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BIN LI

PERFORMANCE ANALYSIS OF MC-CDMA DETECTION SCHEMES FOR D2D COMMUNICATION

Master of Science thesis

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ABSTRACT

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The wireless communication standard has gone to the era of Long Term Evolution which is also known as LTE. The requirements for transmission speed and communication quality become more and more rigorous and the number of wireless communication devices is increasing rapidly. The available spectrum for mobile wireless communication is getting congested. Therefore, more efficient spectrum utilization should be taken into consideration within the future development. New methods need to be implemented to increase the efficiency of spectrum utilization.

To confront this obstacle, orthogonal frequency division multiplexing (OFDM) was developed in 1990's and has been widely deployed in the LTE networks. Multicarrier code division multiple access technique (MC-CDMA) combines code division multiple access (CDMA) with OFDM to acquire advantages from both sides. With the continuous increase of mobile applications, the power consumption of mobile terminals is also increasing significantly. Then device-to-device (D2D) communication, which is a short distance communication technique from one device directly to another one, was invented. The data of users will be transmitted between devices directly without relying on the base station. D2D communication decreases the load of the base station, reduces the terminal power consumption, and improves the spectral efficiency. Due to these merits, D2D has become a significant research topic and various new related applications for D2D have been developed and tested in realistic circumstances.

This thesis applies MC-CDMA into D2D communication and studies different detection schemes for MC-CDMA. The OFDMA cellular user signals appear as significant sources of interference to D2D communication. Three alternative detection schemes are investigated: equal gain combining (EGC), maximum ratio combining (MRC) and linear minimum mean square (LMMSE) equalization. MC-CDMA performance with these detection methods is evaluated based on MATLAB simulations using relevant channel and interference models to find out the best alternative for different D2D scenarios. At the end of this thesis, a conclusion is drawn of which MC-CDMA detection scheme will be a better choice for D2D communication according to the BER performances based on the simulation results on MATLAB.

PREFACE

In May 2015, I started to work on this research in the Department of Electronics Communications Engineering at Tampere University of Technology after two years for which I have stayed in Finland.

At first, I would like to acknowledge my supervisor Prof. Markku Renfors for the opportunity of researching on such a nice topic and his guidance within it. Then I would love to thank my examiner Lic.Tech. Hongnian Xing for his supports both on the development of the research and further technical instructions behind this topic.

Above all, I wish to express my gratitude to my dearest Father and Mother who accompany with my in the past of my life and devote everything to their son, to Han & Chen couple who always cook delicious food for me, to my soul mate Yuan Chen whom I shared both my happiness and unhappiness with, to my brother Zhaodi Gu who is pursuing his dream at this moment. I could not have become who I am now without these people I love the most.

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CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

1G	First Generation
2G	Second Generation
3G	Third Generation
3GPP	3rd Generation Partnership Project
4G	Forth Generation
AP	Access Point.
BER	Bit Error Rate
BPSK	Binary Phase Shift Keying
BS	Base Station
CDL	Clustered Delay Line
CDMA	Multicarrier Code Division Multiple Access
CP	Cyclic Prefix
D2D	Device to Device
DFT	Discrete-Fourier Transform
DS	Direct Sequence Spread Spectrum
EGC	Equal Gain Combining
FDMA	Frequency Division Multiple Access
FFT	Fast Fourier Transform
FH	Frequency Hopping Spread Spectrum
GI	Guard Interval
GMSK	Gaussian Filtered Minimum Shift Keying
GSM	Global System for Mobile Communication
ICI	Inter-Carrier Interference
IDFT	Inverse Discrete-Fourier Transform
IFFT	Inverse Fast Fourier Transform
ISI	Inter-Symbol Interference
ITU	International Telecommunication Union
LMMSE	Linear Minimum Mean Square Error
LOS	Line of Sight
LTE	Long Term Evolution
LTE-A	Long Term Evolution - Advanced
M2M	Machine to Machine
MC-CDMA	Multi-Carrier Code Division Multiple Access
MRC	Maximum Ratio Combining
NLOS	NonLine of Sight
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak-to-Average Power Ratio
QAM	Quadrature amplitude modulation
QPSK	Quadrature Phase Shift Keying
SCM	Spatial Channel Model
SNR	Signal-to-Noise Ratio
SS	Spread Spectrum
TDMA	Time Division Multiple Access
TH	Time Hopping Spread Spectrum
UE	User Equipment
WH	Walsh-Hadamard

1. INTRODUCTION

Since the first generation of wireless communication standards (1G) was formulated in the 1980s, the evolution and improvement of related technologies have been in the forefront of telecommunications research. A 1G system is generally an analog network using frequency division multiple access (FDMA) [1]. Such kind of system is difficult to be popularized due to the problems of spectrum efficiency, interference, and security. Furthermore, different countries could not reach an agreement on 1G global standard.

The first global system for mobile communication (GSM) network was deployed in Finland in 1992, which marked the start of the second generation of the communication systems (2G) era [2]. It turned out a digital system applying time division multiple access (TDMA) and Gaussian filtered minimum shift keying (GMSK) modulation. Security was enhanced by introducing PIN code and new encryption algorithms.

The original idea of spread spectrum (SS) was proposed in 1940 and widely applied in the area of military communications [3]. In the 1990s, SS based code division multiple access (CDMA) techniques were adopted and developed for the third generation of communication systems (3G), due to its advantages of larger system capacity, higher spectrum multiplex ratio, powerful ability against multi-path fading, soft handover, and so on [4].

Long term evolution (LTE), developed by 3rd generation partnership project (3GPP), was introduced as the fourth generation of communication systems (4G). It utilizes orthogonal frequency division multiplexing (OFDM) to obtain high spectrum efficiency [5]. Besides, many technologies have been developed for system performance enhancement at both link level and network levels. On the other hand, there are still some problems to be solved in OFDM, such as Peak-to-Average Power Ratio (PAPR), worse orthogonality under frequency offset and excessive timing offsets, and high demand on accurate channel estimation.

Multi-carrier code division multiple access (MC-CDMA) is the combination of spread spectrum and multi-carrier techniques. High spectral efficiency, high data transmission speed, and strong capabilities of narrow-band interference resistance are its key features [6]. Obviously, the capacity of MC-CDMA and ISI rejection ability are better than the conventional single-carrier CDMA system. The addition of CP provides a buffer for the symbol so that the multipath effect can only have an influence on the current symbol instead of interfering with next symbol. Consequently, these characteristics turn MC-CDMA to be a useful element for the next generation telecommunication standard.

Essentially, system efficiency is one of the key criteria of a communication network. More specifically, the resource (such as spectrum, time, power, and so on) efficiency is the dominant part of system efficiency. Currently, many schemes have been proposed for LTE networks to further improve the resource efficiency. Among them, device-to-device communication (D2D) seems to be one of the promising technologies. D2D communication has been investigated over several decades [7]. In recent years, research has been emphasized on how to get D2D integrated into cellular systems (such as LTE networks) efficiently [8]. Many advantages can be obtained by integration, such as improving the spectrum efficiency, alleviating the load on the cellular network, decreasing the power consumption of mobile devices, increasing bit rate, and improving the robustness of infrastructures. D2D integration can be either network assisted or autonomous. The study of this thesis covers only issues of the network assisted D2D integration. In this scenario, the data communication link is built between terminals (known as user equipment (UE) in 3GPP), while control links are built between UEs and base stations (BS, or eNode B in LTE), as well as between UEs.

1.1 Motivations and Objectives of the Research

Authorized radio frequency bandwidth is limited and the requirements about quantity and quality from users have been being increasing dramatically. It is significant and urgent to address these problems so that users can acquire better communication experience. Besides exploring new radio resources, the dominated way of solving the problems is to improve the system efficiency. OFDM technique already provides a splendid contribution to retrenching spectrum occupation. MC-CDMA makes a further progress in this aspect under the basement of OFDM. The orthogonality is utilized only between sub-carriers to obtain more free spectral spaces in OFDM. However, MC-CDMA is a type of multiple access which could support the transmission of a number of users' information at the same time over the same frequency band [9]. Thus, the orthogonality in MC-CDMA is also applied to multiple users so that the data of a specific user could be recovered with its own spreading code on the receiver side.

On the other hand, the equalization of the system still needs the information of the channel estimated accurately to compensate influence from multipath loss and Doppler shift. Therefore, channel estimation and equalization schemes will affect the performance of the whole communication system.

D2D technique has become a focus of researching due to its attractive features. It could offer a reliable communication link between devices and reduce the power consumption of mobile terminals. Either licensed or unlicensed spectrum can be utilized when establishing a D2D link. Currently D2D integration is still in the research progress, there are still challenges which need to be considered, such as mode selection criteria and schemes, and interference related issues (such as power control and resource management). Thus, many aspects of D2D integration need to be considered, researched, and improved to develop it as a mature technique which can be implemented in a wider range.

This thesis evaluates D2D communication at the link level where the channel estimation and equalization techniques are performed and analyzed with various number of the users under different signal-to-noise ratio (SNR). The bit error rate (BER) results, which represents communication connection quality for different detection schemes, provides good basis to choose the most appropriate detection scheme to be used in future research and implementation of D2D communications.

1.2 Research Approach

In this thesis work, D2D downlink is mainly implemented in MATLAB. Instead of conventional OFDM, MC-CDMA is used as the basic multiple access scheme for D2D users. Mainly, the multiple access interference (MAI) has been simulated in both type of links. Typical WINNER II A1 model is used for D2D links. As the main contributions of the thesis, various channel estimation and equalization techniques (including maximum ratio combining (MRC), equal gain combining (EGC), and linear minimum mean square error (LMMSE)) are investigated. BER as a function of SNR is obtained as the main output of simulations and is used to compare and evaluate the system performance under different detection schemes.

The structure of this thesis is as follows:

> *Chapter 2: D2D Communication.* This chapter presents the background and theory of D2D communication. Furthermore, D2D integration (into cellular networks) is discussed, including a general description of the D2D environment and D2D interference issue. The interference model in D2D scenarios is described. The advantages and challenges of D2D communications are presented as well.

> *Chapter 3: Principles of MC-CDMA.* The basic idea and characteristics of OFDM and fundamentals of MC-CDMA are introduced in the theoretical aspect, also including the theoretical basis of channel estimation and equalization techniques which are utilized in simulations.

> *Chapter 4: System Model.* This chapter describes the system models which will be established in MATLAB according to the desired scenario and parameters in practical perspective. The details of OFDM symbol, pilot structure, and detections schemes are explained as well.

> *Chapter 5: Simulation Results.* Simulation results and corresponding discussions are presented in this chapter. The performance of various detection schemes is compared under different scenarios.

Chapter 6: Conclusion and Future Work. Conclusions drawn from the research result and ideas about the future research are discussed and summarized.

2. DEVICE-TO-DEVICE COMMUNICATION

A brief explanation of the D2D communication concept and practical aspects is given in this chapter which consists of four sections: D2D Concepts and Models, Interference in D2D Scenarios, Indoor D2D Communication Scenario, and Advantages and Challenges of D2D.

The cellular system is known as a network with a centralized control. It is famous for effective wireless resource management and interference control. However, the efficiency of data transmission through a base station is quite low sometimes. For example, when two devices are adjacent to each other but located at the boundary of the cell, both the resource occupation and power consumption are quite high. D2D communication is what can allow the devices to utilize the cell resources for direct communication to other devices without infrastructures [10]. It is similar to the concept of machine-to-machine (M2M) communication. Actually, there are already several related technologies, like peer-to-peer, Ad hoc, Bluetooth, and Wi-Fi Direct…Compared with these techniques, the D2D concept is more flexible. Its data transmission can be performed under the control of infrastructure and also without such control. A device which is under the cover of cellular network can also be utilized as a gateway node for other devices without a network to get connect with.

2.1 D2D Concepts and Models

The D2D communication is not a new concept and it was already proposed a decade ago. But D2D in a cellular network is becoming attractive due to its benefits, especially because 3GPP declaims that the D2D communication is available among LTE devices in LTE Release 12 [7].

The principle of the traditional cellular network is that the data is sent from the transmitting UE to the receiving UE through the base station of its cell, even in the case that the communicating UEs are close to each other in the same cell. However, in such cases the cellular approach leads to high power consumption and low efficiency for the devices within a short distance from each other. D2D is to enable the direct communication link between neighboring UEs without forwarding to BS. The power consumption of terminals is much lower in the D2D case compared with the cellular network, due to short range. Meanwhile, the lower delay can be reached as well.

The D2D model can be classified into two types:

- D2D pair communication (Typical D2D communication model)
- D2D cluster communication

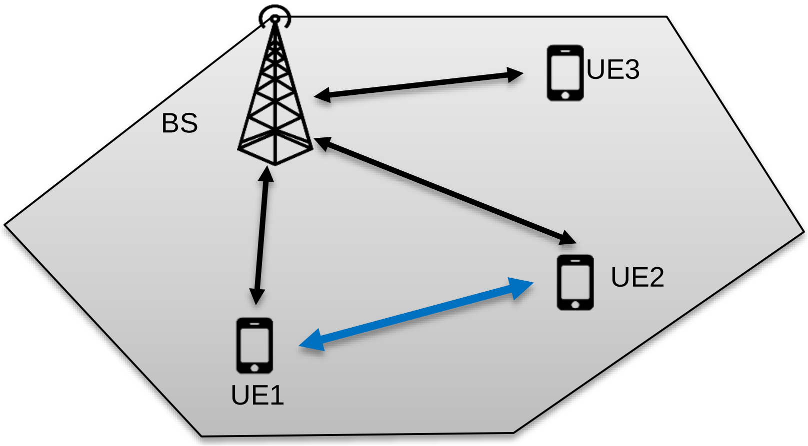

Figure 2.1 D2D pair model

Figure 2.1 represents the typical D2D communication model, D2D pair model under the cellular network. The link between UE1 and UE2 is D2D communication whereas the link between UE3 and BS is a cellular link. The D2D pair connection can be set up under the control of the BS when the two communicating UEs are close to each other. The BS allocates and manages resources for the D2D link, connects the D2D connection with outside networks, if needed, and charges the fee.

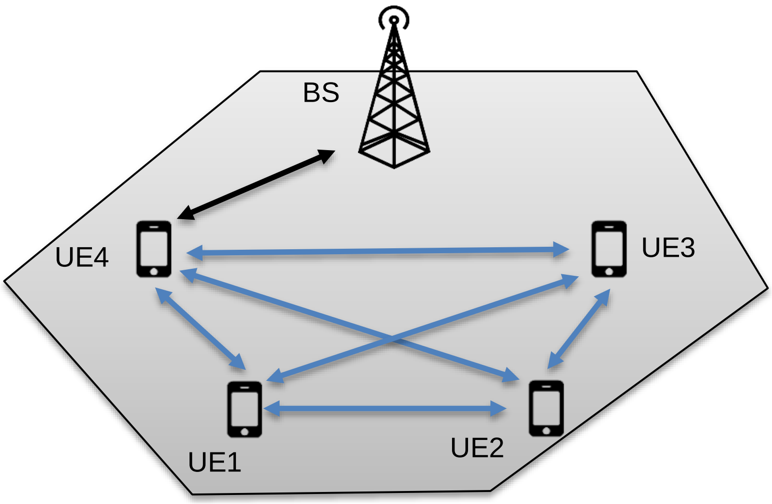

Figure 2.2 D2D cluster model

Figure 2.2 illustrates D2D cluster model which can be seen as an extension of D2D pair communication. Several D2D devices form a group in which there is one device selected as the cluster head to control and relay data within this cluster system. Information is shared by the UEs in the cluster. The cluster head is also in charge of communicating with the BS and the rest of the network, as the gateway node.

Two basic functions are carried out in D2D: Discovery and Communication. Currently, the device discovery is based on cellular network. Each device needs to perform its location registration in a central server at first. After location distribution to other terminals by the central server, the D2D link can be built between two devices if the criteria for D2D operation are satisfied. But it would be better if the process of location registration in the central server can be skipped, in which case devices can discover other devices. It means the device can discover devices autonomously instead of implementing location registration.

From the spectrum perspective, D2D which utilizes cellular resources in the licensed spectrum is called inband D2D whereas operation in unlicensed spectrum is outband D2D. The inband D2D communication can be categorized into overlay and underlay. In overlay communication, free spectrum is deployed to D2D communication. For underlay D2D communication, resources occupied by cellular users are utilized again. Although the latter category can bring interference, it can improves the spectrum efficiency. Therefore, underlay D2D communication is preferable. The purpose of this thesis is to evaluate the performance of various detection schemes for the network-assisted inband underlay D2D communication interfered by cellular users [11].

2.2 Interference in D2D Scenarios

For the establishment of network-assisted D2D [12] communication, the BS will sense whether there are D2D devices within a cell at first. Once an opportunity for D2D communication is detected, the link will be constructed and BS will deploy specific operating frequency band and decide the operating power which will not introduce strong interference to the cellular UEs. D2D operation can be established on both licensed and unlicensed frequency bands. Available unlicensed frequency band can be allocated temporarily for communication between nearby devices via the techniques like Bluetooth, WLAN or Ad hoc. Also LTE operation in unlicensed frequency bands (so-called LTE-U) is under standardization, and it would be a natural choice for LTE-assisted D2D operation in shared bands. But working on the unlicensed frequency band cannot provide a stable service, which is quite important to the business requiring high service quality and some specific users. On the other side, operation in licensed spectrum ensures the quality of D2D communication, keeping the interference under control. In any case, cellular operation in licensed band is always the fallback mode, if D2D operation is not feasible.

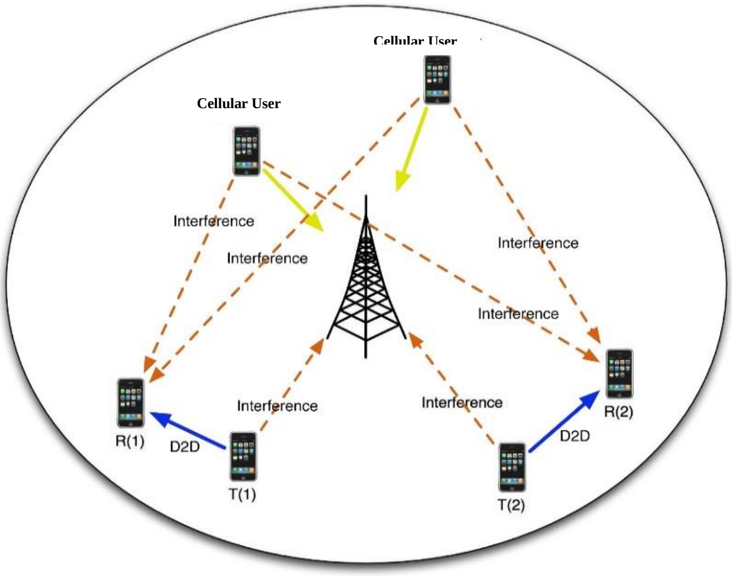

Figure 2.3 Intra-cell interference in D2D communication **[13]**

Figure 2.3 [13] illustrates the basic interference mechanisms in cellular network integrated D2D operation. The solid lines represent the valid communication connections whereas the dashed lines represent different interference. Once the D2D transmission is established, there will be interferences from other active cellular network devices. Besides, D2D communication will bring interference to the cellular network as the D2D transmissions are causing interference to the cellular uplink transmissions at the BS. The BS will control the transmission power of D2D communication to ensure the quality of the cellular network connection after the foundation of D2D link. The transmission power of D2D communication should be reduced in the case of interfering with cellular UEs' connections. The power can be increased when cellular connection quality is in a good condition.

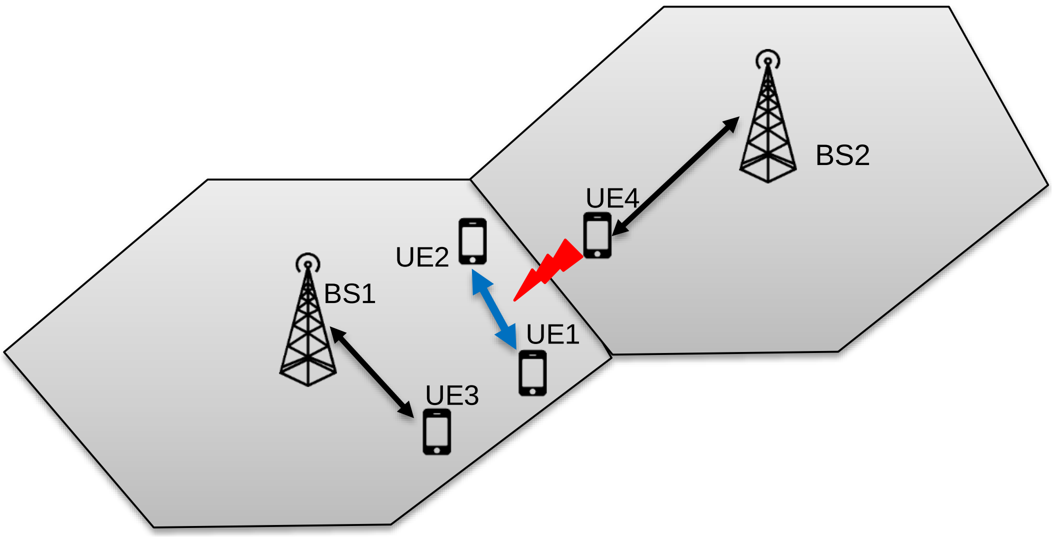

Figure 2.4 Inter-cell interference in network-assisted D2D system

With network's assistance, the spectrum allocated for D2D operation might be reused by cellular users within the same cell, but the interference effects are under control by the base station. Thus, there are no critical interference effects between the D2D and cellular users. But it is difficult to prevent cellular interference from other cells. *Figure 2.4* denotes the resulting intercell interference. With the coordination of BS1, there are no critical interference effects between the D2D pair and UE3. However, BS2 is not aware of which frequency band is utilized by D2D. Thus, it is possible that the same resources could be allocated to the D2D pair and UE4 in the adjacent cell. In the figure above, the length of lines is proportional to the transmission energy. D2D operation is commonly assumed to be based on Orthogonal Frequency Division Multiple Access (OFDMA) [14] or the corresponding single-carrier scheme known as SC-FDMA.

From the link performance and interference management points of view, OFDMA and SC-FDMA can be considered to be equivalent, and either of them is used also for the cellular uplink as well. Then, in the intercell interference situation of *Figure 2.4*, UE4 may transmit to its serving BS in the same resources at a huge power level compared with the D2D link, and the detection of the D2D information fails. One possible way to mitigate such intercell interference cases I to use wideband transmission, like MC-CDMA. If the transmission by UE4 is relatively narrowband, compared to the MC-CDMA bandwidth used for D2D, then the processing gain of MC-CDMA helps to significantly reduce the effect of the interference from the cellular transmission in the same band. Basically, the cellular interference only destroys a small amount of subcarriers of wideband transmission. The remaining interference-free subcarriers are still available for D2D data. This is the reason why D2D based on MC-CDMA is proposed within this thesis.

2.3 Indoor D2D Communication Scenario

Three types of D2D scenarios can be classified according to the locations of transmitter and receiver:

- Transmitter and receiver are located outdoors
- One transmitter or receiver is located outdoors, another is indoor
- Transmitter and receiver are located indoors

This research mainly focuses on the third type that both the transmitter and receiver are located indoors. Compared with outdoor cases, indoor channels have shorter delay spread, which leads to milder frequency selectivity in the indoor cases. Thus, it is easier to carry out the channel equalization in the indoor cases. *Figure 2.5* [15] shows a basic example of indoor office scenario.

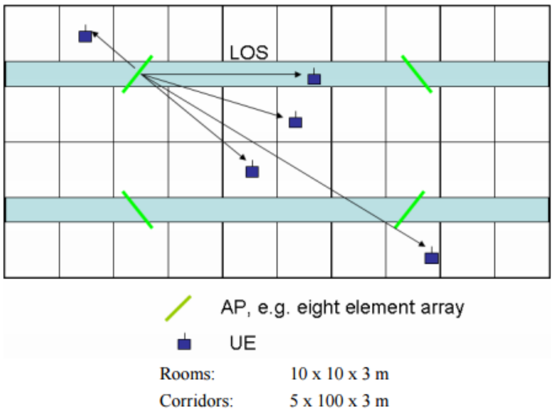

***Figure 2.5 Example of indoor office scenario* [15]**

2.4 Advantages and Challenges of D2D

D2D technique brings diverse advantages. From a technical aspect, D2D communication provides high data rate and low delay which benefits from short distance direct communication. Secondly, it is more efficient to build a link between proximity devices rather than forwarding data through the BS. Thirdly, D2D reduces the load on infrastructure and possibility of congestion. From the economic perspective, autonomous D2D will create more business opportunity and new applications with the development of new D2D discovery schemes like promotion push notification in the supermarket, data sharing among friends, and crucial governmental information broadcasting. For the Public Safety Scenarios, the necessary communication could be ensured by enabling the D2D link between devices specifically under the circumstances when disasters happen or infrastructures break down.

There are also some challenges which need to be solved if D2D is going to be deployed in practice. Firstly, D2D communication might bring interference to cellular users as well, especially in the inband. So interference control is vital through power and resource control schemes. Secondly, an appropriate modulation format should be considered for D2D. Currently, the LTE utilizes OFDMA or SC-FDMA. So further research on modulation format for D2D needs to be carried out for selecting the best choice. Thirdly, D2D can reduce the power consumption by skipping data transmission through BS. But improper protocol on D2D discovery may increase the power consumption of devices at the same time because the protocol can activate devices frequently to discover adjacent UEs.

3. PRINCIPLES OF MC-CDMA

This chapter prensents the fundamental background of MC-CDMA. It is divided into four sections. The first section introduces the concept of OFDM, including also the implementation of OFDM, and the advantages/disadvantages of OFDM. The second section explains the fundamentals of MC-CDMA deriving from OFDM, including the concept of MC-CDMA and implementation of MC-CDMA. Its features are presented in the same section. The third section deals with the channel estimation technique. In this section, ideal channel estimation and pilot based estimation in the frequency domain are considered. At last, equalization methods utilized in simulations are described in the fourth section, including maximum ratio combining (MRC), equal gain combining (EGC), and linear minimum mean square error (LMMSE).

3.1 The Principle of OFDM

WCDMA has been developed for 3G networks. However, it cannot satisfy the criteria of high-speed data transmission due to the existences of Multiple Access Interference (MAI) and Inter-Symbol Interference (ISI). One of the reasons causing ISI is what is called multipath propagation where the transmitted wireless signal arrives at the receiver through many different ways because of reflection and refraction. On the contrary, OFDM [16], which currently has been widely applied for high-speed data transmission, has strong resistance to MAI and ISI. It is easier to aggregate spectrum in OFDM than in CDMA.

3.1.1 Concept of OFDM

OFDM is a Multi-Carrier Modulation (MCM) scheme which converts serial high-speed data signals to parallel low-speed data streams [18]. The available spectrum is separated into several narrowband subcarriers so that the signal experiences flat fading at each subcarrier. The subcarriers are orthogonal and the Inverse Fast Fourier Transform (IFFT) in the transmitter modulates the parallel data streams to different subcarriers. The orthogonality of subcarriers not only avoids the ISI but also acquires higher spectrum efficiency. OFDM has the ability to combat with severe channel conditions even without a complicated equalizer. The spectra of conventional FDM and OFDM are illustrated in *Figure 3.1*.

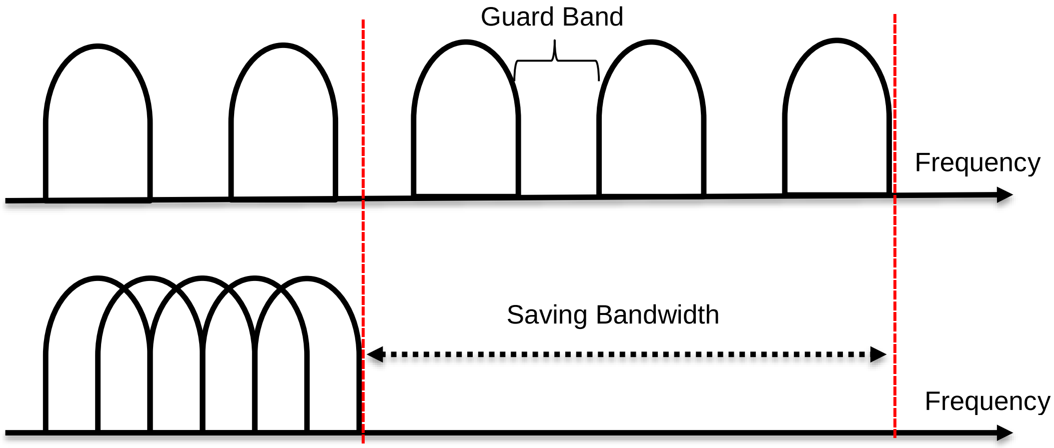

Figure 3.1 Comparison between conventional FDM and OFDM

Generally, the bandwidth of the channel is larger than a transmitted signal bandwidth. Thus, the efficiency is poor if the channel is used for transmitting only one set of signals. The Frequency Division Multiplexing (FDM) is applied for increasing the spectral efficiency. The bandwidth of the channel is segmented into several isolated subbands in the conventional FDM system. The guard band is also set up between subbands so that the effective spectrum utilization ratio is low. OFDM is a technique which can overcome this problem by setting the spacing of subcarriers equal to the reciprocal of symbol duration. The resulting *sinc* frequency responses of each subcarrier processes null values in the adjacent subcarrier frequencies, and the subcarriers are free from ICI.

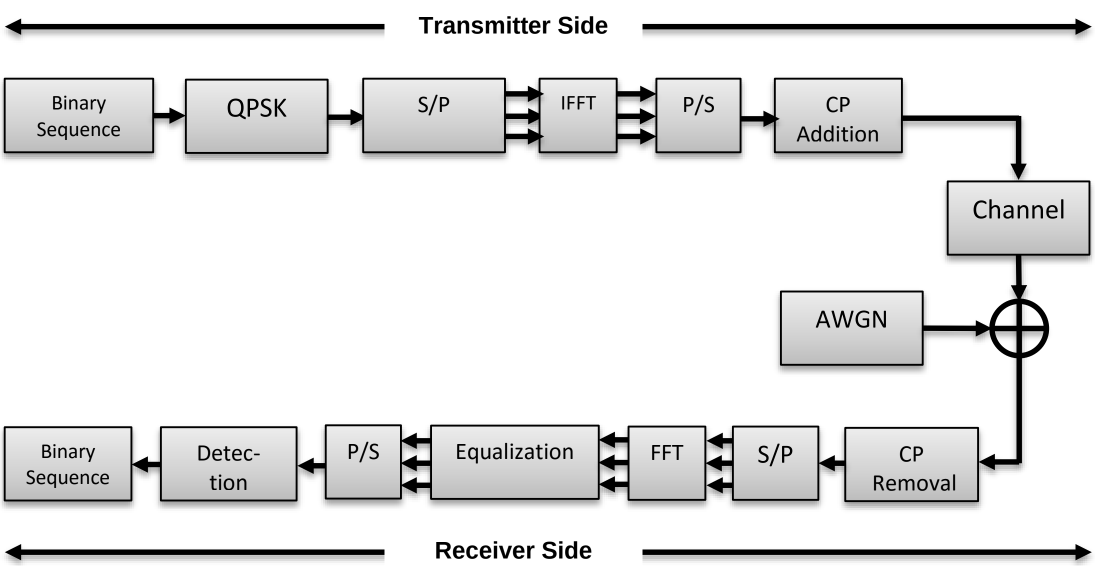

Figure 3.2 OFDM transmitter and receiver block diagram

The structures of OFDM transmitter and receiver [19] are compactly illustrated in *Figure 3.2*. User data from binary sequence generation unite is first converted to QAM symbols, such as BPSK, QPSK, 16-QAM, 64-QAM… Then *N* data symbols (transmitted at the same time) are modulated to *N* orthogonal subcarriers. This modulation implement in a computationally very efficient manner using IFFT. Thus, multiple low symbol rate streams are transmitted in parallel in the channel instead of transmitting a single high symbol rate stream. With proper selection of OFDM symbol length, the impulse response of channel can be viewed as time invariant.

3.1.2 Implementation of OFDM

Figure 3.3 [20] describes the progress of converting user data to OFDM symbols. After transformation of IFFT from the frequency domain to time domain, symbols can be transmitted through the channel.

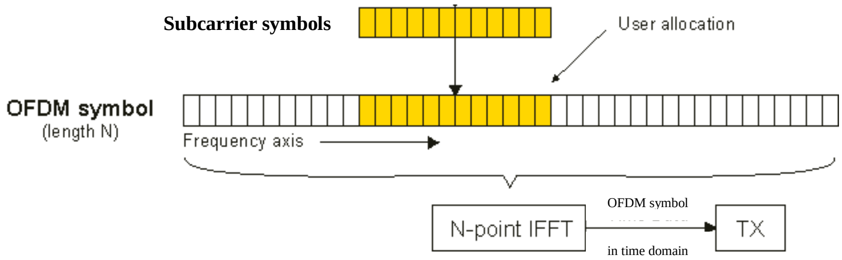

***Figure 3.3 User data converted to OFDM symbol* [20]**

The IFFT block diagram is illustrated in *Figure 3.4*.

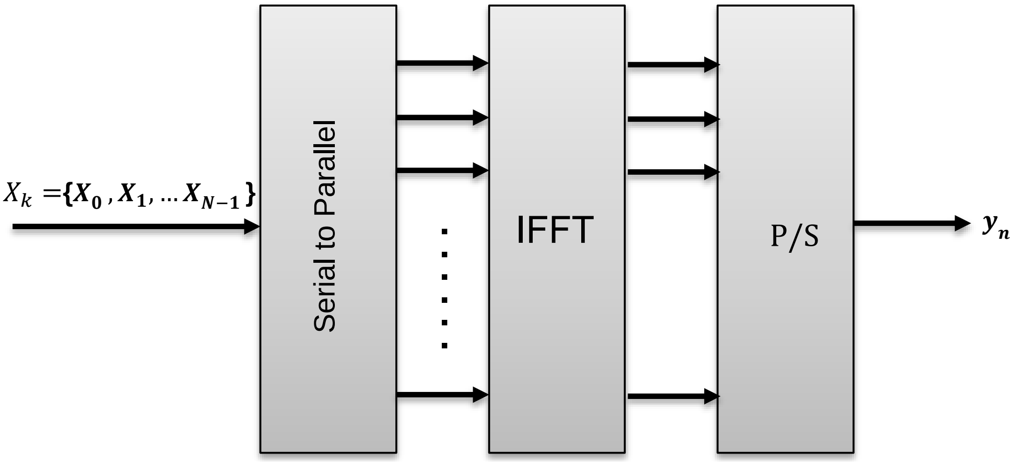

Figure 3.4 Implementation of OFDM by IFFT

In OFDM system, X_k represents the complex symbol from a data stream and it is modulated to k-th subcarriers by Inverse Discrete-Fourier Transform (IDFT) and demodulated by Discrete-Fourier Transform (DFT), which can be implemented in computationally efficient manner by IFFT and FFT algorithms. The IFFT and FFT algorithms in OFDM system are described:

$$y_n = \frac{1}{N_{FFT}} \sum_{k=0}^{N_{FFT}-1} X_k e^{\frac{j2\pi kn}{N_{FFT}}} \tag{3.1}$$

$$X_k = \sum_{n=0}^{N_{FFT}-1} y_n e^{-\frac{j2\pi kn}{N_{FFT}}} \tag{3.2}$$

In the equations above, X_k is a complex symbol in the frequency domain, y_n is the *n*-th sample after IFFT in the time domain and N_{FFT} is the length of IFFT and FFT.

3.1.3 OFDM Advantages and Disadvantages

There are several compelling benefits that promote OFDM to be the prime selected technique in 4G. First of all, a better spectral efficiency is obtained by OFDM. In conventional FDM schemes, a guard band is inserted between subcarriers and it should be sufficient to avoid the possible Inter-Carrier Interference (ICI) so that the transmitted signal can be separated at the receiver side. However, the insertion of guard band decreases the spectral efficiency heavily. Although the subcarriers are overlapped in OFDM signals, the orthogonality between subcarriers can still be preserved so signals can be detected correctly at the receiver side [21]. Therefore the spectrum occupied by guard band is saved for the transmission of useful information.

Stronger ability against ISI is another major distinctive advantage of OFDM. Guard interval which is defined as an empty time slot between OFDM symbols was introduced to maintain the orthogonality and to cope with ISI before CP was invented. The Guard interval is regarded as a buffer for the multipath reflections and it should be set longer than the delay spread of the channel, which is equal to the difference between longest and shortest multipath delays. In this case, the multipath reflection component from one OFDM symbol will not interfere with the next symbol [22]. Nevertheless, ICI is also generated with the guard interval. CP is proposed as a better solution to address this problem. It is the replica of the latter samples of the OFDM symbol and it is attached in front of this symbol such that it ensures the receiver always obtains completed symbol during one IFFT period [23].

One drawback of OFDM is that it leads to high PAPR compared with the single carrier system, especially when the number of subcarriers is large [24]. PAPR increases when the number of subcarriers is raised because an OFDM symbol in time domain is a summation of several sinusoidal sub-channel signals. Thus, the power of this instantaneous summation signal power is much higher than average power when many signals have the same phase. This phenomenon results in stricter and higher requirements to the linearity of the power amplifier in the transmitter. If the amplifier cannot satisfy the requirements, the spectrum of the summation signals will be changed and distortion may be brought into the signals so that the orthogonality between subcarriers is destroyed. Therefore, this increment in PAPR makes the design of RF amplifier complicated and the implementation of the converters between digital and analog signal also becomes more difficult.

OFDM is also quite sensitive towards frequency offset and phase noise which means a higher bit error rate can happen if there is a frequency offset in OFDM signal under demodulation [25]. Rigorous demand towards orthogonality is needed because of overlap of the subcarriers in the spectrum. But time variability of the practical mobile wireless channel may lead to frequency offset during transmissions like the Doppler shift, or frequency deviation between carrier frequency in the transmitter and the oscillator in the receiver, which will destroy orthogonality in OFDM system and introduce ICI. Consequently, strict synchronization is particularly important to maximize OFDM system's performance [26].

3.2 The Fundamentals of MC-CDMA

From the previous sections, it is understood that OFDM has some unique advantages over other multiple access schemes. Therefore, it is natural to investigate some variants of OFDM. One of them combines the idea of OFDM and CDMA. It tries to keep the positive features of both OFDM and CDMA. The combinations of CDMA and OFDM can be divided into two types, as

- Frequency domain spread spectrum
- Time domain spread spectrum

MC-CDMA [17] utilizes the frequency domain spread spectrum scheme. It is the key technology investigated in this thesis.

For one thing, CDMA has the advantages of high capacity and powerful ability against interference as the core technology of 3G whereas it also possesses a lower data transmission rate which cannot satisfy requirements of next generation telecommunication standard. For another, the high data transmission rate is exactly the key feature of OFDM. Based on OFDM and CDMA, Multi-Carrier Code Division Multiple Access (MC-CDMA) is defined as the combination of these two technique to gain the characteristics from both sides.

3.2.1 Concept of MC-CDMA

MC-CDMA spreads data symbols of users in the frequency domain. It means every symbol is duplicated and spread, then modulated into multiple subcarriers in the frequency domain. For the multiple users case, exclusive spreading code is admeasured to each user in the transmitter. In the receiver, signals in all used subcarriers are weighted and summed together intelligently according to various schemes to compensate the signal power variations, and phase shift. Different users' Information will be recovered by multiplying their exclusive codes.

As a multi-access communication scheme, MC-CDMA possesses features of high resistance towards interference. It has also inherited the powerful ability of OFDM to suppress effects multi-path effect. The high spectrum efficiency can be obtained as well.

3.2.2 Implementation of MC-CDMA

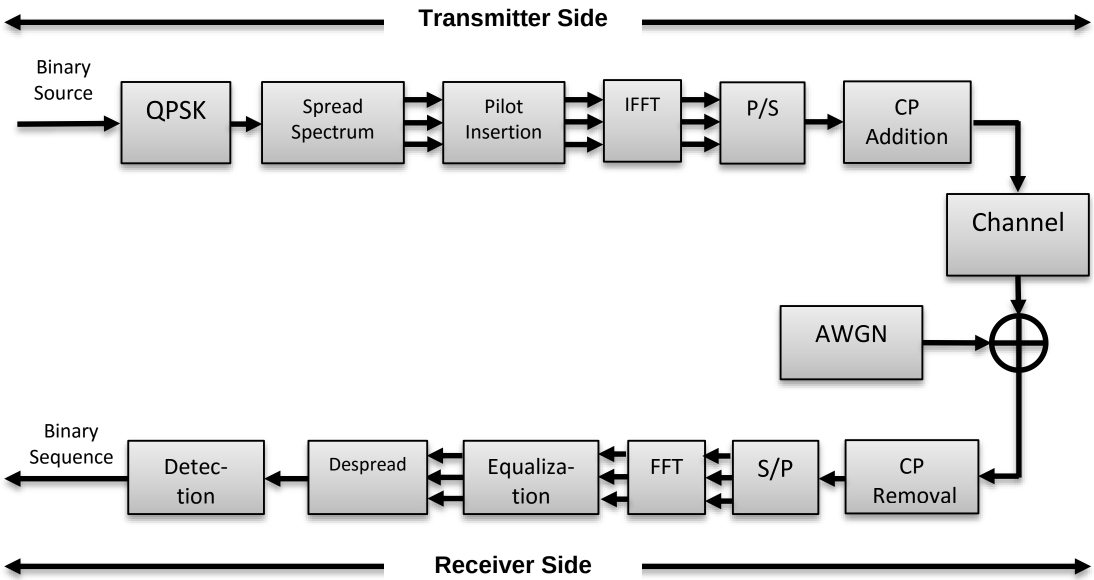

Figure 3.5 Block diagram of MC-CDMA system

The block diagram of a MC-CDMA system is shown in *Figure 3.5* [29]. The modulated data (QPSK in the figure) stream is duplicated to N parallel data streams at first. Every stream is multiplied by one chip of the spreading code in the frequency domain. After pilot insertion, the spread data is modulated to different orthogonal subcarrier by IFFT. At the receiver side, channel estimation (mainly subcarrier based) and equalization are performed before de-spreading operation [27]. In fact, due to the good conditions of D2D channels, simple schemes can be applied for channel estimation and equalization.

Spread spectrum is one technique that processes the information signal to optimize its transmission performance. Spread spectrum spreads the spectrum of the original narrow-band signal to wider bandwidth in order to obtain higher resistance towards multiple-access interference. Meanwhile, spectral efficiency is optimized because multiple users' signals can only be recovered by user specific spreading code on the receiver side. For the same reason, spread spectrum technique is also an effective method for increasing information security during transmission in the wireless channel. The procedure of spread spectrum in the frequency domain on the transmitter side is shown in *Figure 3.6*.

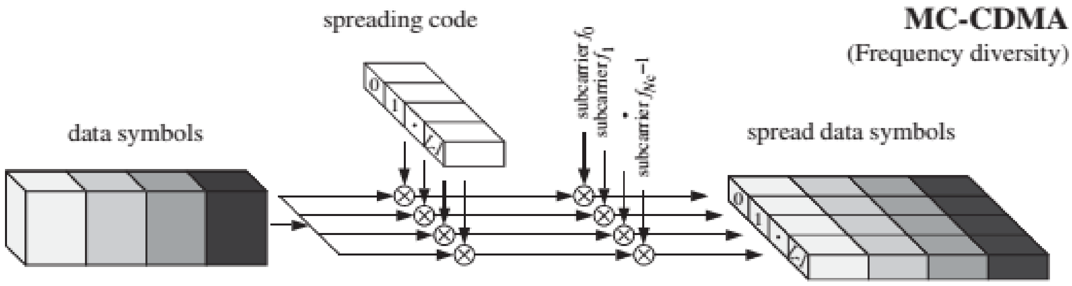

Figure 3.6 Principle of spread spectrum in MC-CDMA transmitter

Typically, there are four types of spread spectrum: Direct Sequence Spread Spectrum (DS), Frequency Hopping Spread Spectrum (FH), Time Hopping Spread Spectrum (TH), and Chirp Modulation [28]. Sometimes, these combinations of techniques above may also be applied like DS/TH, DS/FH/TH…It is more complicated in implementation when combining, but various features from different techniques can be acquired at the same time. For example, in DS/TH system, time multiplexing is added into spread spectrum so that the system can undertake a higher number of users.

DS is chosen as the spread spectrum technique within this research and generally in MC-CDMA. The principle of DS is to multiply the information signal with uncorrelated symbols (typically binary, sometimes QPSK symbols) which are known as spreading codes to expand the spectrum of the signal. Thus, the transmission frequency bandwidth is much larger than the smallest bandwidth that is needed for original signal transmission. Orthogonal Walsh-Hadamard (WH) codes, which come from Walsh-Hadamard matrix possessing binary values of -1 and 1, are applicable in MC-CDMA systems. A dimension of 2^m WH matrix provides orthogonal spreading codes for 2^m users at most and it can be generated by the recursive algorithm which is described as follows:

$$C_n = \begin{bmatrix} C_{n/2} & C_{n/2} \\ C_{n/2} & -C_{n/2} \end{bmatrix}, \ \forall\, n = 2^m, \quad C_1 = 1 \tag{3.3}$$

$$C_2 = \begin{bmatrix} C_1 & C_1 \\ C_1 & -C_1 \end{bmatrix} = \begin{bmatrix} 1 & 1 \\ 1 & -1 \end{bmatrix} \qquad C_4 = \begin{bmatrix} C_2 & C_2 \\ C_2 & -C_2 \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & 1 \\ 1 & -1 & 1 & -1 \\ 1 & 1 & -1 & -1 \\ 1 & -1 & -1 & 1 \end{bmatrix}$$

In a single-user MC-CDMA system shown in *Figure 3.7*, each symbol to be transmitted is repeated in all used subcarriers, after multiplying by the corresponding chips of the code. Then IFFT is used to implement the subcarrier modulation, as in OFDM. It describes the MC-CDMA system with single user and the signal is modulated to N subcarriers. $a[m]$ represents the m-th symbol of this user and c_k means the k-th chip of spreading code.

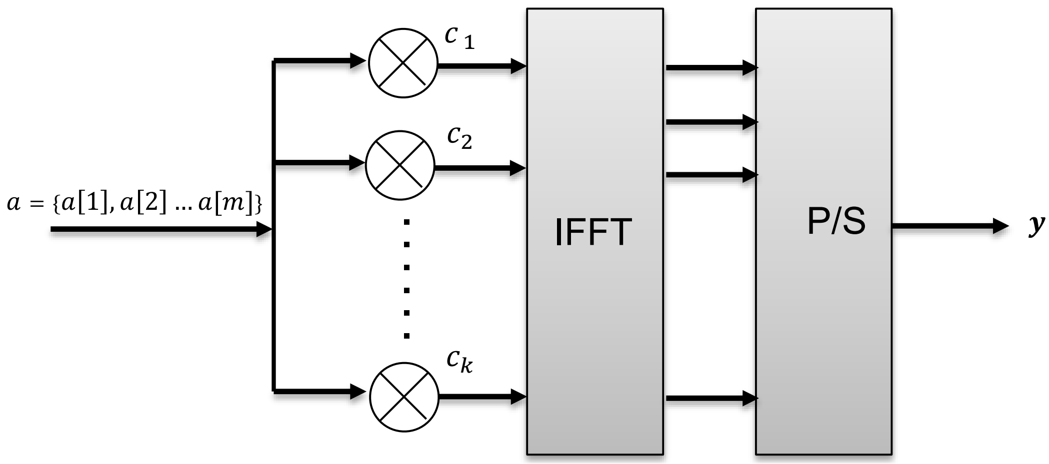

Figure 3.7 Single-user MC-CDMA generation

After the implementation of IFFT or IDFT, the data are converted from frequency domain to time domain. And they are denoted as the equations below:

$$y = \sum_{k=0}^{N_{FFT}-1} a \cdot c_k \cdot e^{\frac{j2\pi kn}{N_{FFT}}} \tag{3.4}$$

$$a = \frac{1}{N_c} \sum_{N_c} c_k \sum_{n=0}^{N_{FFT}-1} y \cdot e^{-\frac{j2\pi kn}{N_{FFT}}} \tag{3.5}$$

Here $N_c$is the length of the spreading code. In multi-user case, another specific spreading codes $c_{i,k}$ is utilized to multiply with the data of the i-th user.

3.2.3 Features of MC-CDMA

The addition of Cyclic Prefix (CP) takes place after IFFT on the transmitter side and it is the key characteristic of both OFDM and MC-CDMA which reduce the influence from multipath propagation. Intersymbol interference can be eliminated with the insertion of CP which is transmitted within the guard interval (GI).

Multipath effect caused by reflection can lead to ISI in wireless communication. Under the multipath circumstance, the front part of next OFDM symbol may reach to the receiver side earlier than the end part of the current symbol. Guard Interval (GI) is used to overcome this problem by adding an empty time period which is supposed to be longer than the maximal delay spread. The insertion of GI improves the immunity to reflections and echoes. It provides a buffer time for avoiding ISI of two adjacent OFDM symbols [30].

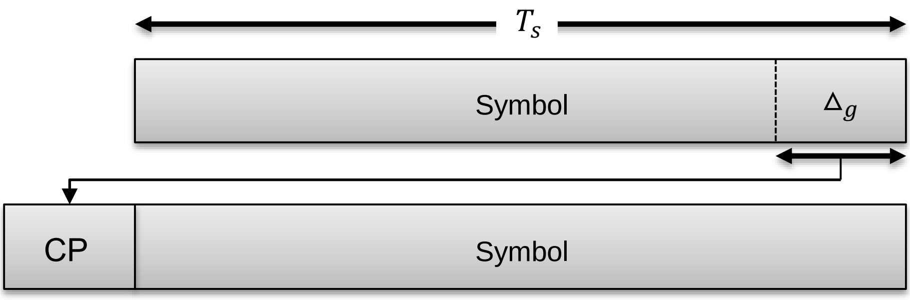

Figure 3.8 Idea of cyclic prefix

As illustrated in *Figure 3.8*, after addition of guard interval (Δg) aiming to eliminate the effect of ISI, the total length (T_s) of OFDM symbol is the summation between useful symbol duration (T_u) and guard interval which is described in the equation below:

$$T_s = T_u + \Delta g \tag{3.6}$$

Because the length of CP is supposed to be larger than the maximal delay spread of the multipath component, it ensures that every component from multipath effect will be received as a complete symbol within one FFT window. When the IFFT is processed in a symbol period, the resulting time sample process is periodic. This helps to maintain orthogonality between subcarriers to eliminate ICI.

Actually, DFT algorithm performs circular convolution in time domain, corresponding to multiplication in frequency domain. With CP insertion, regular convolution ($*$) can be used to construct circular convolution ($\circledast$). If $x[n]$ is extended by duplicating the last v samples at the beginning:

$$\hat{x}[n] = \begin{cases} x[n], & 0 \le n \le N-1 \\ x[n+N], & -v \le n \le -1 \end{cases}$$

It possesses two properties:

$$\{h \circledast x\}[n] = (h * \hat{x})[n] \quad \text{for } 0 \le n \le N-1 \tag{3.7}$$

$$\{h \circledast x\}[n] \xrightarrow{FFT} H_k X_k \tag{3.8}$$

Assuming N samples $S_0, S_1, \ldots, S_{N-1}$ are going to be sent across noisy channel, so after IFFT the signal in time domain is:

$$\hat{s} = [s[N-v], \ldots, s[N-1], s[0], \ldots\ s[N-1]\,]$$

The output after the channel is:

$$y[n] = [p[N-v], \ldots, p[N-1], r[0], \ldots\ r[N-1]\,]$$

After removing CP, $r[n] = h[n] \circledast s[n] + w[n]$. According to the properties, $R_k = H_k S_k + W_k$ can be acquired after FFT where there is no ICI.

In addition, MC-CDMA possesses robustness for signals transmitted in the frequency selective fading channel due to duplicating and spreading data over multiple subcarriers. The processes of Walsh-Hadamard code based spreading and IFFT/FFT transform are simple to be implemented. Multiple users' data could be differentiated and added with each other via orthogonal spreading code to be transmitted together. So the same range of bandwidth could serve more users at the same time, which improves the spectral efficiency. In the extreme case where the number of orthogonal spreading codes is equal to the spreading factor (so-called fully loaded case), the spectrum efficiency reaches that of OFDM. Furthermore, the frequency diversity acquired by spreading data symbols in the frequency domain provides higher signal gains in receivers so that the probability of recovering the interfered original data and the quality of recovered signal are increased.

3.3 Channel Estimation

The channel condition between the transmitter and receiver is complicated. Different with a wired channel, the wireless channel is unpredictable due to its randomicity. The signal received from multipath consists of the direct path, reflection paths, and scattering paths. Frequency selectivity induced by multipath propagation causes different influences on the signal, depending on its bandwidth. The signal will suffer from strong frequency selectively when its bandwidth exceeds the coherence bandwidth [31]. ISI caused by multipath delay spread in the wireless channel has limited the data transmission rate. Complicated channel condition also increases the complexity of the receiver. MC-CDMA could restrain ISI effectively because of the use of CP. However, the multicarrier technique requires strict orthogonality between subcarriers and synchronization at carrier frequency, FFT window position, and sampling clock levels. Consequently, an accurate channel estimation in the receiver side is compulsory to ensure good performance of MC-CDMA system.

Within this research, two kinds of channel estimation implementations are applied:

- Ideal channel estimation
- Pilot-based channel estimation

For the ideal channel estimation, the channel response $h(n)$ used for equalization in the receiver will be obtained.

3.3.1 Pilot-based Channel Estimation

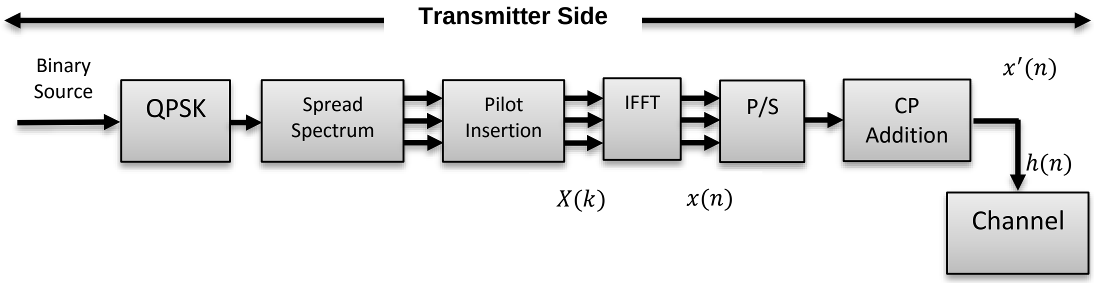

Figure 3.9 Transmitter block diagram of pilot-based MC-CDMA system

In *Figure 3.9* above, users' data in frequency domain $X(k)$ are transformed into time domain $x(n)$ after pilot insertion. The data with CP is denoted as $x'(n)$. The impulse response of the channel is represented by $h(n)$. The expression of the received signal is:

$$y'(n) = x'(n) \otimes h(n) + w(n) \tag{3.9}$$

In *equation (3.9)* $w(n)$ is the Additive White Gaussian Noise (AWGN). AWGN is added after the signal goes through the channel.

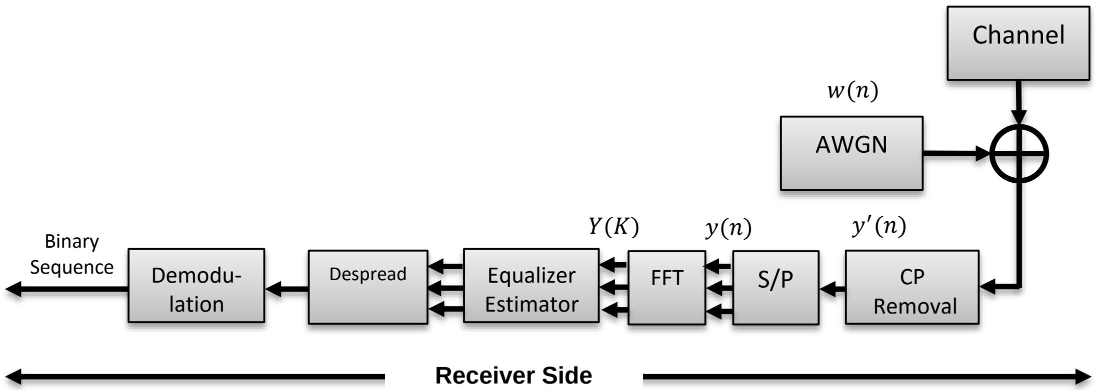

Figure 3.10 Receiver side of pilot-based MC-CDMA system

In the receiver, the received signal transformed to the frequency domain by FFT algorithm under research can be expressed below:

$$Y(k) = X(k) \cdot H(k) + W(k) \quad (k = 0,1,2 \dots N - 1) \tag{3.10}$$

Here $W(k)$ is the noise at k-th subcarrier in frequency domain, $H(k)$ is the transfer function of the channel at k-th subcarrier. N represents the total number of subcarriers. In order to recover the transmitted signal $\hat{X}(k)$, an estimated channel response $\hat{H}(k)$ needs to be acquired by interpolation between adjacent pilot values for all subcarriers symbols.

The pilot-based system can be simply classified into two types depending on their allocation pattern [32]:

- Comb type pilot allocation [33]
- Block type pilot allocation [33]

These two types are denoted in *Figure 3.11*.

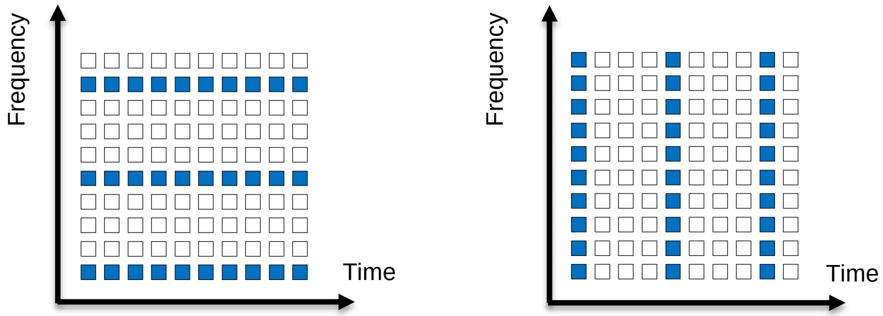

Figure 3.11 (a) Comb type pilot structure (b) Block type pilot structure

For comb type estimator, selected individual subcarriers are occupied by pilot symbols during the whole transmission time like in *Figure 3.11 (a)*. Channel estimation is implemented at every OFDM symbol. Then interpolation needs to be fulfilled along subcarriers without a pilot. This arrangement is more suitable for channels having mild frequency selectivity but high Doppler shift. Compared with block type pilot allocation, the comb-type structure is more sensitive to the frequency selectivity. Therefore, the pilot spacing is required to be smaller than the coherence bandwidth of the channel.

Block type estimation is shown in *Figure 3.11 (b)*. In this case, pilot symbols are allocated along the frequency axis. It occupies the entire MC-CDMA symbol so that the data transmission efficiency will be sacrificed. Such a pilot structure contains all subcarriers so there is interpolation only along the time domain and it is insensitive to the frequency selectivity. Although the data rate is decreased due to the occupation of the whole MC-CDMA symbols by useless information, this kind of allocation still has benefits especially in the channel having high-frequency dispersion and low Doppler shift. Since there is low Doppler shift within this simulated model, the block type pilot structure is selected as the channel estimation method in this thesis.

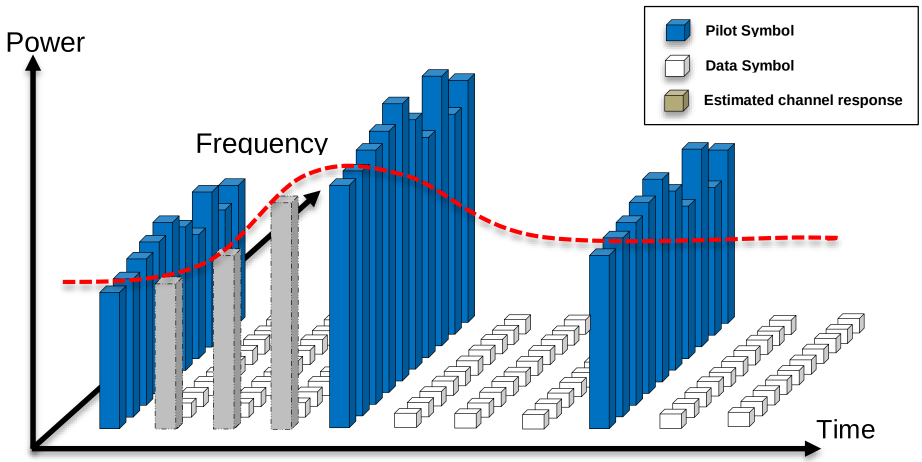

Figure 3.12 Principle of channel interpolation

Figure 3.12 illustrates the general principle of interpolation in channel estimations. Channel estimation is a 2D-dimensional issue no matter which category of the pilot structure is applied [34]. Different interpolation algorithm needs to be implemented along another dimension except the one fully occupied by pilots. Currently, there is no interpolation in this simulation model. The same estimation from a pilot symbol will be used for the next data symbols until the coming of the next pilot symbol.

3.4 Equalization Techniques

Once the channel response is estimated, transmitted signal is able to be recovered by as follows:

$$\hat{X}(k) = \frac{Y(k)}{\hat{H}(k)} \qquad (k = 0,1,2 \dots N-1)$$

$$= \frac{X(k) \cdot H(k) + W(k)}{\hat{H}(k)}$$

$$= X(k) \cdot \frac{H(k)}{\hat{H}(k)} + \frac{W(k)}{\hat{H}(k)} \tag{3.11}$$

Diversity is an effective method of combating with frequency selectivity [35]. As a key feature of MC-CDMA technique, diversity provides multiple copies of the transmitted data symbols which suffer independent channel fading and these copies can be combined together intelligently on the receiver side according to specific rules to achieve better performance in terms of bit error rate (BER). Four categories of diversity are classified [36]:

- Frequency diversity
- Space diversity

- Time diversity
- Polarization diversity

Frequency diversity means multiple data replicas are transmitted at a different frequencies. Multiple antennas are located separately provides space diversity. Time diversity is transmitting data copies over diverse time periods. Multiple duplicates that have various field polarizations forms polarization diversity. Two kinds of equalization methods, namely equal gain combining (EGC) and maximum ratio combining (MRC) are mainly focused within this report. Besides, linear minimum mean square error (LMMSE) scheme is taken into consideration as well.

3.4.1 Maximum Ratio Combining

Signal going through multiple channels will suffer from fading which is not correlative. In order to recover original information by received signals, Maximum Ratio Combining is to add the signals transmitted through each branch together after multiplying them with appropriate weights after phase correction [37]. In MRC combiner, *N* branches signals will be adjusted into co-phase signals for the purpose of combining these coherent signals. Alterable gains exist in each branch to do optimum weighting based on the channel response. *Figure 3.13* shows the principle of the MRC combining algorithm.

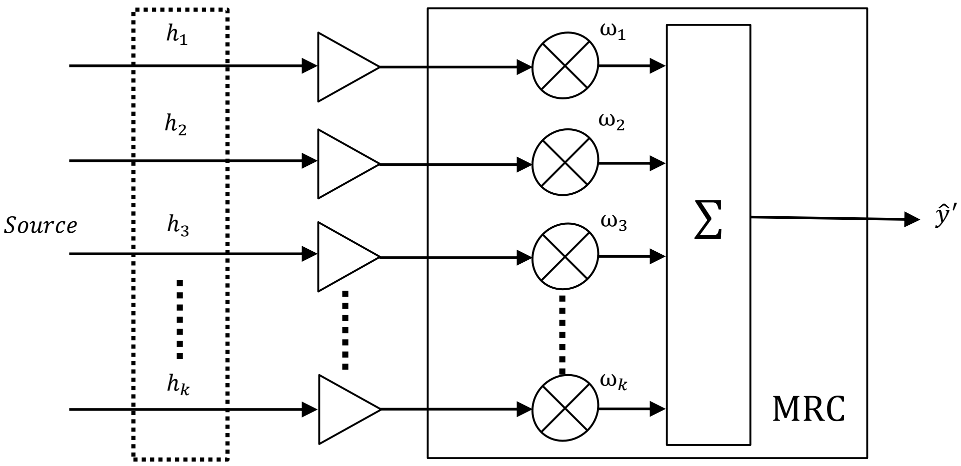

Figure 3.13 Block diagram of MRC

Signal in each branch can be represented by the equation:

$$y_k(t) = x_k(t)h_k + n_k(t) \tag{3.12}$$

Here, h_k is channel gain and $n_k(t)$ represents complex AWGN with equal variance. Thus the output after MRC combiner is:

$$\hat{y}' = \sum_{k=0}^{N-1} \omega_k y_k(t) = \sum_{k=0}^{N-1} \omega_k x_k(t) h_k + \sum_{k=0}^{N-1} \omega_k n_k(t)$$

$$= x_k(t) \cdot \sum_{k=0}^{N-1} \omega_k h_k + n_k(t) \cdot \sum_{k=0}^{N-1} \omega_k \qquad (3.13)$$

The instantaneous power of the combined signal is:

$$\sigma_s^2 = E[|x_k(t)|^2] \cdot \left| \sum_{k=0}^{N-1} \omega_k h_k \right|^2 \qquad (3.14)$$

And the power of noise is after combiner is:

$$\sigma_{n'}^2 = \sigma_n^2 \cdot \sum_{k=0}^{N-1} |\omega_k|^2 \qquad (3.15)$$

Therefore, the SNR can now be expressed as the equation below:

$$SNR_c = \frac{\sigma_s^2}{\sigma_{n'}^2} = SNR_{ave} \cdot \frac{|\sum_{k=0}^{N-1} \omega_k h_k|^2}{\sum_{k=0}^{N-1} |\omega_k|^2} \qquad (3.16)$$

Where SNR_{ave} is the average SNR that is equivalent for all branches. The equation can be maximized by Lagrange multipliers or Cauchy-Schwarz inequality. Here Cauchy-Schwarz inequality can be written as:

$$\left| \sum_{k=0}^{N-1} \omega_k h_k \right|^2 \leq \sum_{k=0}^{N-1} |\omega_k|^2 \cdot \sum_{k=0}^{N-1} |h_k|^2 \qquad (3.17)$$

With the equality satisfied when $\omega_k = c \cdot h_k^*$, in which c represents an arbitrary constant and it is set to 1 to acquire the maximum SNR. Consequently, the maximal SNR after MRC combiner can be calculated:

$$SNR_{MRC} = SNR_{ave} \cdot \sum_{k=0}^{N-1} |h_k|^2 = \sum_{k=0}^{N-1} SNR_k \qquad (3.18)$$

And the gain factor in k-th subcarrier is:

$$g_k = h_k^* \qquad (3.19)$$

Here h_k^* represents conjugation of channel response in k-th subcarrier.

Consequently, the weight of k-th branch is in proportion to signal amplitude such that the weights of signals with higher amplitude will be high as well, reducing the influence from noise. Although the expense and complexity of implementing MRC combiner is somewhat higher in comparison with other diversity combining techniques, MRC is still utilized in plenty of realistic diversity scenarios.

3.4.2 Equal Gain Combining

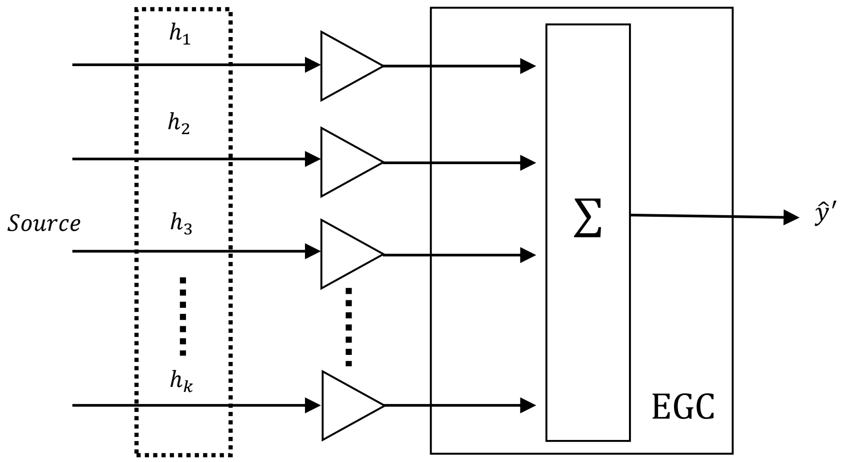

Figure 3.14 Block diagram of EGC

It may be complicated and inconvenient to generate various weights for every branch under some circumstances. Therefore, MRC is not appropriate in some cases. Equal Gain Combining combiner is implemented as a simple version of MRC. Its primary principle is to perform the same processes on the signal from each branch and then add them together [38]. It only corrects the phase instead of adjusting amplitude. In this way, the combiner can still utilize all signals received from each branch. Even if several branches of the signal cannot be restored due to distortion, it is possible to restore the signal via the combination of these branches. EGC corresponds to setting the combiner weights ω_k as $\omega_k = g_k$ $(k = 0,1,2 \ldots N-1)$. *Figure 3.14* denotes the fundamental idea of EGC combining algorithm.

Thus, the received signal is:

$$\hat{y}' = \sum_{k=0}^{N-1} y_k(t) \cdot e^{-j\theta_k} = \sum_{k=0}^{N-1} x_k(t) \cdot h_k \cdot e^{-j\theta_k} + \sum_{k=0}^{N-1} n_k(t) \cdot e^{-j\theta_k} \qquad (3.20)$$

The SNR after EGC combiner can be calculated as below:

$$SNR_{EGC} = SNR_{ave} \cdot \frac{\left|\sum_{k=0}^{N-1} h_k \cdot e^{-j\theta_k}\right|^2}{N} \tag{3.21}$$

Thus, the gain factor when EGC algorithm is implemented is:

$$g_k = \frac{h_k^*}{|h_k|} \tag{3.22}$$

Although the performance of EGC is slightly worse than MRC, but the complexity of EGC combiner is easier to be implemented in comparison with MRC combiner.

3.4.3 Linear Minimum Mean Square Error Detector

Bayes estimation [39] needs to acquire posterior distribution function at first whereas Maximum Likelihood (ML) [40] estimation can be implemented after obtaining likelihood function. However, these functions are unknown under a huge amount of circumstances. Furthermore, ML method can also lead to nonlinearity which results in difficulty in the calculation. Consequently, equalization methods that don't require prior knowledge and easy to solve turn to be more attractive.

As a detection scheme, Minimum Mean Square Error (MMSE) aims to minimize Mean Square Error (MSE) [41], which is an ordinary measure of detector performance. But the equalizer designed under MMSE algorithm is complicated and inconvenient to be implemented. Simply assuming the received symbol before the equalizer as below:

$$Y = H \cdot X + N \tag{3.23}$$

N is statistically independent to X. The equalized signal which is going to be recovered can be represented as:

$$\hat{X} = G^H \cdot Y = G^H(H \cdot X + N) \tag{3.24}$$

Where G is set to minimize the error $E(\|\hat{X} - X\|^2)$.

When the noise is AWGN which means it is a zero-mean model, MMSE is equivalent to Linear Minimum Mean Square Error (LMMSE) algorithm. The system with N subcarriers and a total number of L users are assumed and their data symbol is $X_L(m)$. Then a serial of specific spreading code is generated $c_L = [c_{L,1}, c_{L,2} \dots c_{L,N}]$. The transmitter model is shown in *Figure 3.15*.

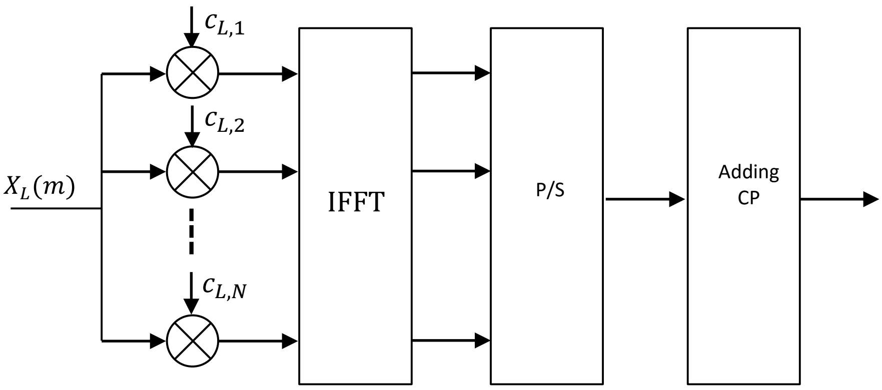

Figure 3.15 MC-CDMA transmitter model

Let's consider first the downlink multi-users (or multi-code) case where the data transmitted with different spreading codes experience the same channel. Then in the receiver before detection, MC-CDMA symbol is in the form:

$$Y = SX + n$$

$$= X_1 \cdot \begin{bmatrix} H_1 c_{1,1} \\ H_2 c_{1,2} \\ \vdots \\ H_N c_{1,N} \end{bmatrix} + X_2 \cdot \begin{bmatrix} H_1 c_{2,1} \\ H_2 c_{2,2} \\ \vdots \\ H_N c_{2,N} \end{bmatrix} + \cdots + X_L \cdot \begin{bmatrix} H_1 c_{L,1} \\ H_2 c_{L,2} \\ \vdots \\ H_N c_{L,N} \end{bmatrix} + \begin{bmatrix} n_1 \\ n_2 \\ \vdots \\ n_N \end{bmatrix} \quad (3.25)$$

Here S denotes the processes of data symbol after the channel but before the noise addition and $S = \Lambda C$:

$$\Lambda = diag\{H_1\ H_2 \ldots H_N\}$$

$$C = [\ c_1\ c_2 \ldots c_L\ ]$$

Here C denotes Walsh-Hadamard code that means each element of C are orthogonal to others and H_N represent coefficients for subchannels.

It is assumed that the data symbol of L-th user after equalization are in the form of $\hat{X}_L = G_L^H \cdot Y$. And the linear minimum mean-squared error optimum factor with despreading $W_{opt,L}^H$which aims to minimize $E\left[|X_L - \hat{X}_{opt,L}|^2\right]$ can be simply expressed as[42][43]:

$$W_{opt,L}^H = c_L^T \Lambda^* \left(\Lambda C C^T \Lambda^* + \frac{\sigma_n^2}{\sigma_X^2} I \right)^{-1}$$

$$= c_L^T \Lambda^* (\Lambda C C^T \Lambda^* + SNR \cdot I)^{-1}$$

$$= c_L^T G_{opt} \quad (3.26)$$

This optimum MMSE equalizer is complicated due to the needed matrix inversion. But it is regarded as a reference while comparing with other simpler equalization schemes. The receiver $W_{opt,L}^{H}$ combines the equalizer coefficient G_{opt} and despreading code c_L^T together in *equation 3.26*.

Within this thesis, per-subcarrier processing of LMMSE algorithm [44] is implemented for the simulation. For reducing the complicated part of matrix inversion of this optimum MMSE methods, a simplified version of MMSE receiver is implemented by per-subcarriers processing [45] [46]. Its principle is to equalize in each subcarrier and then perform despreading. So the collection of equalizer coefficients on subcarrier basis is in the form of $G_{per} = diag\{g_{per,1}\ g_{per,2} \dots g_{per,N}\}$. The equation can be expressed as:

$$g_{per,n} = \frac{H_n^* \sigma_{sp}^2}{|H_n|^2 \sigma_{sp}^2 + \sigma_{AWGN}^2} = \frac{H_n^*}{|H_n|^2 + \frac{N\sigma_{AWGN}^2}{L\sigma_x^2}}$$

$$= \frac{H_n^*}{|H_n|^2 + \frac{N}{L \cdot SNR}} \tag{3.27}$$

When $N = L, sp = CX, \sigma_{sp}^2 \approx (k/N)\sigma_x^2$, it denotes the fully loaded cases. The beneficial aspect of LMMSE is that it takes SNR into the consideration which the diversity combining equalization methods don't when designing the equalizer. Consequently, LMMSE is expected to have better system performance and function quality compared with EGC and MRC.

4. SYSTEM MODEL

This chapter explains the principal background knowledge which has been taken into account within this thesis. General comprehension of the system model is presented. The channel model (D2D WINNER II A1), the cellular interference model, and the noise model are described. Furthermore, the description of the pilot allocation for channel estimation and the definition of symbol error rate which corresponds to the system performance and quality are provided in the chapter.

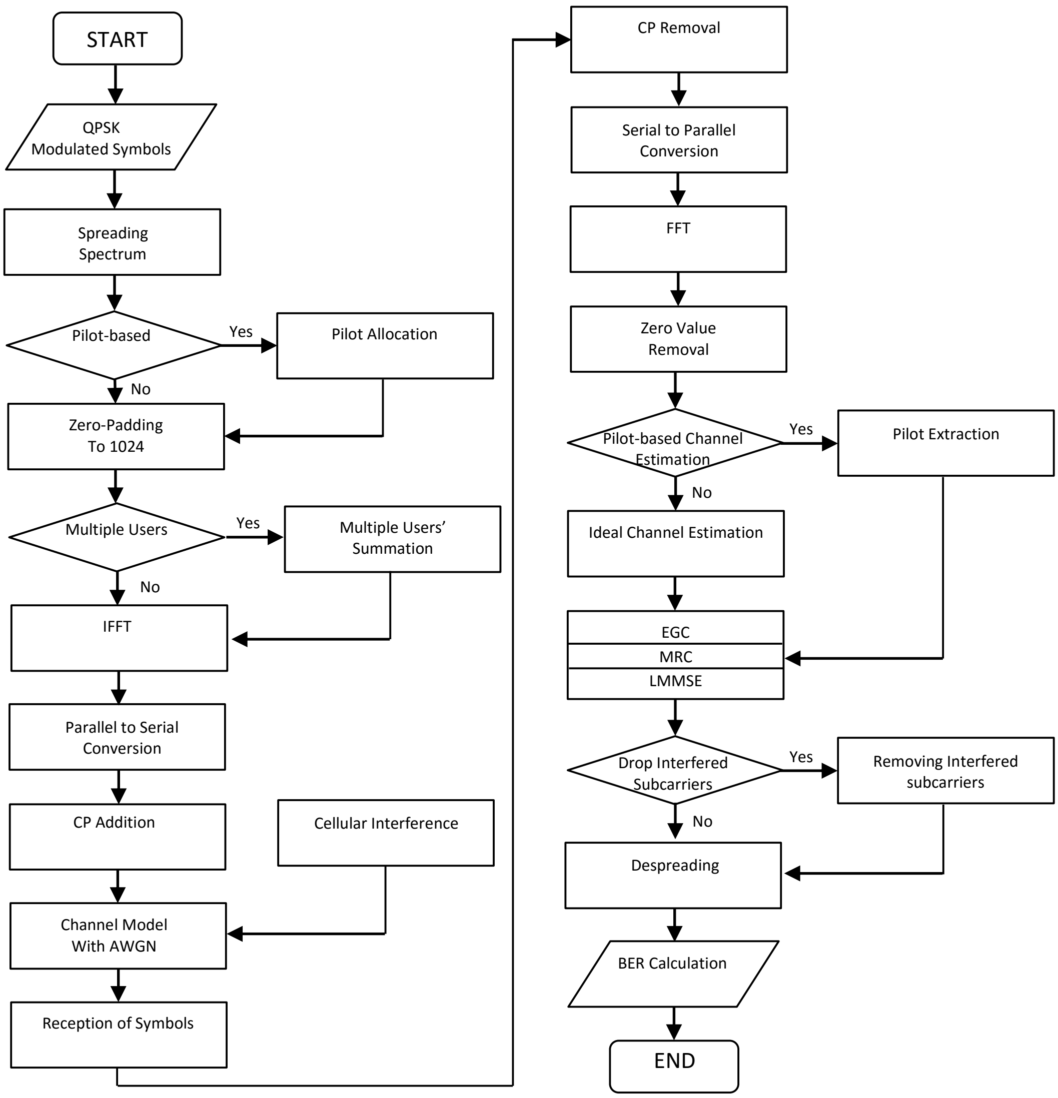

Figure 4.1 Simulation flowchart

Figure 4.1 shows the workflow of the studied system. First of all, a basic framework of single-user case for this research is established for simulations. Then more users and pilots are added so that different scenarios can be simulated. The simulation results will be exhibited and discussed in next chapter.

Based on the flowchart, the first block after START is to generate the original data sequences and modulate them to complex symbols by QPSK. Then spreading spectrum block constructs WH codes to duplicate and spread the QPSK symbols to related orthogonal subcarriers. In the ideal channel estimation case zeros padding is done directly, whereas in the pilot symbol based estimation case, pilot symbols are allocated before zero padding. Multiple-user data multiplied with their specific spreading codes are added together in next block and the conversion of parallel to serial is performed after IFFT. Then CP is added so that the data will be ready to be propagated through the channel with AWGN. OFDMA based cellular interference which can occupy several specific subcarriers is generated and transformed to the time domain, then it is summed with the data after the channel.

In the receiver, CP is removed from the received signal. The data is converted from serial to parallel in next block and the length is changed to the size of IFFT again to perform FFT algorithm. Then the zero values padded in the transmitter are omitted. The pilot symbol will be extracted so that the channel response can be estimated. In the ideal channel estimation case the impulse response of the simulated channel will be used directly for channel equalization. In equalization block, three categories of algorithms are applied, including EGC, MRC, and LMMSE described in chapter 3. Then two processes on the interfered subcarriers are separately carried out, which is either dropping or keeping them when performing despreading. Finally, the data spread to different subcarriers is combined together to recover the signal. In the output block, BERs for all the cases are calculated and exhibited in the figures for evaluating and comparing the performance.

4.1 Channel Model

In simulations, we select WINNER II channel models [47] as the D2D channel models. More precisely, the indoor office A1 channel model is used. WINNER channel model is an enhanced version of 3GPP Spatial Channel Model (SCM) developed by the former Nokia Siemens Networks.

For A1 indoor office model, the parameters follow *Table 4-1* [48]. The corresponding power-delay profile and frequency correlation are drawn in *Figure 4.2* [48].

***Table 4-1 Scenarios A1: LOS clustered delay line model, indoor environment* [48]**

Cluster #	Delay [ns]			Power [dB]			AoD [º]	AoA [º]	Ray power [dB]		Cluster ASD = 5º	Cluster ASA = 5º	XPR = 11 dB
1	0	5	10	0	-15.1	-16.9	0	0	-0.23*	-22.9**			
2	10			-15.8			-107	-110	-28.8				
3	25			-13.5			-100	102	-26.5				
4	50	55	60	-15.1	-17.3	-19.1	131	-134	-25.1				
5	65			-19.2			118	121	-32.2				
6	75			-23.5			131	-134	-36.5				
7	75			-18.3			116	-118	-31.3				
8	115			-23.3			131	-134	-36.4				
9	115			-29.1			146	149	-42.2				
10	145			-14.2			102	105	-27.2				
11	195			-21.6			-126	129	-34.6				
12	350			-23.4			131	-134	-36.4				

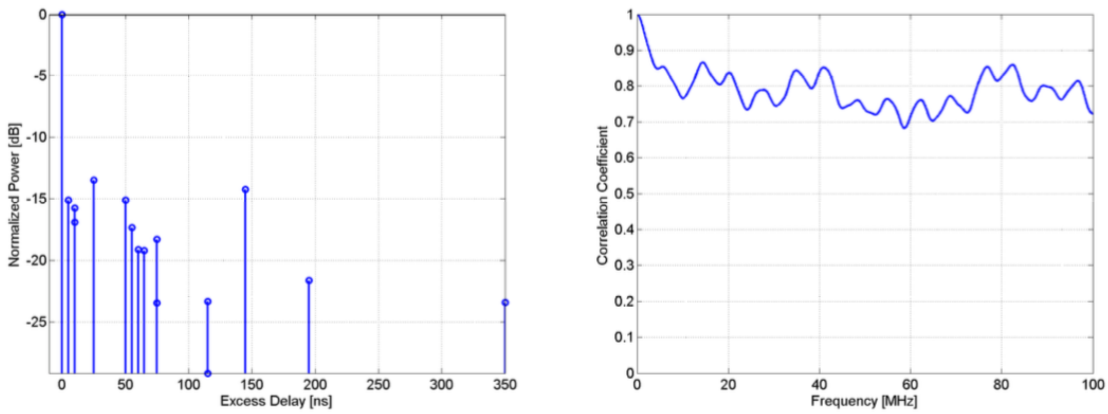

***Figure 4.2 Power-delay profile and frequency correlation* [48]**

The Impulse response and frequency response which exhibit the characteristics of the channel are illustrated in *Figure 4.3*.

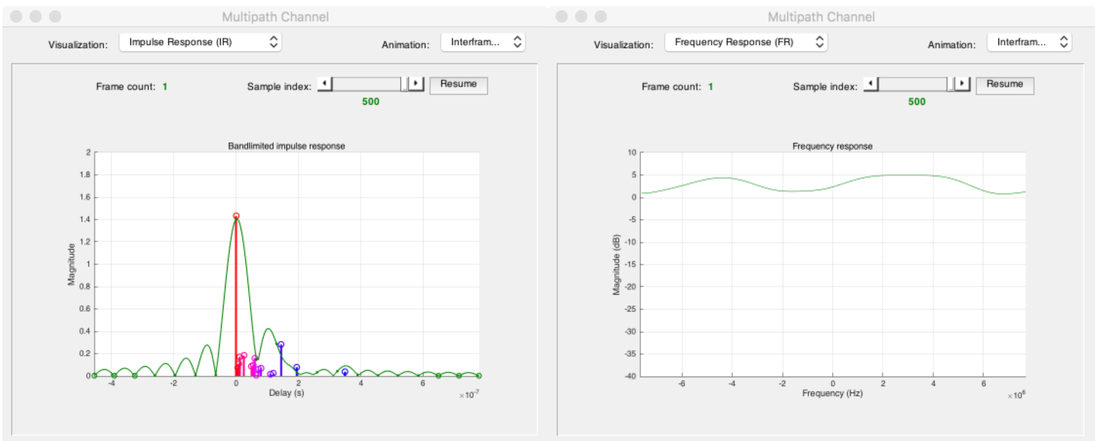

Figure 4.3 Examples of channel impulse response and frequency response

The A1 channel model is implemented by MATLAB by utilizing *rayleighchan* function. The sampling frequency is chosen as 15360000. The impulse response denotes the amplitudes of multipath components with different time delays. The reason for using this channel model is that it represents a typical channel for D2D communication in indoor scenarios. In such short-distance communication, indoor cases are considered to be more challenging than outdoor scenarios, due to higher number of reflections. From Figure 4.3 it can be observed that his channel represent relatively mild frequency selectivity, due to the short delay spread. The shape of its spectrum is relatively flat so that the orthogonality can be maintained well.

4.2 Interference Model and Noise Model

Besides the multiple access interference (MAI) within the D2D system, we consider the interference from cellular mode UEs as well. In simulations, we investigate the case of having only one cellular mode interferer. In general, the cellular mode UE uses OFDMA or SC-FDMA. We consider the cases of using 1 Resource Block (RB) and 3 consecutive Resource Blocks, respectively. Compared to MC-CDMA, OFDMA with low data rate is a type of narrowband transmission. A set of signal powers of cellular mode UE has been simulated. That is, it has the power of 3 dB, 9 dB and 15 dB higher power spectral density (power per subcarrier) than the desired signal at the D2D receiver. In the receiver, two de-spreading schemes are applied. One is to keep all the spread RBs in the de-spreading operation. Another is to delete the most interfered RBs exceeding the used threshold level. The parameters used in the simulations can be found from *Table 4-2*.

Table 4-2 Parameters of cellular interference

<table>
<tr><th>Parameters</th><th colspan="5">Cellular mode UE (interference)</th></tr>
<tr><td>Modulation Method</td><td colspan="3">OFDMA</td><td colspan="2">OFDMA</td></tr>
<tr><td>Number of Resource Blocks</td><td colspan="3">1</td><td colspan="2">3</td></tr>
<tr><td>Number of Subcarriers</td><td colspan="3">12</td><td colspan="2">12*3</td></tr>
<tr><td>Occupied OFDM Symobls</td><td colspan="3">7</td><td colspan="2">7</td></tr>
<tr><td>Power per RB(s) Higher than Signal (dB)</td><td>3</td><td>9</td><td>15</td><td>3</td><td>9</td></tr>
<tr><td>Process of RB(s) in Receiver</td><td colspan="5">Dropping RB(s) & Keeping RB(s)</td></tr>
</table>

Generally, AWGN is used as the noise model in simulations. AWGN having complex values is generated in the time domain and added to the received signal. AWGN is the basic noise model in which the real and imaginary parts follow the Gaussian distribution and power spectral density satisfies uniform distribution. The noise is created in MATLAB by *randn* function which generates random numbers that follow a Gaussian distribution based on the dimensions of user data then added to the signal. *Figure 4.4* denotes the spectrum of the noise generated in the code with the normalized amplitude.

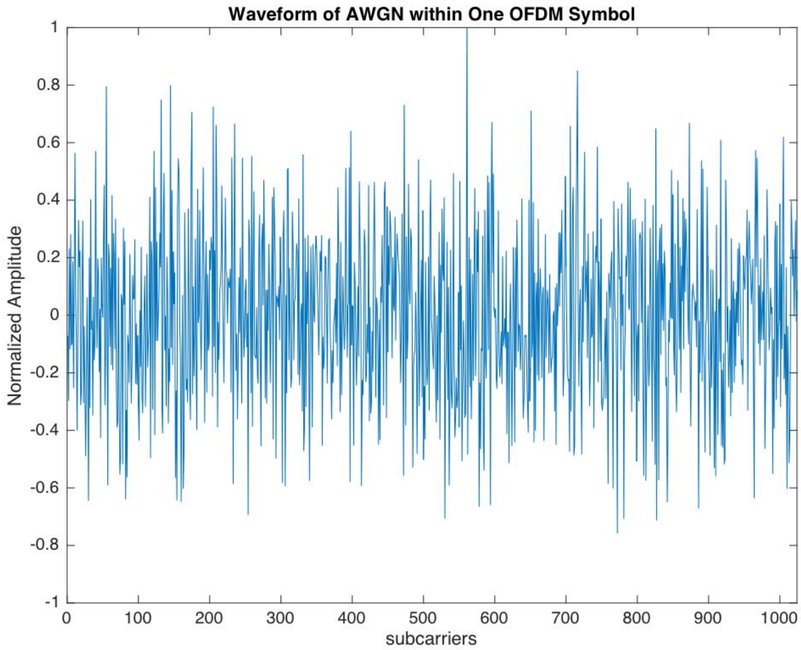

Figure 4.4 Spectrum of normalized AWGN

4.3 MC-CDMA Symbol

Link level model for the MC-CDMA based D2D system has been constructed. Some OFDM related parameters follow the specification of LTE. UE's data is randomly generated with the size of 200 bits. QPSK is selected as the modulation method which converts signal bits to 100 complex symbols. The dimension of WH code is chosen as 64 in the study and one digit of WH code (chip) is used for one RB in the system. In total, $64 * 12RBs = 768$ subcarriers are utilized for data transmitting so that the data will be duplicated and spread to 768 subcarriers to acquire diversity. The length of IFFT/FFT transformation (1024) is achieved by zero padding on the two sides of 768 data subcarriers. After IFFT transformation, the size of CP is determined as 5% of the size of IFFT length. Thus, $ceil(1024 * 5\%) = 52$ samples are applied to the system to maintain the orthogonality between adjacent subcarriers according to the OFDM and MC-CDMA theory described in the third chapter. Main system parameters can be found from *Table 4-3*.

Table 4-3 Parameters of system

Parameters	Downlink
Number of Channel Instances	1000
Number of Users	Single User vs. 64 Users
Generated Bits	200
Modulation Type	QPSK
Number of Modulated Symbol	100
Dimension of WH Code	64*64
Subcarrier Number for Data	64*12
Subcarrier Spacing (kHz)	15
Overall Bandwidth (MHz)	15.36
Size of IFFT	1024
Size of CP	52
Sampling Frequency (Hz)	15360000
Pilot Interval	14
Pilot Value	BPSK symbols, enery equals to the transmitted subcarrier symbol energy

4.4 Pilot Structure

The basic pilot structure has been introduced and explained in Section 3.3.1. As it is illustrated in *Figure 4.5*, pilots are deployed in all subcarriers in the frequency domain.

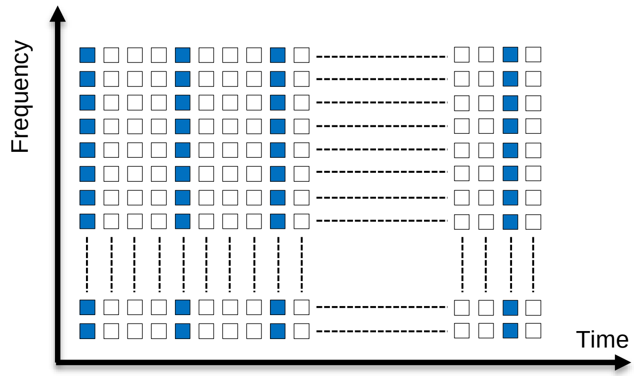

Figure 4.5 Pilot structure for simulations for single-user case

The transmitted signal contains pilot symbols, i.e., OFDM symbols with pilots only. In the time domain, the pilot symbols are inserted once per 14 data symbols. Since we consider only the low mobility scenario, the channel is stationary in the time domain so the pilot symbol density is good enough for obtaining acceptable performance.

The pilot assignment for multiple users in 3D is illustrated in *Figure 4.6*.

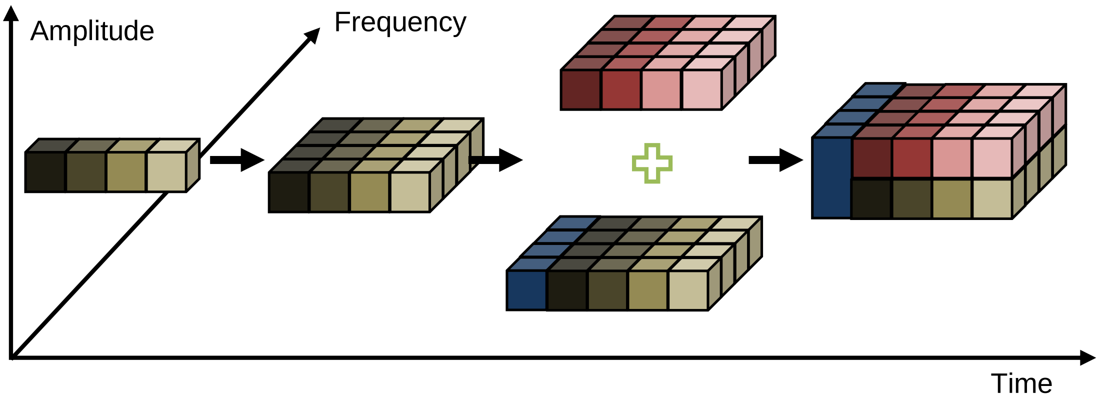

Figure 4.6 Frame structure for two users in a 3D model

As it is shown in the figure, data for multiple UEs (gray and red) are spread separately at first. Same pilot symbols (blue) are allocated all UEs. So in fully loaded case (maximum number of UEs, which is 64 in this study), the pilot power is 64 times higher than the pilot power of single UE case.

Interpolation in the time domain is not applied to the simulation for the reason that the channel is almost time-invariant. Therefore, after pilot symbol extraction and evaluation, the estimated channel response for the current pilot symbol is utilized for the following consecutive 13 data symbols before the coming of next pilot symbol. Using more dense pilot symbols can improve the system performance because channel response can be tracked more accurately, however, the data transmission efficiency is decreased because more OFDM symbols are occupied by pilots. Hence, the optimizations on pilot arrangements (based on certain channel estimation scheme) can be considered as a topic for future works.

4.5 Bit Error Rate

Digital bits or symbols of transmitted data stream are likely to be altered after propagating in the channel or getting distortion and loss. Therefore at the final stage, a criterion for verifying performance and functionality of the system is to calculate its Bit Error Rate or Symbol Error Rate (SER) after signal detection.

BER is the ratio between the quantity of erroneous digital bits and a total number of data bits after detection at the receiver side, whereas SER is the ratio between the amount of incorrect modulated QPSK symbols and the total number of data symbols transmitted. Sometimes with binary symbols, SER and BER are equivalent methods. BER is accepted as the criterion within this research and it is expressed as:

$$BER = \frac{Number\ of\ Erroneous\ Signals\ in\ Bit\ Unit}{Total\ Number\ of\ Signal\ in\ Bit\ Unit} \tag{4.1}$$

5. SIMULATION RESULTS

This chapter exhibits the results of simulation of a MC-CDMA based D2D integrated OFDMA system in the specified D2D environment. The results without interference from cellular mode UEs are provided first in Section 5.1. Then the interference from cellular mode UEs is considered in Section 5.2. Primarily, the simulation results of EGC, MRC, and Optimum LMMSE methods are analyzed and compared in order to find what kind of detection method is suitable for D2D communication. Then the chosen detection method is simulated under the circumstance with different cellular interference scenarios. Furthermore, two different despreading schemes are investigated and compared.

5.1 Performance Comparison of Different Equalization Schemes

The first group of results is set for comparing these three detection schemes to obtain their basic performance in the D2D environment. After constructing the system successfully based on the system model described in Chapter 4, simulations have been carried out for 1000 independent channel instances, each consisting of 100 MC-CDMA symbols for acquiring the average values of BER. Exactly the same set of channel instances is established for all tested cases in order to compare the results using different equalization schemes. The results of using ideal channel estimation are shown in *Figure 5.1*.

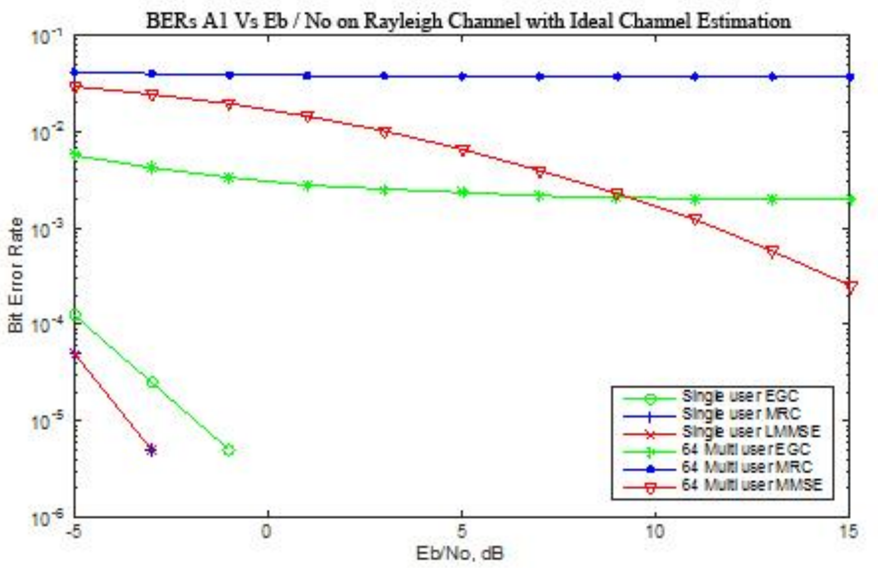

***Figure 5.1** MC-CDMA performance with ideal channel estimation in single-user and fully loaded cases.*

In our studies, the ideal channel estimation is used as a reference. As it is shown in the figure, in the single user case, MRC and LMMSE have rather similar performance, while both of them reach better performance than EGC. However, in the multi-user case, MRC becomes the worst scheme as expected. Meanwhile, EGC provides good performance at low and moderate SNR regions, while LMMSE provides best results at high SNR region. Among different equalization schemes, it seems that EGC and LMMSE can be selected as the equalization schemes for MC-CDMA based D2D mode UEs.

The simulation results using pilot symbol based channel estimation are presented in *Fig-*

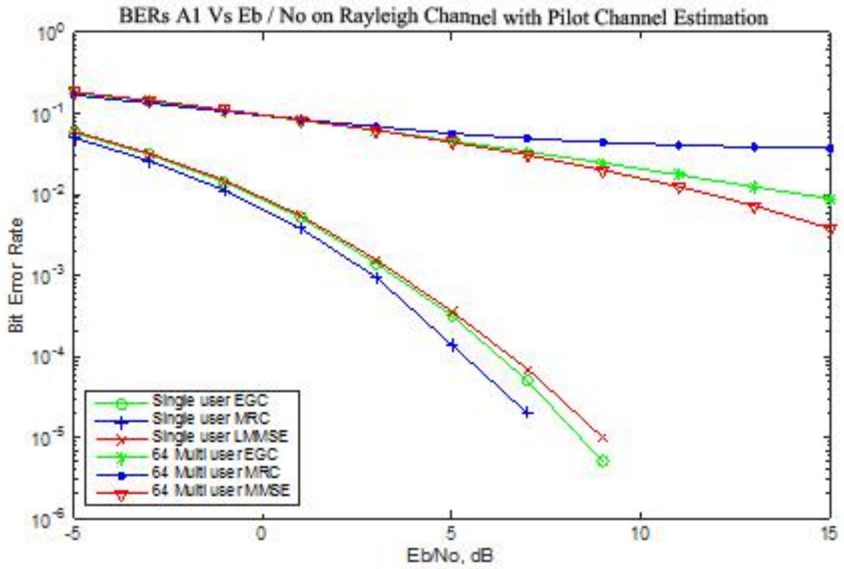

Figure 5.2 MC-CDMA performance with pilot symbol based channel estimation in single-user and fully loaded cases.

ure 5.2. In this case, MRC provides still the best performance among these three detection schemes in the single-user scenario. However, in multi-user case, LMMSE turns to be the best choice. Compared with the ideal channel estimation, the pilot symbol-based channel estimation is the practical scheme. Since there are two D2D modes, the D2D pair mode and the D2D cluster mode, so the selection of equalization must consider the performance of both cases. Therefore, LMMSE detection scheme is selected as a suitable method for the subsequent tests due to acceptable performance in both scenarios.

In the single-user scenario, MRC has better performance because it emphasizes those subcarriers with high SNR. Meanwhile, in this case there is no multiple access interference (MAI) so user orthogonality is not critical. However, MRC cannot work well anymore with the increment of the number of users since it destroys the orthogonality between users when multiplying/weighting branches. Nevertheless, LMMSE and EGC are suitable for MC-CDMA because both of them correct the channel distortion by either the amplitude or the phase. According to the principle described in Chapter 3, LMMSE takes also noise into consideration which is regarded to be better than MRC and EGC. However, dispreading is an operation of averaging the noise effect so the improvement of using LMMSE instead of EGC can be less significant than expected. This can be found from simulation results shown in *Figure 5.1* and *Figure 5.2*.

5.2 Evaluation of Narrowband Interference from Cellular Mode UEs

The interference from cellular mode UEs is investigated in this section. From the result of the previous section, LMMSE is chosen to be the equalization scheme for studies in this section. Furthermore, we will present the simulation results using only the pilot-symbol based channel estimation, since it is more important to emphasize on the performance using practical schemes.

Two interference scenarios are considered, even though we considered the interference from a single cellular mode UE only. In the first scenario, the interference bandwidth is 1RB (12 subcarriers), while 3RBs is used for the second scenario. The reason for using two different bandwidths is to investigate the MC-CDMA's capability against interference of different bandwidths.

In our investigation, we use a simplified version of LMMSE algorithm shown in (3.27) in Chapter 4. Such an algorithm can obtain the optimum performance only in the single user and fully loaded cases (when all codes used). However, compared to the optimum LMMSE solution, the implementation of the simplified version is much simpler.

5.2.1 LMMSE with 1RB interference from a cellular mode UE

The BER performance of MC-CDMA based D2D UEs with 1RB (12 subcarriers) interference from a single cellular UE is given below.

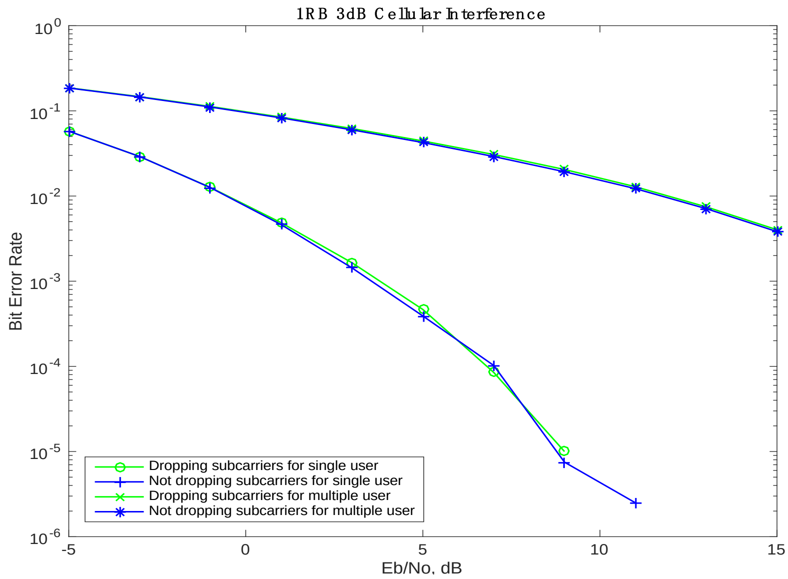

Figure 5.3 MC-CDMA performance for 1-user and 64-user cases with LMMSE equalizer and 1RB interference with 3 dB power

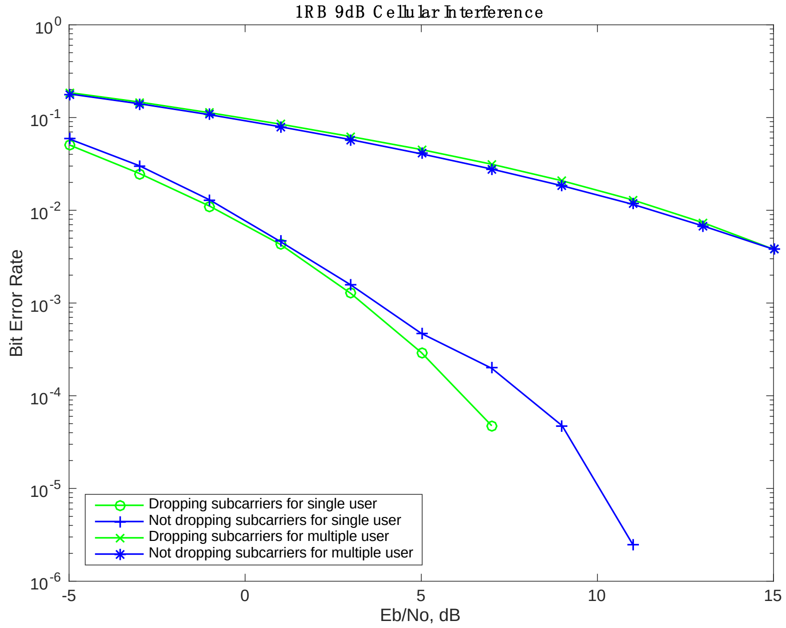

Figure 5.4 MC-CDMA performance for 1-user and 64-user cases with LMMSE equalizer and 1RB interference with 9 dB power

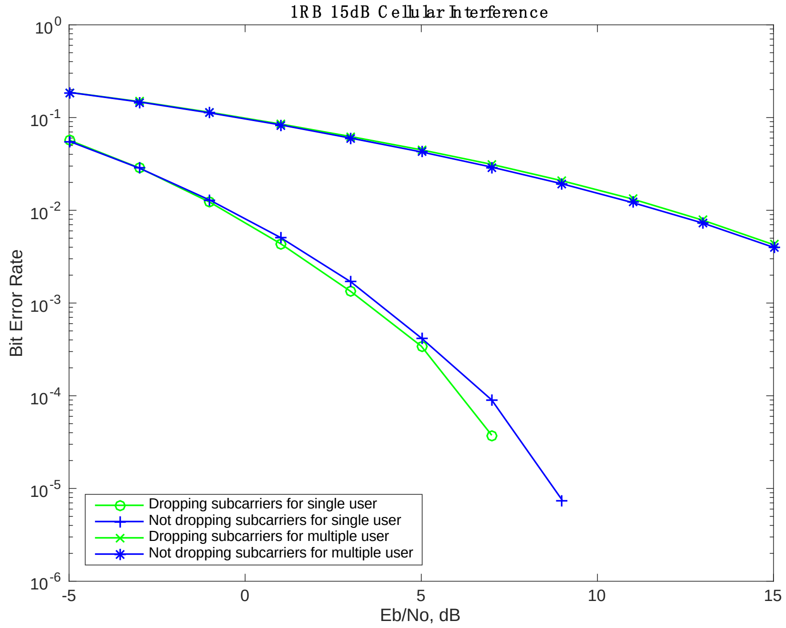

Figure 5.5 MC-CDMA performance for 1-user and 64-user cases with LMMSE equalizer and 1RB interference with 15 dB power

Three interference power levels have been used in simulation. That is, the interference power is set to be 3 dB, 9 dB, or 15 dB higher than the D2D signal power when measured at the RB level. For the single-user case, it is observed that the scheme with dropping the interfered subcarriers shows better performance than the conventional way where all the subcarriers are kept in the despreading operation. In case of having 3 dB interference, the conventional scheme is good enough since the interference power is not high so that the processing gain obtained by despreading is sufficient. When the interference power is increased, the processing gain is not enough anymore in the high SNR range. Therefore, compared to the effect of suffering a high narrow-band interference, the orthogonality loss due to the dropping of a single RB is not critical anymore if the spreading factor is sufficiently large. As shown in *Figure 5.4* and *Figure 5.5*, we can find that the gain can be obtained by dropping the interference chips. Such a gain can be very significant at the high SNR region.

In a multi-user case which contains 64 users, it is difficult to observe the gap between two despreading schemes. There are two reasons for this. First of all, the MAI effect is significant so that the effect of dropping of a single RB is negligible. Secondly, the MAI effect is enhanced due to the loss of orthogonality by the chip (RB) dropping. That is, MC-CDMA acquires not only the orthogonality between subcarriers but also the orthogonality among multiple users via their specific spreading code. Although dropping the interfered subcarriers can remove the interference out of the desired signals when implementing combining, it also causes damage to the orthogonality of multiple users.

5.2.2 LMMSE with 3RBs interference from a cellular mode UE

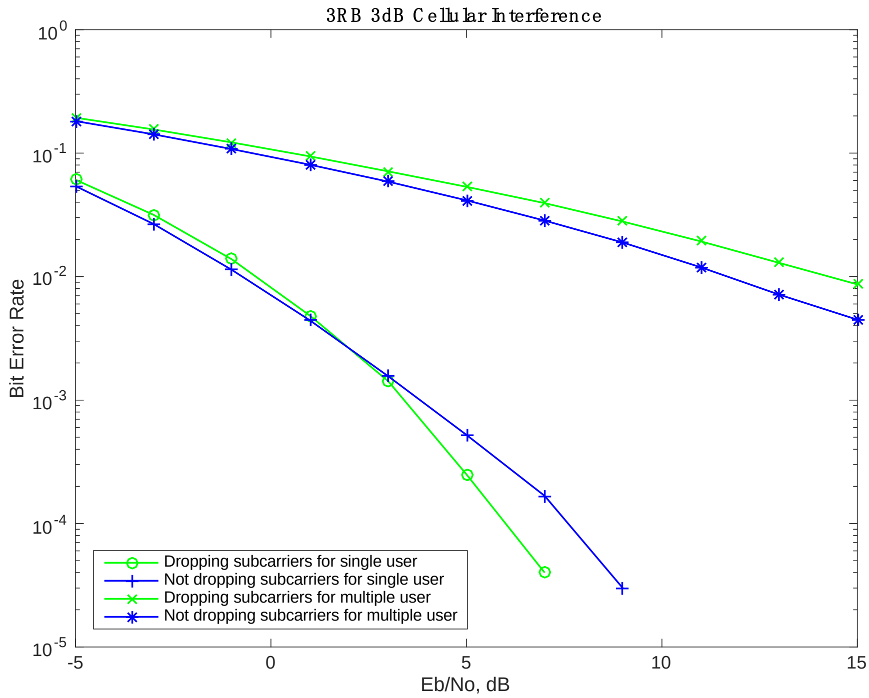

Figure 5.6 MC-CDMA performance for 1-user and 64-user cases with LMMSE equalizer and 3RBs interference with 3 dB power

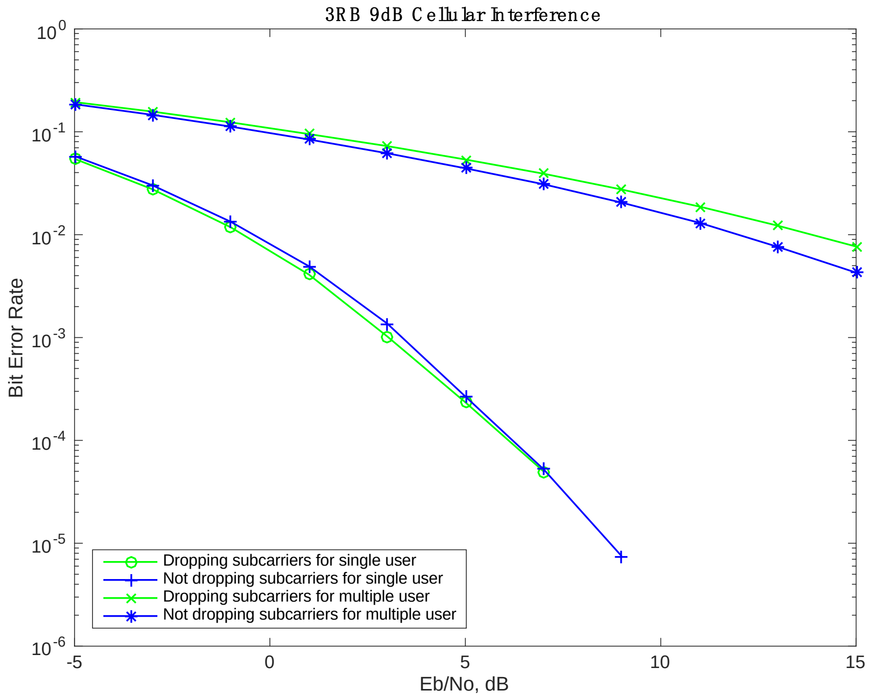

Figure 5.7 MC-CDMA performance for 1-user and 64-user cases with LMMSE equalizer and 3RBs interference with 9 dB power

A more severe condition is considered in the section, where the data is interfered by the cellular UE having three consecutive RBs. *Figure 5.6* and *Figure 5.7* present the results for two different interference power levels.

When the interference has 3RBs bandwidth, it cannot be considered as narrowband anymore if the spreading factor is not sufficiently large. As shown in the figure, the chip/RB dropping in this scenario has more significant effect than the case of having only 1RB interference bandwidth. In the single UE case, due to the absent of MAI, the scheme of dropping interfered chips/RBs can still work better than the conventional scheme. In the multiple UE case, however, the loss of orthogonality due to the chip/RB dropping becomes very significant. So it is better to keep them in the despreading operation, even when they are heavily interfered.

6. CONCLUSION AND FUTURE WORK

A MC-CDMA D2D integrated OFDMA cellular network has been studied in the link level in this thesis. Different detection schemes (channel equalization and despreading) have been investigated. A link level simulator of a MC-CDMA D2D system (including D2D channel models) has been built and the BER performance has been evaluated by simulations. Two kinds of interference, namely multiple access interference from D2D UEs and narrowband interference from cellular UEs have been considered in the study.

Three channel equalization methods, namely MRC, EGC, and LMMSE schemes have been tested. Based on the simulation results, we find that MRC is the best choice in the single user case because it maximizes the SNR after combining SNR. The code orthogonality is not well preserved, but this is not critical since there is no MAI in the single user case. In multi-user case, MRC will not work anymore due to the damage to the orthogonality of multiple users. For the multi-user case when MAI is critical, EGC and LMMSE are appropriate choices. LMMSE possesses a slight superiority compared with EGC, for the reason that it takes noise into consideration to control the gain factor for different subcarriers. Due to the despreading operation, however, the performance gap between LMMSE and EGC is not very significant.

Two despreading schemes, conventional despreading scheme and interfered chip dropping scheme have been investigated and compared. In the presence of cellular interference, dropping the interfered subcarriers has a slight benefit in the single-user scenarios whereas these subcarriers should be kept in a multi-user case if the number of interfered subcarriers is significant. Removing the interfered subcarriers can increase the BER if the number of users is low. However, removing of all interfered subcarriers will destroy the orthogonality among multiple users so that the data of the desired user cannot be recognized correctly. It is worth to know that general intra-cell interference can be avoided by the resource scheduling so that the dominated interference to D2D mode UEs is from the cellular mode UEs of neighboring cells. This is particularly important at cell edges. According to simulation results, we can find that MC-CDMA based D2D is rather robust to narrowband interference, if the receiver algorithms are properly chosen.

As shown in the thesis, the work is emphasized on the study of channel equalization and despreading schemes. There are still many aspects which can be extended as future works. First of all, the channel estimation has to be improved with different pilot structures. Secondly, different channel models should be considered for different scenarios, since in the thesis, only WINNER A1 channel mode has been used as the D2D channel. Furthermore, multiuser uplink scenarios should be investigated by simulation as well. In general, we understand that with the proper design of link level algorithms, MC-CDMA based D2D

UEs have the capabilities against critical narrowband interference. Therefore, it is a promising MA scheme for D2D mode UEs in D2D integrated system, especially at cell edges if the ICI is significant.

REFERENCES

[1] Frenzel, Louis E., *Principles of Electronic Communication Systems*, 3rd Edition, McGraw Hill, 2008.

[2] Anton A. Huurdeman, The Worldwide History of Telecommunications, John Wiley & Sons, 31 July 2003, pp 529

[3] R. A. Scholtz, The Origins of Spread-Spectrum Communications, this issue, pp. 822-854.

[4] R. Prasad, CDMA for Wireless Personal Communications, Artech House Publishers, 1996.

[5] J. K. Moon and S. I. Choi. The performance of Channel Estimation Methods for OFDM System in Multipath Fading Channels. IEEE Trans. Consumer Electronics, vol. 46, no. 1. pp. 61-72. Feb. 2000. 79P.

[6] Fazel, K. and S. Kaiser, Multi Carrier and Spread Spectrum: From OFDM and MC-CDMA to LTE and WiMAX, 2nd Ed., Wiley, 2008.

[7] T. Doumi *et al.*, “LTE for Public Safety Networks,” *IEEE Commun. Mag.*, vol. 51, no. 2, Feb. 2013, pp. 106–12.

[8] Qualcomm, “Study on LTE Device to Device Proximity Services,” RP-122009, Dec. 2012.

[9] Hara, S. Prasad R. Overview of multicarrier CDMA, IEEE communications Magazine. Dec 1997, Vol.35, no.12, PP 126 – 133

[10] 3GPP TR36.843, Study on LTE Device to Device Proximity Services[S], 2014: 9.

[11] Ghazanfari A., Coordinated Beamforming and Power Control for Network Controlled Device-to-Device (D2D) Communication. University of Oulu, Jan 2014, pp 7-8.

[12] K. Doppler *et al.*, “Device-to-Device Communication as an Underlay to LTE-Advanced Networks,” *IEEE Commun. Mag.*, vol. 7, no. 12, 2009, pp. 42–49.

[13] Going Direct: Communication in a Device-to-Device Network - See more at: http://eng-cs.syr.edu/college-news/going-direct-communication-in-a-device-to-device-network/#sthash.F9WIcPM3.dpuf

[14] S. Lee *et. al*., “ The wireless broadband (WiBro) system for broadband wireless internet services,”, *IEEE Communications Magazine*, July 2006, vol. 45, pp.106-112.

[15] IST-4-027756 WINNER II D1.1.2 V1.1, *WINNER II Channel Models*, pp. 16. Available: http://www.ist-winner.org

[16] S. Hara and R. Prasad, Multicarrier Techniques For 4G Mobile Communications, Artech House Publishers, Norwood, MA, USA, 2003.

[17] K. Fazel and L. Papke, “On the Performance of Convolutionally-Coded CDMA/OFDM for Mobile Communication System,” *Proc. Of IEEE PIMRC’93*, Yokohama, Japan, Sept. 1993, pp 468-72.

[18] R.V. Nee and R. Prasad, OFDM for Wireless Multimedia Communications, Artech House Publishers, Norwood, MA, USA, 2000.

[19] Andrea Goldsmith, Wireless Communications, Cambridge University Press, 2005.

[20] http://rfmw.em.keysight.com/wireless/helpfiles/89600b/webhelp/subsystems/lte/content/lte_overview.htm

[21] U.S. Jha, Low Complexity Resource Efficient OFDM Based Transceiver Design, Ph.D. Thesis, Aalborg University, Denmark, September 2002

[22] R.V. Nee and R. Prasad, OFDM for Wireless Multimedia Communications, Artech House Publishers, Norwood, MA, USA, 2000.

[23] D. Matic, OFDM Synchronization and Wideband Power Measurements at 60 GHz for Future Wireless Broadband Multimedia Communications, Ph.D. Thesis, Aalborg University, Denmark, September 2001.

[24] T. Jiang and Y. Wu, *“An overview: Peak-to-average power ratio reduction techniques for OFDM signals”*, IEEE Trans. on Broadcasting, vol. 54, no. 2, pp. 257-268, Jun. 2008.

[25] H. Sari et al., Transmission Techniques for Digital Terrestrial TV Broadcasting, IEEE Comm. Mag., vol. 33, no. 2, pages 100–109, February 1995.

[26] Ove Edfors et al., An Introduction to Orthogonal Frequency-Division Multiplexing, Research Report, no. 1996:16, Division of Signal Processing, Lulea University of Technology, Sweden, September 1996.

[27] S.Hara and R.Prasad, Overview of Multicarrier CDMA, *IEEE Communications Magazine*, pp. 126-133, Dec. 1997.

[28] D. L.Schilling, L. B.Milstein, R. L. Pickholtz, and R. Brown, “Optimization of the processing gain of an M-ary direct sequence spread spectrum communication system,” *IEEE Trans. Commun.*, vol.COM-28,pp. 1389-1398, Aug.1980.

[29] https://ska22.wordpress.com/2011/02/14/mc-cdma-pada-fpga/

[30] R. Nee and R. Prasad, “OFDM Wireless Multimedia Communications”, Artech House Boston London, 2000.

[31] Biglieri, Ezio; Caire, Giuseppe; Taricco, Giorgio (1999). "Coding for the Fading Channel: a Survey". In Byrnes, J.S. *Signal Processing for Multimedia*. IOS Press. p. 253. ISBN 978-90-5199-460-5.

[32] M.-H. Hsieh and C.-H Wei, “Channel Estimation for OFDM Systems Based on Comb-type Pilot Arrangement in Frequency Selective Fading Channels,” *IEEE Transmission on Consumer Electronics*, vol.44, no. 1, pp. 217-225,1998.

[33] E Tufvesson and T Maseng, “Pilot-assisted channel estimation for OFDM in mobile cellular systems,” in Proc. *IEEE 47th Vehicular Technology Conference*, Phoenix, USA, May 1997, pp. 1639-1643.

[34] J. Rinne and M. Renfors, “Pilot spacing in orthogonal frequency division multiplexing systems on practical channels,” *IEEE Trans. Consumer Electronics*, vol. 42, no. 4, Nov. 1996.

[35] M. Schnell, S. Kaiser, “Diversity considerations for MC-CDMA systems in mobile communications,” *IEEE*, pp. 131 - 135 vol.1, ISBN 0-7803-3567-8, 22-25 Sep 1996.

[36] .G.Brennan, “Linear diversity combining techniques,” *Proceedings of the IEEE*, Volume: 91, Issue: 2 pp. 331 - 356, Feb. 2003.

[37] M. Z. Win and J. H. Winters, “Analysis of hybrid selection/maximal-ratio combining in Rayleigh fading,” *IEEE Trans. on Commun*., vol. 47, pp. 1773-1776, Dec. 1999.

[38] Q. Zhang, “Probability of error for equal gain combiners over rayleigh channels: some closed form solutions.,” *IEEE Transactions on Communications*, vol. 45, pp. 270–273, Mar. 1997

[39] Lehmann, E. L.; Casella, G. (1998). *Theory of Point Estimation (2nd ed.).* Springer. ISBN 0-387-98502-6.

[40] G. D. Forney Jr., “Maximum-likelihood sequence estimation of digital sequences in the presence of intersymbol interference,” *IEEE Trans. Inform.* Theory, vol. 18, pp. 363–378, May 1972.

[41] Kay, S. M. (1993). *Fundamentals of Statistical Signal Processing: Estimation Theory*. Prentice Hall. pp. 344–350. ISBN 0-13-042268-1.

[42] J.-F. Helard, J.-Y. Baudais, and I. Citeme, “Linear MMSE detection technique for MC-CDMA,” *Electron. Len.*, vol. 36, pp. 665-666, Mar. 2000.

[43] T. Hidalgo Stitz, M. Valkama, I. Rinne, and M. Renfors, “Performance of MC-CDMA vs. OFDM in Rayleigh fading channels,” in *Proc. Int. Workshop Multi-Carrier Spread-Spectrum Future Generation Wireless Syrt.*, Oberpfaffenhofen, Germany, Sept. 2003.

[44] Mikko Valkama, Tobias Hidalgo Stitz, and Markku Renfors, “Enhanced Per-Carrier Processing for MC-CDMA Downlink,” *IEEE*, ISBN 0-7803-8104-1,2003

[45] S. Hara and R. Prasad, “Overview of multicarrier CDMA,” *IEEE Commun. Mag.*, vol. 35, pp 126-133, Dec. 1997.

[46] Z. Li and M. Latva-aho, “Performance comparison of frequency domain equalizers for MC-CDMA systems,” in *Proc. IEEE Conf. Mobile Wireless Commun. Networks*, Recife, Brazil, Aug. 2001.

[47] IST-4-027756 WINNER II D1.1.2 V1.2. (2008, Feb.) WINNER II Channel Models. [Online]. Available: http://www.ist-winner.org

[48] IST-4-027756 WINNER II D1.1.2 V1.1, *WINNER II Channel Models*, pp. 61. Available: http://www.ist-winner.org