\dagger(\mathbf{RC} - \mathbf{Y})\right\}. \tag{4.18}$$

Applying the orthogonality principle, we have

$$E\left\{(\mathbf{RC} - \mathbf{Y})\mathbf{R}^\dagger\right\} = 0 \tag{4.19}$$

and consequently,

$$\mathbf{C} = E\left\{\mathbf{YR}^\dagger\right\}(E\left\{\mathbf{RR}^\dagger\right\})^{-1}. \tag{4.20}$$

Substituting Eq. 4.12 into Eq. 4.20, the $\mathbf{C}$ can be consequently derived as

$$\begin{aligned}
\mathbf{C} &= E\{\mathbf{Y}(\mathbf{YH}+\mathbf{V})^\dagger\}(\mathbf{E}\{(\mathbf{YH}+\mathbf{V})(\mathbf{YH}+\mathbf{V})^\dagger\})^{-1} \\
&= E\{\mathbf{YY}^\dagger\}\mathbf{H}^\dagger(\mathbf{H}E\{\mathbf{YY}^\dagger\}\mathbf{H}^\dagger + E\{\mathbf{VV}^\dagger\})^{-1} \\
&= \mathbf{H}^\dagger\left(\mathbf{HH}^\dagger + \tfrac{1}{\gamma_{in}}\mathbf{I}\right)^{-1},
\end{aligned} \tag{4.21}$$

where $\mathbf{I}$ is the identity matrix with the same size of $\mathbf{H}$, and $\gamma_{in}$ is the input SNR before equalization.

As seen from Eq. 4.21, the MMSE equalization requires the knowledge of the input SNR. If this knowledge is not available, ZF equalization can be performed by assuming no noise is present at the receiver and selecting the equalizer coefficients to force the ISI to zero. Hence, for ZF equalization, the equalizer coefficient can be expressed as

$$\mathbf{C} = \mathbf{H}^\dagger\left(\mathbf{HH}^\dagger\right)^{-1}. \tag{4.22}$$

However, pure ZF equalization enhances noise power when the input SNR is low and causes dividing-by-zero problem at null subcarriers. In practice, we can design a general expression of the linear equalizer coefficient $\mathbf{C}$ according to an estimated reference SNR $\gamma_{ref}$ as

$$\mathbf{C} = \mathbf{H}^{\dagger}\left(\mathbf{H}\mathbf{H}^{\dagger} + \frac{1}{\gamma_{ref}}\mathbf{I}\right)^{-1}. \tag{4.23}$$

Apparently, if $\gamma_{ref} = \gamma_{in}$ this linear equalization becomes the MMSE equalization, and as $\gamma_{ref} \to \infty$ it becomes the ZF equalization.

Therefore, according to above analysis, the output signal vector after the MIMO detection and linear equalization becomes $\hat{\mathbf{Y}} = \mathbf{RC} = (\hat{\mathbf{Y}}_1,\ \hat{\mathbf{Y}}_2)$. It is then sent to the following module, where the block despreading is performed to yield the decision variable vector $\mathbf{d} = (\mathbf{d}_1,\ \mathbf{d}_2)$ and finally the estimated data symbol vector $\hat{\mathbf{x}} = (\hat{\mathbf{x}}_1,\ \hat{\mathbf{x}}_2)$ can be retrieved after hard decision on the decision variable vector.

### 4.3.4 Block despreading

The process of block despreading includes three steps that are described as follows. First, the $MN$-point DFT is performed to transform the received signals $\mathbf{r}_t, t = 1$ or 2 from time domain to frequency domain. Second, a N factor down-sampling is applied on the $MN$ length frequency domain signals yeild baseband signals $\mathbf{R}_t$ with length of $M$. The above two steps are done at the beginning of the receiver. Finally, after the MIMO detection and linear equalization to remove the effect of multipath channels, a despreading matrix is assigned to recover the transmitted data symbol vector $\hat{\mathbf{x}}_t$ from the spreading vector $\hat{\mathbf{Y}}_t$, where data symbols are block coded and spread across the subcarriers.

According to the frequency domain characteristics of the transmitted BS-OFDMA signal shown in Figure 4.3, the $M$ data symbols for each specific user are mixed and spread over whole system frequency band of $MN$ length, where $N$ is the total number of users in the system. In spite of the symbol spreading characteristic, we first take account of the bandwidth usage in the system. Rather than dividing the wide frequency band into a serial of narrowbands and separately assigning those narrowbands to each user, the frequency band in the proposed system is shared by all users. In other words, the data symbols for each user in the system are interleaved across equally spaced subcarriers. Since the total length of the system frequency band is $MN$ and each user only occupies the $M$ equally spaced subcarriers, the $MN$-point DFT and $N$ factor down-sampling are required to yield the baseband signals with length of $M$ corresponding to a specific user.

We assume that $R_t[k], k = 0, 1, \cdots, MN - 1$ represents the output of the $MN$-point DFT of received signals $r_t[i], i = 0, 1, \cdots, MN - 1$. As shown in Figure 4.7, the $N$ factor down-sampling of $R_t[k]$ is based on the user index $K$ and implemented starting from $R_t[K]$, where $K = 0, 1, \cdots, N-1$. Note that the $MN$-point DFT and $N$ factor down-sampling are done at the beginning of the receiver in order to reduce the computation complexity for the following system decoding processes.

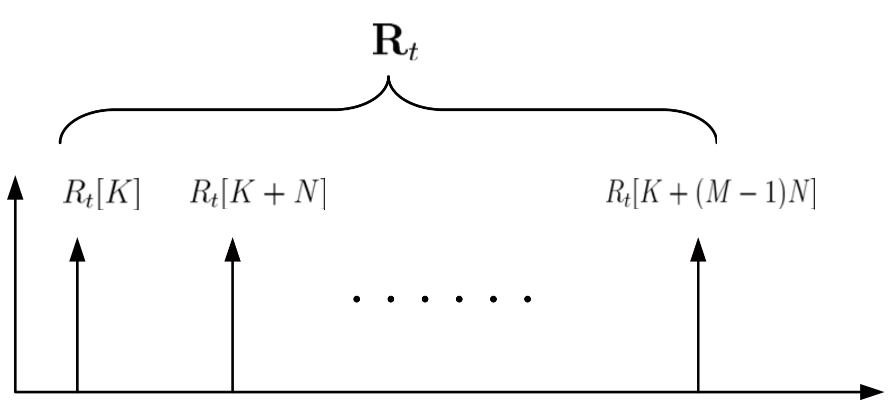


Figure 4.7: The $N$ factor down-sampling for a specific user with index $K$.

To recover the transmitted data symbols from the decoded spreading vector $\hat{\mathbf{Y}}_t$, a despreading matrix $\mathbf{W}_M^{-1}$ is designed according to 4.6. It is shown in below

$$\mathbf{W}_M^{-1} = \frac{1}{N} \begin{bmatrix} e^{\beta K\times 0} & e^{\beta K\times 1} & \cdots & e^{\beta K\times (M-1)} \\ e^{\beta (K+N)\times 0} & e^{\beta (K+N)\times 1} & \cdots & e^{\beta (K+N)\times (M-1)} \\ \vdots & \vdots & \ddots & \vdots \\ e^{\beta [K+(M-1)N]\times 0} & e^{\beta [K+(M-1)N]\times 1} & \cdots & e^{\beta [K+(M-1)N]\times (M-1)} \end{bmatrix}, \tag{4.24}$$

where $\beta$ denotes $j\frac{2\pi}{MN}$. By performing the despreading matrix to yeild the decision variable vector $\hat{\mathbf{x}}_t$, we have

$$\hat{\mathbf{x}}_t = \hat{\mathbf{Y}}_t \mathbf{W}_M^{-1}. \tag{4.25}$$

According to Eq. 4.25, the $m$th element of $\hat{\mathbf{x}}_t$ is obtained from $\hat{Y}_t[l]$ by

$$\begin{aligned} \hat{x}_t[m] &= \frac{1}{N}\sum_{l=0}^{M-1} \hat{Y}_t[l] e^{j\frac{2\pi}{MN}(K+lN)m}, \\ &= \frac{1}{N}\sum_{l=0}^{M-1} \hat{Y}_t[l] e^{j\frac{2\pi}{MN}Km} e^{j\frac{2\pi}{M}lm}, \\ &= \frac{1}{N} e^{j\frac{2\pi}{MN}Km} \sum_{l=0}^{M-1} \hat{Y}_t[l] e^{j\frac{2\pi}{M}lm}, \\ m &= 0, 1, \cdots, M-1. \end{aligned} \tag{4.26}$$

Note that, if there is no noise or multipath present, i.e., $\mathbf{Y}_t = \mathbf{R}_t = \hat{\mathbf{Y}}_t$, we can expect that $\hat{\mathbf{x}}_t$ is the recovered transmitted data symbol vector $\mathbf{x}_t$. This can be confirmed from Eq. 4.26. According to Eq. 4.3, we have

$$\begin{aligned} Y_t[l] &= N\sum_{m=0}^{M-1} x_t[m] e^{-j\frac{2\pi}{MN}(K+lN)m}, \\ l &= 0, 1, \cdots, M-1. \end{aligned} \tag{4.27}$$

Since $\hat{Y}_t[l] = Y_t[l]$, substituting Eq. 4.27 in Eq. 4.26, consequently we can obtain

$$\hat{x}_t[m] = e^{j\frac{2\pi}{MN}Km} x_t[m] e^{-j\frac{2\pi}{MN}Km} = x_t[m]. \tag{4.28}$$

Therefore, with noise and multipath present, $\hat{\mathbf{x}}_t$ can be used as a hard decision variable vector to retrieve the transmitted data information.

## 4.4 Chapter summary

In this chapter, we propose an advanced OFDMA system where the block spreading technique and STC-MIMO scheme are effectively combined with the OFDMA modulation. Like other OFDM system with block spreading, a significant performance improvement is achieved compared to the system without block spreading as block spreading technique is used to eliminate or at least mitigate the effect of frequency selective fading channels by providing frequency diversity. However, in contrast to the traditional BS-OFDM/OFDMA systems, the combination of block spreading and OFDMA in the proposed system is addressed by simply using a complex exponential sequence instead of any explicit precoding process and IFFT implementation, thus greatly reducing the computation complexity and simplifying the design structures for the transmitter and receiver. The mathematical models and theoretical analyses are presented to describe the proposed BS-OFDMA approach in detail and demonstrate the advantage that it is able to provide.

The STC-MIMO using Alamouti code is used to gain additional diversity. The Alamouti code in our MIMO scheme is imposed to block basis and performed in space and frequency. First, we explain this scheme based on an example with two transmit antennas and one receive antenna. Then, the scheme is extended to two transmit antennas and two receive antennas. Finally, a general mathematical expression is derived to extend the scheme to two transmit antennas and multiple receive antennas, where a higher diversity gain can be obtained at the cost of slightly increased computation complexity.

We further propose the design of receiver, where STC-MIMO decoding, channel equalization and block despreading are performed, respectively. With the number of the receive antennas increases, the computation complexity of STC-MIMO decoding increases as more corresponding multipath channels present. The MMSE equalization is preferable as it provides better performance than ZF equalization and less complexity than ML detection. The despreading matrix is used to retrieve the data symbols from the spreading vector, where symbols are mixed and spread across the subcarriers. At last, simulations are carried out to implement the proposed system and confirm the expected performance improvement. The simulation implementation will be described in detail in next chapter as well as revelant result analyses.

# Chapter 5

# System performance simulations

In this chapter, we describe the simulation implementation in detail and consequently provide the simulation results in regard to BER performance comparisons between the proposed block spread STC-MIMO OFDMA system and other conventional schemes. In last chapter, we have predicted that the proposed system can achieve better system performance due to the diversity advantages provided by the block spreading and STC-MIMO scheme. Simulations are, therefore, carried out to confirm those advantages and demonstrate its estimated performance improvement by comparisons with the conventional OFDMA system without using any block spreading or MIMO scheme. In addition to the proposed system scheme, the perfromance can be affected by some other issues, such as the symbol group size, the number of receive antennas and different linear equalizations. Accordingly, simulations are carried out to demonstrate how system performance is effected by these issues.

This chapter is organized as follows. The simulation parameters and some implementation issues are first presented to start this chapter. The numerous simulation comparisons are shown as following with the performance analyses based on different simulation results. In order to demonstrate the significant advantage of the proposed system, we present a performance comparison between the proposed system and other schemes. Then we present a similar performance comparison with a larger symbol group size. We also present a performance comparison between the proposed system with one receive antenna and that with two receive antennas. The performance comparison of MMSE and ZF equalization respectively applied on the proposed system is shown at last.

## 5.1 Implementation issues

From practical implementation aspects, some simulation issues may need to be considered and appropriate simulation parameters should be accordingly defined. This section discusses some of the crucial implementation issues according to the proposed system design. Then the parameters used for the simulations are given in detail.

### 5.1.1 Power requirements

If the system is radiaion power limited, we assume that the total transmit power from the two antennas for the proposed STC-MIMO BS-OFDMA system is the same as the transmit power from the single transmit antenna for the conventional OFDMA system with and without block spreading. In order to address this assumption, we normalize the power of signals transmitted from each antenna of the proposed system to be half of the transmitted power in a single antenna system. Although the reduction of the signal power for each transmit antenna by half incurs a penalty in the BER performance, it provides a fair environment for comparison with known single antenna systems. Moreover, the reduction of power in each transmit chain results to cheaper, smaller, or less linear power amplifiers in practice. It is often less expensive to employ two half-power amplifiers rather than a single full power amplifier.

### 5.1.2 Antenna configuration

In practice, the primary requirement for diversity improvement is that the signals transmitted from the different antennas be sufficiently uncorrelated and that they have almost equal average power. For this purpose, we assume that the amplitudes of fading from each transmit antenna to each receive antenna are mutually uncorrelated and the average signal powers from each transmit antenna to each receive antenna are normalized to be the same.

Consider the proposed system using two transmit antennas and one receive antenna, we use the tapped delay line model to create two frequency selective multipath channels and the multipath diversity order for each channel is assumed to be $L_P$. In order to obtain the full diversity in practice, the antennas should be sufficiently separated and therefore each channel for a specific link can be considered to be independent. MIMO brings diversity gain to systems in practice due to the advantage of multipath channels. In our simulation work, however, the diversity gain generated by channels is unified among different systems in order to make performance comparisons under the normalized SNR. Therefore, the channel normalization is required. The coefficients for each channel of the two transmit antennas and one receive antenna system are modeled as complex Gaussian random variables with zero-mean and variance $1/2L_P$.

Similarly, consider the proposed system using two transmit antennas and two receive antennas, we accordingly create four frequency selective multipath channels with the same multipath order of $L_P$ for each channel, and the coefficients for each channel are also modeled as complex Gaussian random variables with zero-mean and variance $1/4L_P$.

### 5.1.3 Parameters for simulations

In a multiuser environment, we only consider the simulations on a specific user in terms of its user index $K$, which can be any value from 0 to $N-1$ and $N$ is the total number of users in the system. Here we choose $N = 8$ and $K = 3$, respectively. Another important issue about the simulation parameters is how to select a proper symbol group size for block spreading. Intuitively, the larger the symbol group size is, the better the system performance wil be. However, a larger symbol group size also implies higher implementation complexity. On the other hand, if the symbol group size is too small, the available diversity provided by the multipath channel cannot be fully exploited. Therefore, determining a proper symbol group size according to the available multipath diversity order is of significance to the proposed block spread OFDMA scheme. In order to make a comparison between different symbol group sizes, we use $M = 16$ or $M = 32$ to be the size of block unit, respectively. Accordingly, the number of multipaths for each channel is defined as $L_P = 8$. The length of cyclic prefix is defined as $L = 16$ to satisfy the requirement that the length of CP must be sufficiently longer than the maximum multipath delay to avoid interference between adjacent symbols. For MIMO configuration, two antennas are applied at the transmitter and at the receiver, either one or two antennas are used respectively to achieve different diversity orders. The maximum Doppler frequency is another factor that can influence the system performance as it breaks the orthogonality of OFDM subcarriers. In our system, the maximum Doppler frequency is defined to be 50Hz. We use the QPSK modulation as the signal constellation where informantion bits are mapped to modulated symbols. The parameters used for the simulations are given in Table 5.1.

Table 5.1: Parameters for Simulations

| **Parameter** | **Value** |
|---|---|
| Number of users $N$ | 8 |
| Index of a specific user $K$ | 3 |
| Size of block unit $M$ | 16 or 32 |
| Cyclic prefix length $L$ | 16 |
| Number of multipaths $L_P$ | 8 |
| Number of transmit antennas | 2 |
| Number of receive antennas | 1 or 2 |
| Maximum Doppler frequency | 50Hz |
| Modulation | QPSK |
| Number of simulation runs | 10000 |

## 5.2 Numerical simulation results

In this section, numerical simulation results are provided. First, a BER performance comparison between the conventional OFDMA system, OFDMA systems with either block spread or STC-MIMO and the proposed STC-MIMO BS-OFDMA system is presented, where the benefits provided by block spreading and STC-MIMO can be easily recognized. Next, BER performance for systems with a larger symbol group size is shown to demonstrate that a further performance improvement can be obtained by increasing the symbol group size for block spreading. Then, we increase the number of receive antennas from one to two for the proposed STC-MIMO BS-OFDMA system and consequently the related performance comparison is shown. It demonstrates that the system performance can be further improved by increasing the number of receive antennas. Finally, we present the performance comparison between the systems using different linear equalizations. As the same to that we analyzed previously, the MMSE equalization always achieves better performance than the ZF equalization.

### 5.2.1 Simulation results for the proposed system

Figure 5.1 shows the BER performance comparison between the conventional OFDMA system and the OFDMA systems with either proposed block spreading approach or STC-MIMO scheme. In this case, the symbol group size for block spreading is $M = 16$ and two transmit antennas and one receive antenna are used for MIMO transmission.

As we can see from Figure 5.1, both OFDMA systems with block spreading and STC-MIMO can provide improved BER performance over the conventional OFDMA system. For example, the STC-MIMO OFDMA system provides 5dB SNR gain over the conventional OFDMA system at BER$= 10^{-4}$. This is because that the STC-MIMO scheme is able to offer OFDMA systems with spatial diversity, therefore improving system performance. As we analyzed before, the proposed block spreading approach is supposed to achieve a significant performance improvement for OFDMA systems as it greatly mitigates the effect of frequency selective fading channels by spreading data symbols across all subcarriers for each user. Now this anticipated performance improvement is approved by the simulation result. As illustrated, a 5dB SNR gain is achieved by the BS-OFDMA system at BER$= 10^{-4}$, compared with the conventional OFDMA system.

We can further notice that the BS-OFDMA system can achieve better performance than the STC-MIMO OFDMA system at low SNRs. For example, the performance curve of the BS-OFDMA system is always below the curve of the STC-MIMO OFDMA system before 15dB SNR. However, the performance curve of the STC-MIMO OFDMA system comes above that of the BS-OFDMA system at high SNRs, say after 15dB SNR. Therefore, we can conclude that the STC-MIMO may achieve better performance than the block spreading when SNR goes high.

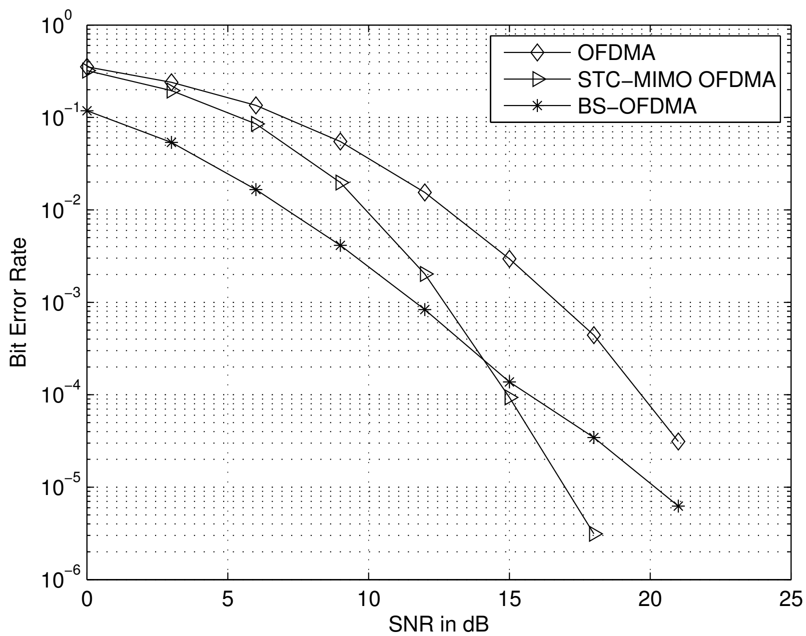


Figure 5.1: Performance comparison between OFDMA system, STC-MIMO OFDMA system and BS-OFDMA system.

So far, we have demonstrated that the proposed block spreading approach and STC-MIMO scheme can be used separately to improve OFDMA system performance. However, a more significant performance improvement is anticipated in the proposed STC-MIMO BS-OFDMA system, where the effects of block spread and STC-MIMO are added up.

Figure 5.2 shows the BER performance comparison between the STC-MIMO OFDMA system, BS-OFDMA system and the proposed STC-MIMO BS-OFDMA

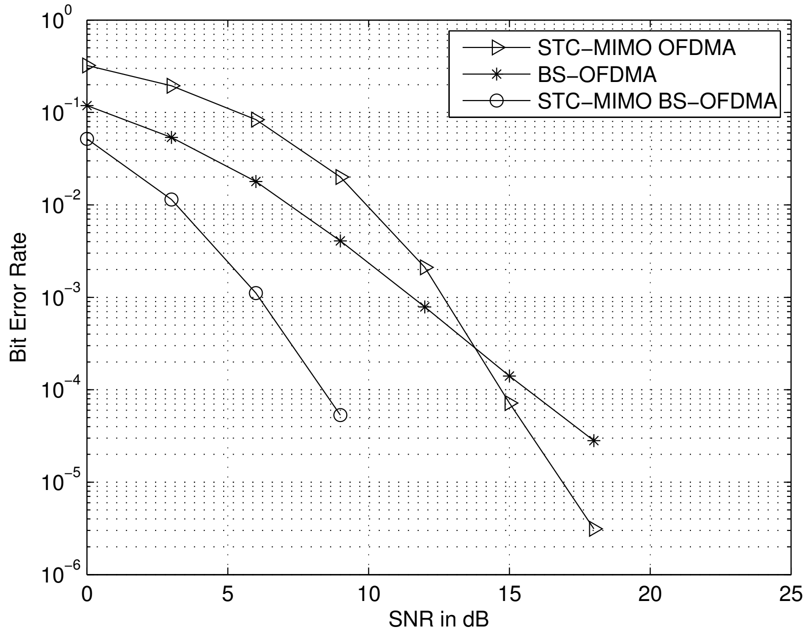


Figure 5.2: Performance comparison between STC-MIMO OFDMA system, BS-OFDMA system and STC-MIMO BS-OFDMA system.

system. In this case, we keep the symbol group size for block spreading as $M = 16$ and maintain the MIMO architecture in terms of two transmit antennas and one receive antenna.

As we can see from Figure 5.2, the proposed STC-MIMO BS-OFDMA system provides the best performance among the considered systems. Compared to STC-MIMO OFDMA system and BS-OFDMA system, the proposed system can achieve a very small bit error rate at a low SNR. In particular, it provides 7dB SNR gain over BS-OFDMA system and 6dB SNR gain over STC-MIMO OFDMA system, respectively, at BER$= 10^{-4}$.

This simulation result has approved the significant performance improvement that we anticipated for the proposed system. Therefore, we may conclude that the advantages of block spread and STC-MIMO can be successfully accumulated in the proposed system and consequently a combined significant performance improvement is achieved.

### 5.2.2 Simulation results for a larger block spreading size

It is noted that, besides depending on the block spreading and STC-MIMO scheme, the behavior of the proposed STC-MIMO BS-OFDMA system also depends on other parameters, such as the symbol group size $M$. The selection of a proper symbol group size usually is based on the number of the multipath channels presented in the system. If the symbol group size is too small, the available diversity provided by the multipath channels can not be fully exploited. Normally, the larger the symbol group size is, the better the system performance will be. However, a larger symbol group size also results to higher implementation complexity.

In our simulations, the proper symbol group size is strictly related to the multipath diversity order, which is defined as $L_P$. The principle that we use to determine a proper symbol group size for our proposed system is that the symbol group size $M$ should be equal to or slightly larger than the multipath diversity order $L_P$. For example, given the multipath diversity order $L_P = 16$, the proper symbol group size should be 16 or 32. As shown previously, Figure 5.1 and 5.2 present the simulation results, where $M = 16$ is used for the symbol group size. Then, we increase the symbol group size to $M = 32$ and as a result, different simulation results are shown as following.

Figure 5.3 presents a BER performance comparison between OFDMA system, STC-MIMO OFDMA system and BS-OFDMA system with a larger symbol group size. Compared to Figure 5.1, in this case, we increase the symbol group size to $M = 32$. By comparing Figure 5.3 and 5.1, we can see that the performance curves of OFDMA system and STC-MIMO OFDMA system do not change too much, but the performance for BS-OFDMA system has a significant improvement when the symbol group size increases. For example, to achieve the same BER$= 10^{-5}$, the former BS-OFDMA system with $M = 16$ requires 20dB SNR, and the latter BS-OFDMA system with $M = 32$ only requires 17dB SNR, therefore the system with a larger symbol group size for block spreading achieves a 3dB SNR advantage over the system with a smaller symbol group size.

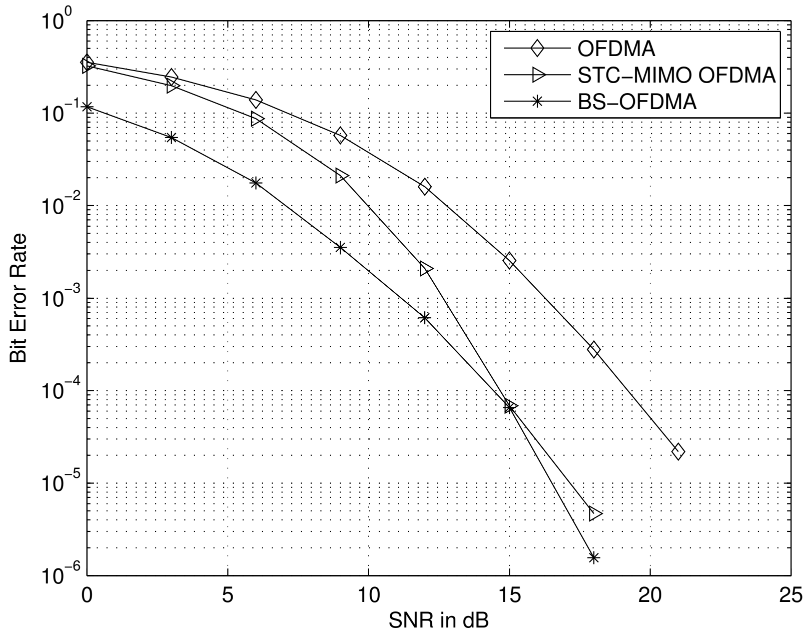


Figure 5.3: Performance comparison between OFDMA system, STC-MIMO OFDMA system and BS-OFDMA system with a larger symbol group size.

Figure 5.4 presents a BER performance comparison between STC-MIMO OFDMA system, BS-OFDMA system and STC-MIMO BS-OFDMA system with a larger symbol group size. Similarly, we increase the symbol group size to $M = 32$. Compared Figure 5.4 with 5.2, we can realize that the proposed STC-MIMO BS-OFDMA system still provides the best system performance in terms of achieving a 7dB SNR gain over the BS-OFDMA system and STC-MIMO OFDMA system at BER$= 10^{-4}$, respectively. Moreover, we also realize that the STC-MIMO BS-OFDMA system with a larger symbol group size can achieve better performance than that with a smaller symbol group size. The performance curve of the STC-MIMO BS-OFDMA system with $M = 32$ gets closer to BER$= 10^{-5}$ at 9dB SNR than the system with $M = 16$ does.

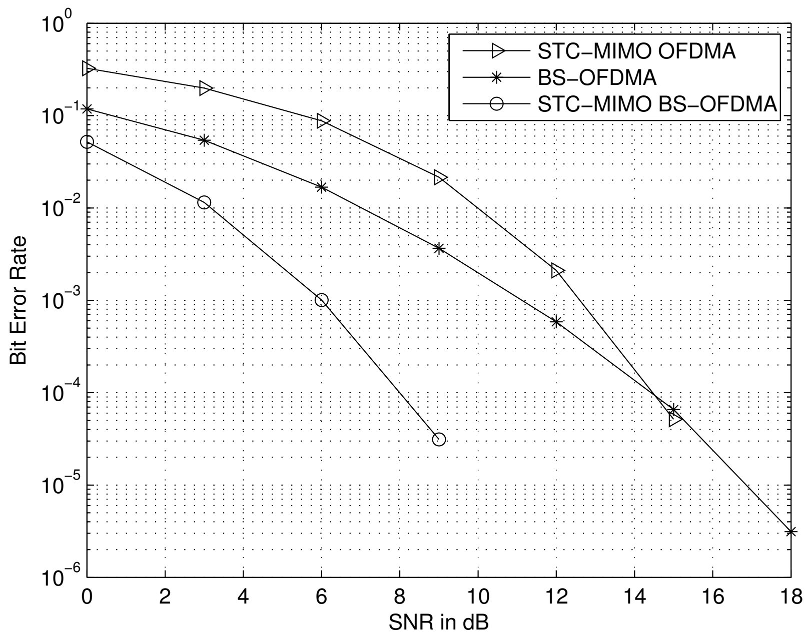


Figure 5.4: Performance comparison between STC-MIMO OFDMA system, BS-OFDMA system and STC-MIMO BS-OFDMA system with a larger symbol group size.

### 5.2.3 Simulation results for two receive antennas

As we described in the previous chapter, the application of multiple antennas at the receiver can provide the proposed system with a higher order of diversity than the single antenna does, therefore achieving a further performance improvement. Simulations are carried out to demonstrate this anticipated performance improvement. In this case, we increase the receive antennas from one to two and maintain other parameters. For computational simplicity, the symbol group size used this time is back to $M = 16$.

Figure 5.5 presents a BER performance comparison between STC-MIMO BS-OFDMA systems with one receive antenna and two receive antennas. As we can see, the system with two receive antennas further improves system performance by achieving nearly 3dB SNR gain over the system with one receive antenna at BER$= 10^{-5}$. Therefore, we may conclude that increasing receive antennas can offer a higher diversity order and as a result, the system performance can be continuely improved.

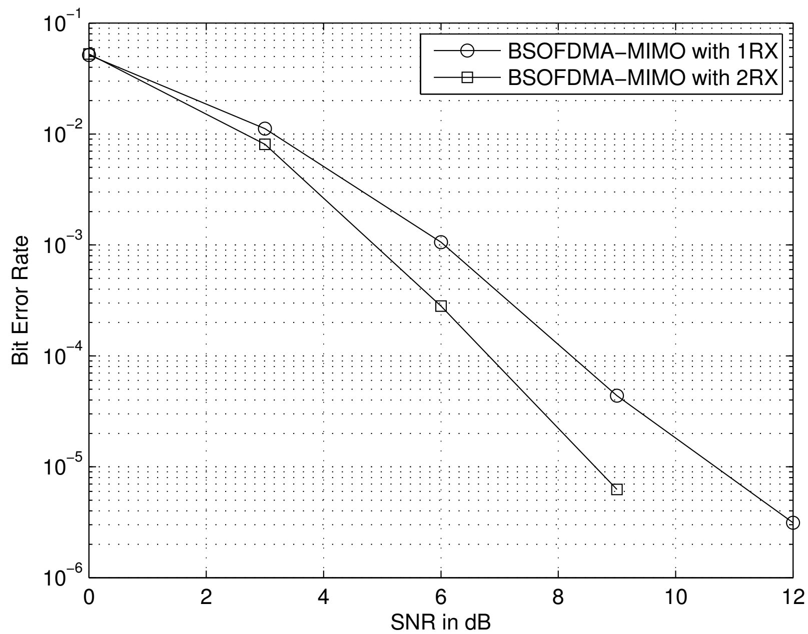


Figure 5.5: Performance comparison between STC-MIMO BS-OFDMA systems with one receive antenna and two receive antennas.

### 5.2.4 Simulation results for different linear equalizations

The system performance does not only depend on the proposed system encoding schemes, which although are the most important factors, but also relies on the different equalizations used for decoding process. As we described before, the ML equalization increases computation complexity exponentially when the symbol group size goes high, therefore it is not widely used in practice even though it is able to theoretically provide the best system performance. In our project, we prefer using linear equalizations, which include the MMSE equalization and the ZF equalization. Of the two linear equalization techniques, MMSE equalization is more practical as it considers the effect of noise in channels while the ZF equalization assumes no noise is present. Consequently, the MMSE equalization is expected to result in better system performance than the ZF equalization. This anticipated performance improvement by MMSE equalization over ZF equalization is demonstrated by the following simulation result.

Figure 5.6 presents a BER performance comparison between systems with different linear equalizations. In this case, we apply two linear equalizations, MMSE and ZF equalizations, for BS-OFDMA system and STC-MIMO BS-OFDMA system, respectively. This time, the symbol group size is $M = 16$ and one receive antenna is used for the STC-MIMO BS-OFDMA system.

As we can see, for both systems the MMSE equalization achieves better BER performance than the ZF equalization does. For example, for the BS-OFDMA system, a 10dB SNR gain is achieved by the MMSE equalization over the ZF equalization at BER of $10^{-3}$. For the STC-MIMO BS-OFDMA system, a 3dB SNR gain is achieved by the MMSE equalization over the ZF equalization at BER of $10^{-4}$. Therefore, regarding the performance of systems with linear equalizations, we can conclude that the MMSE equalization is the best choice as it provides a compromise option between performance and complexity. Note that we use the MMSE equalization for all the previous simulation works.

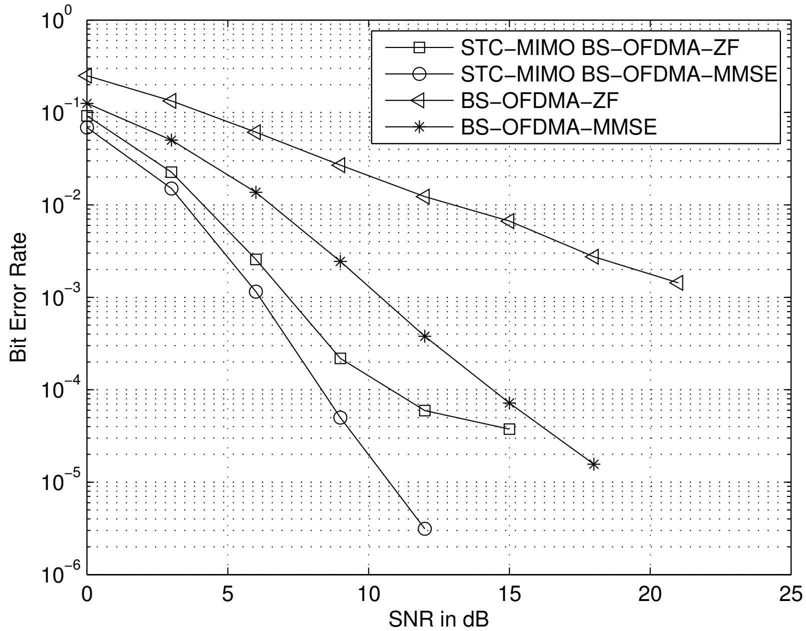


Figure 5.6: Performance comparison between different linear equalizations.

## 5.3 Chapter summary

This chapter first presents the simulation implementation in detail in terms of introducing useful parameters and some important implementation issues. The power normalization is used to address the assumption that all systems in our simulations have the same total transmit power. The antenna configurations are specified such that the channels from each transmit antenna to each receive antenna are mutually uncorrelated and their average power is normalized to unity. The other parameters used in simulations are also given.

Numerical simulation results are subsequently provided. First, we present a BER performance comparison between the conventional OFDMA system, BS-OFDMA system, STC-MIMO OFDMA system and the proposed STC-MIMO BS-OFDMA system. Among these considered systems, the proposed STC-MIMO BS-OFDMA system provides the best performance due to diversity advantages from both block spreading and STC-MIMO. Next, a BER performance comparison between those systems with a larger symbol group size is presented. It is shown that the performance improvement is achieved for BS-OFDMA and STC-MIMO BS-OFDMA systems by increasing the symbol group size for block spreading. Then, a BER performance comparison between the STC-MIMO BS-OFDMA system with one receive antenna and that system with two receive antennas. Compared to one receive antenna, two receive antennas can provide a higher diversity order and therefore improve the system performance. At last, a BER performance comparison between systems with different linear equalizations is presented. For both BS-OFDMA system and STC-MIMO OFDMA system, the MMSE equalization achieves better performance than the ZF equalization does.

Chapter 6

# Conclusions

This thesis proposes a system design for the next generation wireless communications. The proposed system is called block spread OFDMA combined with STC-MIMO (STC-MIMO BS-OFDMA) system. OFDM is a multicarrier modulation technique of delivering high data rates with strong resistance to ISI. Considering OFDMA as a strong candidate for multiple access technique of future wireless communications, it is necessary to add it new features so that, besides being strong to resist ISI, it can also combat the effect of frequency selective fading channels. The block spreading technique is applied to provide OFDMA systems with additional frequency diversity. Due to our novel approach, the combination of block spreading and OFDMA in the proposed system is simply addressed by using a complex exponential sequence instead of any explicit precoding process and IFFT, thus greatly reducing the system complexity. The STC-MIMO using Alamouti code is further used to gain spatial diversity. The Alamouti code in our MIMO scheme is imposed to block basis and performs in space and frequency. We design two receiver architectures for different MIMO schemes; two transmit antennas and one receive antenna MIMO scheme and two transmit antennas and two receive antennas MIMO scheme. This chapter is organized as follows. In Section 6.1, we summarise the major research activities undertaken during this project. In Section 6.2, we give the concluding remarks.

## 6.1 Research summary

The research activities have been documented in several chapters of the thesis. They are summarised as follows.

- **Chapter 2: Overview of 4G**

  We briefly take a review of the evolution histroy of wireless communications from 1G to 4G, with the emphasis on 4G system features. Multicarrier systems, such as OFDM and MC-CDMA, become the hottest technologies for 4G systems. Some standardizations of 4G systems haven been developed based on different perspectives.

- **Chapter 3: Improvement for OFDM**

  We focus on the OFDM system and discuss several techniques to improve system performance. Block spread approach is one of attractive techniques to provide system with diversity gain and thus improve performance over frequency selective channels. The common process to implement block spreading on OFDM systems is to use spreading matrices before IFFT. This process is known as precoding process. STC-MIMO is another technique to improve OFDM system performance and can be effectively combined with OFDM systems. The idea of STC-MIMO is to take advantage of multipath channels and offer spatial diversity.

- **Chapter 4: Block spread OFDMA system with STC-MIMO**

  We propose an advanced OFDMA system where the block spreading technique and STC-MIMO scheme are effectively combined. In this system, block spreading is effectively combined with OFDM modulation without any explicit precoding process and IFFT, therefore reducing computation complexity. The STC-MIMO using Alamouti code is imposed to block basis and performed in space and frequency to gain additional diversity. The MIMO scheme is classified to MIMO with two transmit antennas and one receive antenna and MIMO with two transmit antennas and two receive antennas.

- **Chapter 5: System performance simulations**

  We conduct simulations to demonstrate the anticipated performance improvement of the proposed system. We present a BER performance comparison between OFDMA system, BS-OFDMA system, STC-MIMO OFDMA system and the proposed STC-MIMO BS-OFDMA system. We also present a BER performance comparison between the STC-MIMO BS-OFDMA systems with different parameters, such as block size and number of receive antennas. Finally, we present a BER performance comparison between systems with MMSE and ZF equalizations, respectively. Simulation results are consequently provided.

## 6.2 Conclusion

In conclusion, this thesis has proposed a STC-MIMO BS-OFDMA system for next generation wireless communications. The system has simpler structures to effectively combine block spread, STC-MIMO and OFDMA, therefore greatly reducing computational complexity. Our simulations indicate that the proposed system can result in significant improvement in the BER performance compared to other systems. Using larger block size for spreading and more receive antennas can both further improve system performance due to higher order of diversity advantage they may offer. In terms of accuracy and computational complexity, the MMSE equalization is more suitable for the proposed system on practical applications.

# References


[1] H. Sampath, S. Talwar, J. Tellado, V. Erceg, and A. Paulraj, “A fourth-generation MIMO-OFDM broadband wireless system: design, performance, and field trial results,” *IEEE Communications Magazine*, vol. 40, no. 9, pp. 143–149, 2002.

[2] H. Yang, “A road to future broadband wireless access: MIMO-OFDM-based air interface,” *IEEE Communications Magazine*, vol. 43, no. 1, pp. 53–60, 2005.

[3] K. R. Santhi, V. K. Srivastava, G. SenthilKumaran, and A. Butare, “Goals of true broad band's wireless next wave (4G-5G),” in *IEEE 58th Vehicular Technology Conference*, vol. 4, 2003, pp. 2317–2321.

[4] B. G. Evans and K. Baughan, “Visions of 4G,” *Electronics and Communication Engineering Journal*, vol. 12, no. 6, pp. 293–303, 2000.

[5] H. Jeounglak, S. Kim, and D. Kim, “A phased approach to 4G mobile network system,” in *10th International Conference on Telecommunications*, S. H. Kim, Ed., vol. 2, 2003, pp. 1318–1322.

[6] J. Sun, J. Sauvola, and D. Howie, “Features in future: 4G visions from a

technical perspective," in *IEEE Global Telecommunications Conference*, vol. 6, 2001, pp. 3533–3537.

[7] R. Caldwell and A. Anpalagan, "Meeting mobile's demands with multicarrier systems," *IEEE Potentials*, vol. 24, no. 5, pp. 27–31, 2005.

[8] F. Adachi, "Evolution towards broadband wireless systems," in *The 5th International Symposium on Wireless Personal Multimedia Communications*, vol. 1, 2002, pp. 19–26.

[9] K. Murota and N. DoCoMo, "Mobile communications trends in japan and NTT DoCoMo's activities towards 21st century," in *ACTS Mobile Summit99*, Sorrento, Italy, 1999.

[10] J. Silva, "Beyond IMT-2000," in *ITU-R WP8F workshop*, Geneva, 2000.

[11] F. Williams, "Fourth generation mobile," in *ACTS Mobile Summit99*, Sorrento, Italy, 1999.

[12] H. Huomo, "Fourth generation mobile," in *ACTS Mobile Summit99*, Sorrento, Italy, 1999.

[13] S. Frattasi, R. L. Olsen, M. De Sanctis, F. H. P. Fitzek, and R. Prasad, "Heterogeneous services and architectures for next-generation wireless networks," in *2nd International Symposium on Wireless Communication Systems*, 2005, pp. 213–217.

[14] Y. Ji and P. Zhang, "Muse: a vision for 4G service and architecture," in *IEEE 60th Vehicular Technology Conference*, vol. 7, 2004, pp. 4842–4845.

[15] "Everywhere and at any time: Wireless multimedia communications," in *VDE-IGT Positionspapier Mobil-kiommunication*, 2005.

[16] J. M. Pereira, "Fourth generation: now, it is personal!" in *The 11th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 2, 2000, pp. 1009–1016.

[17] S. J. Vaughan-Nichols, "OFDM: back to the wireless future," *Computer*, vol. 35, no. 12, pp. 19–21, 2002.

[18] S. G. Glisic, *Advanced wireless communications : 4G cognitive and cooperative broadband technology*, 2nd ed. Chichester :: John Wiley, 2007.

[19] K. Baybakov, T. Sviridova, M. Lobur, and R. Kohut, "Using OFDM for multiple access schemes in 4G communication systems," in *The Experience of Designing and Application of CAD Systems in Microelectronics*, 2003, pp. 572–573.

[20] C. Liu and F. Li, "On spectrum modeling of OFDM signals for digital broadcasting," in *7th International Conference on Signal Processing*, vol. 3, 2004, pp. 1886–1889.

[21] K. Zheng, L. Huang, W. Wang, and G. Yang, "TD-CDM-OFDM: Evolution of TD-SCDMA toward 4G," *IEEE Communications Magazine*, vol. 43, no. 1, pp. 45–52, 2005.

[22] H. Schulze and C. Luders, *Theory and applications of OFDM and CDMA : wideband wireless communications*. Chichester :: Wiley, 2005.

[23] G. Parsaee and A. Yarali, "OFDMA for the 4th generation cellular networks," in *Electrical and Computer Engineering Conference*, vol. 4, 2004, pp. 2325–2330.

[24] L. Loyola and T. Miki, “An OFDMA/CDMA-based bandwidth resource allocation scheme for future broadband mobile networks,” in *IEEE 56th Vehicular Technology Conference*, vol. 1, 2002, pp. 42–46.

[25] R. Esmailzadeh, M. Nakagawa, and A. Jones, “TDD-CDMA for the 4th generation of wireless communications,” *IEEE Wireless Communications*, vol. 10, no. 4, pp. 8–15, 2003.

[26] K. Kim, “Key technologies for the next generation wireless communications,” in *Hardware/software codesign and system synthesis*, 2006, pp. 266–269.

[27] J. G. Andrews, A. Ghosh, and R. Muhamed, *Fundamentals of WiMAX : understanding broadband wireless networking.* Upper Saddle River, N.J. ; London :: Prentice Hall, 2007.

[28] S. V. Anand, “Next GEN mobile terminal architecture: A vision,” in *Proceedings of the First Mobile Computing and Wireless Communication International Conference*, 2006, pp. 133–138.

[29] U. H. Reimers, “DVB-the family of international standards for digital video broadcasting,” *Proceedings of the IEEE*, vol. 94, no. 1, pp. 173–182, 2006.

[30] U. Ladebusch and C. A. Liss, “Terrestrial DVB (DVB-T): a broadcast technology for stationary portable and mobile use,” *Proceedings of the IEEE*, vol. 94, no. 1, pp. 183–193, 2006.

[31] V. Ollikainen and C. Peng, “A handover approach to DVB-H services,” in *IEEE International Conference on Multimedia and Expo*, 2006, pp. 629–632.

[32] K. Ohsaki, T. Kimura, and N. Kawai, "Transmission structure of digital broadcasting," in *IEEE International Conference on Communications*, 1994, pp. 853–858.

[33] H. Asami and M. Sasaki, "Outline of ISDB systems," *Proceedings of the IEEE*, vol. 94, no. 1, pp. 248–250, 2006.

[34] M. Takada and M. Saito, "Transmission system for ISDB-T," *Proceedings of the IEEE*, vol. 94, no. 1, pp. 251–256, 2006.

[35] H. Katoh, "Transmission system for ISDB-S," *Proceedings of the IEEE*, vol. 94, no. 1, pp. 289–295, 2006.

[36] B. Umasankar and X. Fernando, "OFDM impairment mitigation techniques," in *Second International Conference on Access Networks and Workshops*, 2007, pp. 1–6.

[37] S. Kim, J. Chung, and H. Ryu, "PAPR reduction of the OFDM signal by the SLM-based WHT and DSI method," in *IEEE Region 10 Conference*, 2006, pp. 1–4.

[38] Y. Park and S. L. Miller, "Peak-to-average power ratio suppression schemes in DFT based OFDM," in *IEEE Vehicular Technology Conference*, vol. 1, 2000, pp. 292–297.

[39] H. Wang, "PAPR reduction for OFDM system with a class of HNN," in *International Symposium on Communications and Information Technologies*, 2006, pp. 492–497.

[40] D. Wulich, "Definition of efficient PAPR in OFDM," *IEEE Communications Letters*, vol. 9, no. 9, pp. 832–834, 2005.

[41] C. R. N. Athaudage, "BER sensitivity of OFDM systems to time synchronization error," in *The 8th International Conference on Communication Systems*, vol. 1, 2002, pp. 42–46.

[42] C. Yan, J. Fang, Y. Tang, S. Li, and Y. Li, "OFDM synchronization using PN sequence and performance," in *14th IEEE Proceedings on Personal, Indoor and Mobile Radio Communications*, vol. 1, 2003, pp. 936–939.

[43] S. K. Manusani, R. S. Kshetrimayum, and R. Bhattacharjee, "Robust time and frequency synchronization in OFDM based 802.11a WLAN systems," in *Annual India Conference*, 2006, pp. 1–4.

[44] T. C. W. Schenk and A. van Zelst, "Frequency synchronization for MIMO OFDM wireless LAN systems," in *IEEE 58th Vehicular Technology Conference*, vol. 2, 2003, pp. 781–785.

[45] C. Athaudage, J. Wang, and A. Jayalath, "An efficient framework to exploit frequency diversity in OFDM: Precoding with adaptive subcarrier selection," in *IEEE 17th International Symposium on Personal, Indoor and Mobile Radio Communications*, 2006, pp. 1–5.

[46] L. Van der Perre, J. Tubbax, F. Horlin, and H. A. De Man, "A single-carrier/OFDM comparison for broadband wireless communication," in *IEEE International Conference on Acoustics, Speech, and Signal Processing*, vol. 2, 2004, pp. ii–329–32.

[47] Q. Li, K. Li, and K. Teh, "MIMO-OFDM systems based on space-time coding and OFDM carrier block spreading," in *The 6th International Conference on Information, Communications and Signal Processing*, 2007, pp. 1–5.

[48] T. Seki, M. Itami, H. Ohta, and K. Itoh, "A study of OFDM system applying frequency diversity," in *The 11th IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, vol. 2, 2000, pp. 1385–1389.

[49] R. Geevarghese and R. K. Rao, "Adaptive frequency diversity using OFDM for wireless communications," in *Canadian Conference on Electrical and Computer Engineering*, vol. 2, 2003, pp. 809–812.

[50] K. Eunseok and D. Hong, "Improved space-time block coding with frequency diversity for OFDM systems," in *IEEE International Conference on Communications*, vol. 6, 2004, pp. 3217–3220.

[51] A. D. S. Jayalath and C. Tellambura, "The use of interleaving to reduce the peak-to-average power ratio of an OFDM signal," in *IEEE Global Telecommunications Conference*, vol. 1, 2000, pp. 82–86.

[52] M. Lin, Y. Tsai, and C. Yang, "Selective-mapping type peak power reduction techniques for turbo coded OFDM," in *International Conference on Wireless Networks, Communications and Mobile Computing*, T. Yung-Chih, Ed., vol. 1, 2005, pp. 119–122.

[53] H. Ryu, J. Kim, and H. Ryu, "Interleaving method without side information for the PAPR reduction of OFDM system," in *International Symposium on Communications and Information Technologies*, 2007, pp. 72–76.

[54] F. Zbynek, M. Roman, and S. Vladimir, "Interleaving optimization in OFDM PAPR reduction," in *17th International Conference Radioelektronika*, 2007, pp. 1–3.

[55] M. L. McCloud, "Coded block OFDM for the frequency selective fading channel," in *Conference Record of the Thirty-Eighth Asilomar Conference on Signals, Systems and Computers*, vol. 1, 2004, pp. 329–333.

[56] ——, "Optimal binary spreading for block OFDM on multipath fading channels," in *IEEE Wireless Communications and Networking Conference*, vol. 2, 2004, pp. 965–970.

[57] A. Bury, J. Egle, and J. Lindner, "Diversity comparison of spreading transforms for multicarrier spread spectrum transmission," *IEEE Transactions on Communications*, vol. 51, no. 5, pp. 774–781, 2003.

[58] M. L. McCloud, "Analysis and design of short block OFDM spreading matrices for use on multipath fading channels," *IEEE Transactions on Communications*, vol. 53, no. 4, pp. 656–665, 2005.

[59] I. Raad and X. Huang, "A new approach to BSOFDM - parallel concatenated spreading matrices OFDM," in *International Symposium on Communications and Information Technologies*, 2007, pp. 77–81.

[60] I. S. Raad, X. Huang, and R. Raad, "A new spreading matrix for block spread OFDM," in *IEEE Singapore International Conference on Communication systems, 2006*, 2006, pp. 1–5.

[61] L. Tran, X. Huang, E. Dutkiewicz, and J. A. Chicharo, "STC-MIMO block spread OFDM in frequency selective rayleigh fading channels," in *IEEE Symposium on Computers and Communications*, 2006, pp. 277–282.

[62] I. Raad, X. Huang, and R. Raad, "New higher order rotation spreading matrix for BSOFDM," in *The 2nd International Conference on Wireless Broadband and Ultra Wideband Communications*, 2007, pp. 17–17.

[63] I. Raad, X. Huang, and D. Lowe, "A study of different angles for the new spread matrix for BSOFDM in UWB channels," in *Third International Conference on Wireless and Mobile Communications*, 2007, pp. 67–67.

[64] I. Raad, X. Huang, and R. Raad, "A study of different angles for higher order rotation spreading matrix for BSOFDM in UWB channels," in *The 2nd International Conference on Wireless Broadband and Ultra Wideband Communications*, 2007, pp. 18–18.

[65] D. Gesbert, M. Shafi, D. Shiu, P. J. Smith, and A. Naguib, "From theory to practice: an overview of MIMO space-time coded wireless systems," *IEEE Journal on Selected Areas in Communications*, vol. 21, no. 3, pp. 281–302, 2003.

[66] S. M. Alamouti, "A simple transmit diversity technique for wireless communications," *IEEE Journal on Selected Areas in Communications*, vol. 16, no. 8, pp. 1451–1458, 1998.

[67] A. Zooghby, *Smart antenna engineering.* Boston: Artech House, 2005.

[68] A. Wittneben, "Basestation modulation diversity for digital simulcast," in *41st IEEE Vehicular Technology Conference*, 1991, pp. 848–853.

[69] ——, “A new bandwidth efficient transmit antenna modulation diversity scheme for linear digital modulation,” in *IEEE International Conference on Communications*, vol. 3, 1993, pp. 1630–1634.

[70] N. Seshadri and J. H. Winters, “Two signaling schemes for improving the error performance of frequency-division-duplex (FDD) transmission systems using transmitter antenna diversity,” in *IEEE 43rd Vehicular Technology Conference*, 1993, pp. 508–511.

[71] J. H. Winters, “The diversity gain of transmit diversity in wireless systems with rayleigh fading,” *IEEE Transactions on Vehicular Technology*, vol. 47, no. 1, pp. 119–123, 1998.

[72] B. Vucetic, *Space-time coding.* Hoboken, NJ: Wiley, 2003.

[73] D. Agrawal, V. Tarokh, A. Naguib, and N. Seshadri, “Space-time coded OFDM for high data-rate wireless communication over wideband channels,” in *48th IEEE Vehicular Technology Conference*, vol. 3, 1998, pp. 2232–2236.

[74] V. Tarokh, N. Seshadri, and A. R. Calderbank, “Space-time codes for high data rate wireless communication: performance criterion and code construction,” *IEEE Transactions on Information Theory*, vol. 44, no. 2, pp. 744–765, 1998.

[75] B. Lu and X. Wang, “Space-time code design in OFDM systems,” in *IEEE Global Telecommunications Conference*, vol. 2, 2000, pp. 1000–1004.

[76] V. Tarokh, H. Jafarkhani, and A. R. Calderbank, “Space-time block codes from orthogonal designs,” *IEEE Transactions on Information Theory*, vol. 45, no. 5, pp. 1456–1467, 1999.

[77] ——, "Space-time block coding for wireless communications: performance results," *IEEE Journal on Selected Areas in Communications*, vol. 17, no. 3, pp. 451–460, 1999.

[78] R. S. Blum, L. Ye Geoffrey, J. H. Winters, and C. Yan, "Improved space-time coding for MIMO-OFDM wireless communications," *IEEE Transactions on Communications*, vol. 49, no. 11, pp. 1873–1878, 2001.

[79] R. S. Blum, Q. Yan, Y. Li, and J. H. Winters, "Improved techniques for 4 transmit and 4 receive antenna MIMO-OFDM for wireless communications," in *IEEE VTS 53rd Vehicular Technology Conference*, vol. 2, 2001, pp. 1298–1302.

[80] S. Suthaharan, A. Nallanathan, and B. Kannan, "Space-time coded MIMO-OFDM for high capacity and high data-rate wireless communication over frequency selective fading channels," in *4th International Workshop on Mobile and Wireless Communications Network*, 2002, pp. 424–428.

[82] R. Harish and T. M. Duman, "Space-time coded ofdm with low papr," in *IEEE Global Telecommunications Conference*, vol. 2, 2003, pp. 799–803.

[83] Z. Liu, Y. Xin, and G. B. Giannakis, "Space-time-frequency coded OFDM over frequency-selective fading channels," *IEEE Transactions on Signal Processing*, vol. 50, no. 10, pp. 2465–2476, 2002.

[84] S. Savary, H. T. Huynh, J. Y. Chouinard, and S. Roy, "A space-frequency-time diversity scheme for MIMO-OFDM systems," in *Canadian Conference on Electrical and Computer Engineering*, 2005, pp. 1375–1379.

[81] J. Kim, J. Heath, R. W., and E. J. Powers, “Receiver designs for Alamouti coded OFDM systems in fast fading channels,” *IEEE Transactions on Wireless Communications*, vol. 4, no. 2, pp. 550–559, 2005.

[85] J. Yue and J. D. Gibson, “Performance of a space-time block coded OFDM system,” in *Conference Record of the Thirty-Sixth Asilomar Conference on Signals, Systems and Computers*, vol. 2, 2002, pp. 1862–1866.

[86] M. Uysal, N. Al-Dhahir, and C. N. Georghiades, “A space-time block-coded OFDM scheme for unknown frequency-selective fading channels,” in *IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, ., Ed., vol. 2, 2001, pp. G–93–G–97.

[87] B. Chiang, D. Lin, H. Li, and J. Wang, “Improved transmit diversity block coded OFDM systems for highly dispersive channels,” in *The 57th IEEE Semiannual Vehicular Technology Conference*, vol. 2, 2003, pp. 1173–1177.