

The Application of Multiuser Detection to Spectrally Efficient MIMO or Virtual MIMO SC-FDMA Uplinks in LTE Systems

by

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In the name of God, the Most Gracious, the Most Merciful.

Abstract

Single Carrier Frequency Division Multiple Access (SC-FDMA) is a multiple access transmission scheme that has been adopted in the 4th generation 3GPP Long Term Evolution (LTE) of cellular systems. In fact, its relatively low peak-to-average power ratio (PAPR) makes it ideal for the uplink transmission where the transmit power efficiency is of paramount importance. Multiple access among users is made possible by assigning different users to different sets of non-overlapping subcarriers. With the current LTE specifications, if an SC-FDMA system is operating at its full capacity and a new user requests channel access, the system redistributes the subcarriers in such a way that it can accommodate all of the users. Having less subcarriers for transmission, every user has to increase its modulation order (for example from QPSK to 16QAM) in order to keep the same transmission rate. However, increasing the modulation order is not always possible in practice and may introduce considerable complexity to the system. The technique presented in this thesis report describes a new way of adding more users to a SC-FDMA system by assigning the same sets of subcarriers to different users. The main advantage of this technique is that it allows the system to accommodate more users than conventional SC-FDMA and this corresponds to increasing the spectral efficiency without requiring a higher modulation order or using more bandwidth. During this work, special attentions were paid to the cases where two and three source signals are being transmitted on the same set of subcarriers, which leads respectively to doubling and tripling the spectral efficiency. Simulation results show that by using the proposed technique, it is possible to add more users to any SC-FDMA system without increasing the bandwidth or the modulation order while keeping the same performance in terms of bit error rate (BER) as the conventional SC-FDMA. This is realized by slightly increasing the energy per bit to noise power spectral density ratio (E_b/N_0) at the transmitters.

Résumé de thèse

Le Single Carrier Frequency Division Multiple Access (SC-FDMA) est une technologie de codage radio à accès multiple utilisée dans les réseaux de téléphonie mobile de 4^{ème} génération tel que spécifiée par la norme 3GPP Long Term Evolution (LTE). Grâce à son faible peak-to-average power ratio (PAPR), SC-FDMA constitue un très bon choix pour la communication sans fil dans le sens de transmission montant car elle permet d'optimiser la consommation énergétique du terminal mobile. Cette technique d'accès multiple partage la bande fréquence en répartissant le signal numérique de chaque utilisateur sur différents groupes de sous-porteuses. Avec les spécifications actuelles, si un système SC-FDMA opère à pleine capacité et qu'un nouvel utilisateur demande un accès au canal, le système redistribue les sous-porteuses en partageant celles-ci entre tous les utilisateurs. Avec moins de sous-porteuses disponibles pour la transmission, chaque utilisateur doit augmenter le nombre de phases de modulation (par exemple de QPSK à 16QAM) afin de garder le même débit de transmission. Toutefois, aller à une modulation de plus grand ordre n'est pas toujours possible en pratique et peut aussi introduire une complexité considérable au système. La technique proposée dans ce rapport de thèse permet de remédier à ce problème en permettant au système SC-FDMA d'ajouter un nouvel utilisateur sur des sous-porteuses qui sont déjà utilisées par d'autres utilisateurs. Entre autre, cette nouvelle méthode permet au système SC-FDMA d'accommoder plus d'utilisateurs et ceci correspond à augmenter la capacité du canal de transmission sans aller à une modulation plus complexe ou utiliser plus de bande passante. Tout au long de ce travail, une attention spéciale a été accordée aux cas où deux et trois signaux de sources sont transmis sur le même groupe de sous-porteuses, ce qui correspond respectivement à doubler et tripler la capacité du canal. Les résultats de simulations montrent qu'en utilisant la technique proposée dans ce rapport, il est possible d'ajouter des utilisateurs à n'importe quel système SC-FDMA sans augmenter la bande passante ou l'ordre de modulation tout en gardant la même performance qu'un système conventionnel en terme de taux d'erreur. Ceci est réalisé en augmentant légèrement le ratio de l'énergie par bit à la densité spectrale de puissance de bruit (E_b/N_0) aux transmetteurs.

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List of Acronyms

AMPS	Advanced Mobile Phone System
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
BLAST	Bell Labs Layered Space Time
BPSK	Binary Phase Shift Keying
CCDF	Complementary Cumulative Distribution Function
CDS	Channel Dependant Scheduling
CIR	Channel Impulse Response
CP	Cyclic Prefix
DFDMA	Distributed FDMA
DFT	Discrete Fourier Transform
DTV	Digital Television
ETSI	European Telecommunication Standard Institute
FDM	Frequency Division Multiplexing
FFT	Fast Fourier Transform
FFT	Fast Fourier Transform
GSM	Global System for Mobile
ICI	Inter-cell Interference
IDFT	Inverse Discrete Fourier Transform
IEEE	Institute of Electrical Engineering
IFDMA	Interleaved FDMA
IFFT	Inverse Fast Fourier Transform
ISI	Inter-symbol Interference
ITU	International Telecommunication Union
LFDMA	Localized FDMA
LS	Lest Square
LTE	Long Term Evolution
MBS	Multicast and Broadcast Service

MIMO	Multiple Input Multiple Output
MMSE	Minimum Mean Square Error
MRC	Maximal Ratio Combiner
MU-MIMO	Multi-user MIMO
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak-to-average Power Ratio
PS	Pulse Shaping
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Keying
RAN	Radio Access Network
RC	Raised-cosine
SC-FDE	Single-carrier Modulation with Frequency-domain Equalization
SC-FDMA	Single Carrier Frequency Division Multiple Access
SDMA	Space-division Multiple Access
SIMO	Single Input Multiple Output
SNR	Signal-to-noise Ratio
TIA	Telecommunication Industry Association
TR	Technical Reports
TS	Technical Specifications
UMB	Ultra Mobile Broadband
UTRAN	Universal Terrestrial Radio Access Network
WCDMA	Wide band Code Division Multiple Access
WLAN	Wireless Local Area Network
ZF	Zero Forcing

List of Symbols

N_r	Number of antennas at receiver
N_t	Number of transmit antennas
N	Length of SC-FDMA symbol
\mathbf{x}	Transmitted symbol in conventional SC-FDMA
$\hat{\mathbf{x}}$	Output symbol in conventional SC-FDMA
\mathbf{x}_j	Received symbol at the j th receiver in conventional SC-FDMA
\mathbf{n}_j	Complex Gaussian noise added at the j th receiver antenna
\mathbf{X}	Frequency domain representation of the transmitted symbol in conventional SC-FDMA
$\hat{\mathbf{X}}$	Frequency domain representation of the output symbol in conventional SC-FDMA
\mathbf{X}_j	Frequency domain representation of the received symbol at the j th receiver in conventional SC-FDMA
η_j	Frequency domain representation of the Complex Gaussian noise added at the j th receiver antenna
\mathbf{H}_j	Channel frequency response between the transmitter and the j th receiver in conventional SC-FDMA
\mathbf{x}_k	k th transmitted symbol in SC-FDMA with subcarrier sharing and multiuser detection
$\tilde{\mathbf{x}}_k$	k th output symbol in SC-FDMA with subcarrier sharing and multiuser detection
\mathbf{s}_j	Received signal at the j th receiver in SC-FDMA with subcarrier sharing and multiuser detection
\mathbf{X}_k	Frequency domain representation of the k th transmitted symbol in SC-FDMA with subcarrier sharing and multiuser detection
$\hat{\mathbf{X}}_k$	Frequency domain representation of the k th output symbol in SC-FDMA with subcarrier sharing and multiuser detection estimated using MRC only
$\tilde{\mathbf{X}}_k$	Frequency domain representation of the k th output symbol in SC-FDMA with subcarrier sharing and multiuser detection estimated using MRC + ZF

\mathbf{S}_j	Frequency domain representation of the received signal at the j th receiver in SC-FDMA with subcarrier sharing and multiuser detection
\mathbf{H}_{kj}	Frequency response of the wireless channel between the transmitter k and the j th receiver
A_{cp}	Cyclic prefix addition
R_{cp}	Cyclic prefix removal
F	N point DFT
F^{-1}	N point IDFT
\hat{W}	Frequency domain equalizer

Chapter 1

Introduction

1.1 Development of Wireless Technologies

Although cellular technology is constantly under development, some major advances mark the transition from one generation of technology to another. The advancement in mobile telephony can be traced in four successive generations. First generation (1G) systems, introduced in the early 1980s, were characterized by analog speech transmission. The first system widely deployed in North America was the Advanced Mobile Phone System (AMPS) [4]. Although 1G systems helped drive mass market usage of cellular technology, they had many serious limitations such as the transmission requiring a significant amount of wireless spectrum and being easily interceptable because the calls were sent in an unencrypted form. First generation systems became obsolete with the advent of second generation (2G) wireless technology in the 1990s. Second generation systems differed from the previous generation by using digital instead of analog transmission. This allowed for considerable improvements in network security as well as call reliability and voice quality. Global System Mobile (GSM) was one of the most successful 2G digital technologies and it was the first to introduce the possibility of text messaging. The use of 2G phones became widespread very quickly and it was very clear that the increasing number of mobile phone users would result in an increasing demand for data speeds and that's when third generation (3G) cellular systems came up. The main focus of the 3G technology is to deliver higher bit rates with greater spectrum efficiency and provide information services in addition to voice telephony. In 2000, the International Telecommunication Union (ITU) issued a set of recommendations endorsing five technologies as the basis of 3G mobile communication systems. In 2008, the two mostly deployed 3G

technologies by cellular operation companies were WCDMA (Wide band Code Division Multiple Access) and CDMA2000 which is an upgrade of the CDMA technology used in 2G systems.

From one cellular generation to another, the bandwidth requirements of transmitted signals increased significantly. For example, first generation systems were occupying bandwidths of 25 and 30 kHz while the two widely deployed second generation systems, GSM and CDMA, occupied bandwidths of 200 kHz and 1.25 MHz respectively. 3G systems such as WCDMA used even wider bandwidths by transmitting on 5 MHz bands. This constant need for wider radio frequency bands is mainly justified by the growth of bandwidth intensive applications such as video and audio streaming, online games, interactive media, etc. While 3G systems can provide most of these services, it has the limitation of not being able to make all these services available at the same time and at the desired speed. The next generation technology, 4G, which is the subject of many researches, has the ambitious goal of addressing these needs by using up to 20 MHz channel bandwidths and targeting speed improvements of up to 10-fold over 3G technologies. Two 4G candidate systems are commercially deployed, the Mobile WiMAX and Long Term Evolution (LTE) standards. The main 4G standards are described in the next section. Single Carrier Frequency Division Multiple Access (SC-FDMA), which is the subject of this thesis, is a novel method of radio transmission adopted as the uplink multiple access scheme in the 3GPP LTE wireless communication standard. SC-FDMA represents one step in the rapid evolution of cellular systems..

1.2 Cellular Standards Organizations

There are three main organizations that publish cellular standards used throughout the world in commercial products with a mass market. The Institute of Electrical Engineering (IEEE) is one of these important organizations. Within the IEEE LAN/MAN standards committee, there are several working groups responsible for wireless communications technologies. One of the most important working groups standardizing OFDM technology is IEEE 802.16, which is responsible for wireless metropolitan area networks. Among the standards produced by this group is the IEEE 802.16e, which is commonly referred to as WiMAX. One of the main features of WiMAX is the ability to offer end-to-end IP-based Quality of Service (QoS), multicast and broadcast service (MBS) and up to 63 Mb/s for downlink and 28 Mb/s for uplink. This technology is maintained by the WiMAX Forum [5], which consists of more than 400 operators and communications

companies.

Two Third Generation Partnership Projects are also responsible for publishing cellular standards. The Partnership Projects consist of organizational, representation and individual partners. Organizational partners are the regional and national standard organizations such as the European Telecommunication Standard Institute (ETSI) and the Telecommunication Industry Association (TIA) in North America. Representation partners are industry associations promoting the deployment of a specific technology and individual members are generally communication companies associated with one or more organizational partners. While the original Partnership Project, 3GPP is concerned with advanced versions of the Global System for Mobile (GSM), the other project, 3GPP2 is concerned with the descendants of the original CDMA cellular system. 3GPP and 3GPP2 have work in progress on advanced mobile broadband systems using frequency division transmission technology. In fact, 3GPP2 is responsible for developing the Ultra Mobile Broadband (UMB) while 3GPP focuses on the Long Term Evolution (LTE). The LTE goals are data rates up to 100 Mbps in full mobility wide area deployment and up to 1 Gbps in low mobility wide area deployment [6]. In this context, SC-FDMA is proposed by LTE for transmission from the mobile stations to the base station.

1.3 3GPP Long Term Evolution

3GPP's work on the evolution of the 3G mobile system started with the Radio Access Network (RAN) Evolution workshop in November 2004 [7]. During this workshop, many operators, manufacturers and research institutes presented their proposals, views and suggestions on the evolution of the Universal Terrestrial Radio Access Network (UTRAN), which is at the foundation of WCDMA systems. UTRAN LTE started within 3GPP with the aim of creating a technology capable of being competitive in the long-term future by meeting increasing user demand in terms of service provisioning and cost reduction. In order to reach this objective, a set of high level requirements were identified. Among these requirements are increased service provisioning, reduced cost per bit and reasonable terminal consumption. A feasibility study on the UTRAN LTE started in December 2004. Its main focus was on means to support flexible transmission bandwidths, introduction of new antenna schemes and advanced multi-antenna technologies. This study resulted in an agreement on many requirements such as [8]:

- Peak data rates of 100 Mbps within a 20 MHz downlink bandwidth (5 b/s/Hz) and

50 Mbps (2.5 b/s/Hz) within a 20 MHz uplink bandwidth.

- An increase in spectral efficiency by a factor of three to four times in downlink transmission and two to three times in uplink.
- Significantly reduced user-plane latency (less than 10 msec in roundtrip delay for small IP packets).
- Improved control-plane capacity (at least 200 users per cell should be supported for spectrum allocations up to 5 MHz).
- Ability to operate on spectrum allocations of different sizes including 1.25 MHz, 1.6 MHz, 2.5 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz for both downlink and uplink transmission.
- Optimized performance for user speed of less than 15 km/h and high performance for speeds up to 120 km/h. Also, connection should be maintained with speeds up to 350 km/h depending on the frequency band.

Another significant evolution is the deployment of Orthogonal Frequency Division Multiplexing (OFDM) made possible by the availability of OFDM transceivers at feasible cost. OFDM is a frequency domain multiplexing scheme used for the modulation of multi-carrier transmissions. The main idea is to divide information data into a set of parallel data streams carried by orthogonal sub-carriers. Each sub-carrier is modulated with a conventional modulation scheme such as Quadrature Phase Shift Keying (QPSK) or 16-Quadrature Amplitude Modulation (16QAM). One of the main advantages of OFDM is the simplicity of channel frequency equalization. Other advantages include high spectral efficiency, efficient implementation via Fast Fourier Transform (FFT) and flexibility of bandwidth allocation by varying the number of sub-carriers used for transmission. However, this technique also has some disadvantages such as a high peak-to-average power ratio (PAPR) and sensitivity to frequency synchronization. OFDM will be discussed in more details in chapter 3.

1.4 SC-FDMA Radio Access Scheme

Among the OFDM-based multiple access techniques, Orthogonal Frequency Division Multiple Access (OFDMA) has been selected for the downlink transmission in LTE.

However, this technique could not be used in the uplink transmission given that the high PAPR would require high power consumption on the mobile handset resulting in poor battery life. For this reason, Single Carrier Frequency Division Multiple Access (SC-FDMA), also known as DFT-precoded OFDMA, was selected for the uplink transmission in LTE systems. SC-FDMA sub-carriers are transmitted sequentially rather than in parallel as it is the case for OFDMA, and this is the main reason why it has a lower peak-to-average power ratio (PAPR) than OFDMA. Therefore, 3GPP LTE decided to choose SC-FDMA for the uplink transmission in order to reduce the power consumption at the transmitter and thus, the cost and weight of the mobile terminal. Figure 1.1 shows a comparison between OFDMA and SC-FDMA systems transmitting a sequence of eight QPSK data symbols. The number of sub-carriers in each system is set to four. In the case of OFDMA, the data symbols are transmitted in parallel, each one occupying 15 kHz during all the period of the OFDMA symbol. One thing to note here is that the data symbols have the same length as the OFDMA symbols. Also, a cyclic prefix (CP) is inserted between consecutive OFDMA symbols. As it will be discussed later, a cyclic prefix is simply a set of redundant data symbols that are transmitted during the guard time in order to avoid inter-symbol interference (ISI). For the case of SC-FDMA systems, the data symbols are transmitted sequentially rather than in parallel. Therefore, the period of each data symbol is much shorter than the period of the SC-FDMA symbol. However, SC-FDMA systems allocate more bandwidth to every data symbol in order to compensate for the short period of time and provide the same data rate as OFDMA. All in all, SC-FDMA, which utilizes single carrier modulation, DFT pre-coded orthogonal frequency multiplexing and frequency domain equalization, offers reduced power consumption and better coverage while retaining most of the benefits of OFDMA. A more detailed description of SC-FDMA systems will be presented in chapter 3.

1.5 Thesis Outline

The following is an outline of the remaining chapters of the thesis:

- Chapter 2: *Thesis Scope and Objectives* - This chapter provides a brief description of the current SC-FDMA technology and discusses its main limitations. It also explains the main motivations and objectives of this thesis' work and presents its main contributions.

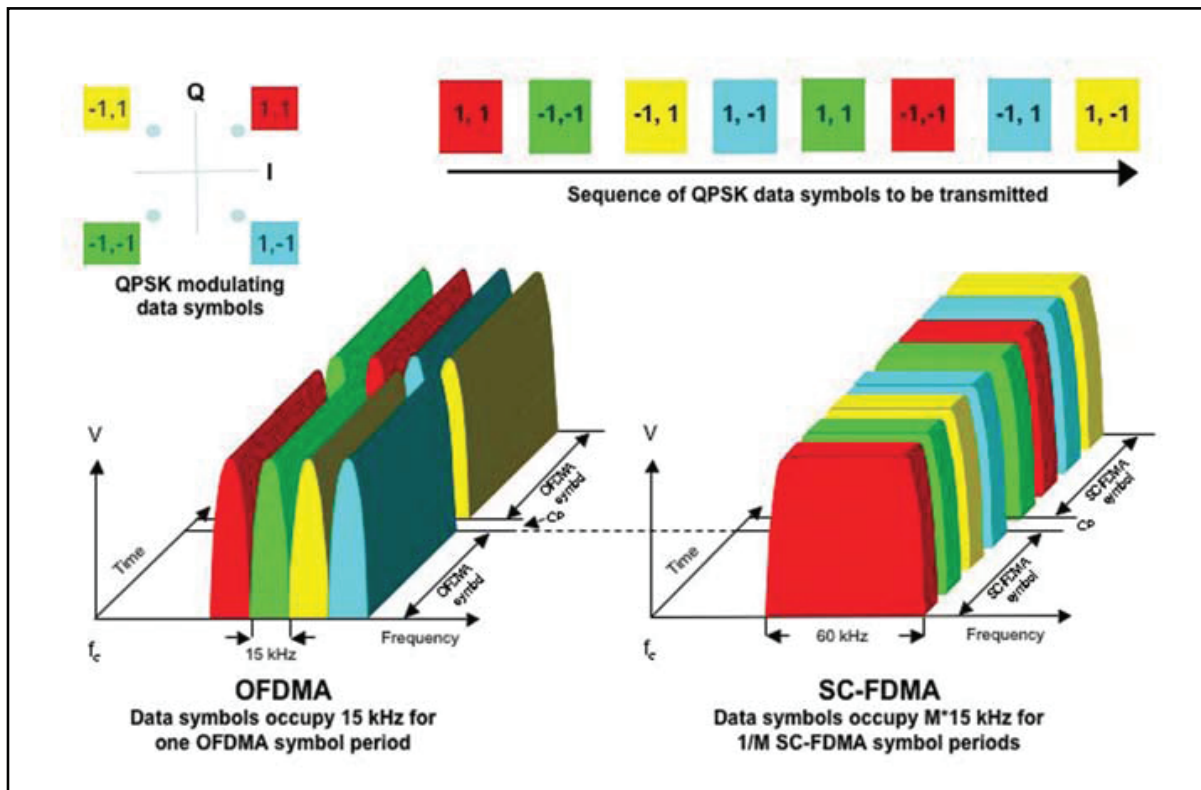


Figure 1.1: An example OFDMA and SC-FDMA systems transmitting a sequence of 8 QPSK data symbols [1].

- Chapter 3: *Single Carrier Frequency Division Multiple Access* - This chapter describes OFDM multi-carrier modulation technique and compares it with SC-FDE. This comparison is extended to the multiple access schemes derived from these two techniques, that is, OFDMA and SC-FDMA respectively. The main objective is to have an overview of SC-FDMA and understand its main characteristics. This chapter also describes two different approaches to assigning mobile terminals to subcarriers and present a study of the peak power characteristics of SC-FDMA signals. Understanding how SC-FDMA works is the first step before looking into ways to improve the system.
- Chapter 4: *Multi-receive Antenna SC-FDMA with Subcarrier Sharing and Multiuser Detection* - This chapter presents a multiuser detection technique that can be applied to a SC-FDMA system in order to improve its spectral efficiency. It starts by introducing some concepts related to MIMO transmission, diversity combining techniques as well as some important linear channel equalizers. These concepts are then used in the proposed algorithms, which can be applied at the receiver side of the SC-FDMA system in order to improve its spectral efficiency. All the mathematical details necessary to understand these algorithms are presented in this chapter.
- Chapter 5: *System Model and Simulations* - This chapter studies the performance of the proposed multiuser detection algorithms. It starts by giving a general overview of the SC-FDMA system model and provides the main parameters and assumptions that were used for the computer simulations. Also, it presents link level simulations of several SC-FDMA systems for different study cases. The main objective is to evaluate the performance of the proposed algorithms and make comparative studies.
- Chapter 6: *Conclusion and Future Work* - This chapter presents a brief summary of this dissertation and comments the main results derived from the research. It also presents some interesting subjects for future work.

Chapter 2

Thesis Scope and Objectives

With each generation of mobile systems, higher data rates are aimed in order to provide advanced multimedia services with better quality and improved reliability. Thus, modern mobile technologies must cope with the challenge of providing high data rates over wireless channels that are limited in bandwidth and power. The main target of 3GPP LTE is to provide improved coverage and system capacity as well as increased data rates and reduced latency. Single Carrier Frequency Division Multiple Access (SC-FDMA) has been considered to be the most promising multiple access technique for the uplink of 3GPP LTE due to its low PAPR. SC-FDMA is a combination of FDMA and single-carrier modulation with frequency-domain equalization (SC-FDE) and has a very similar structure and performance as OFDMA. In fact, SC-FDMA can be considered as an OFDMA system with pre-coding and inverse pre-coding stages added to the transmitter and receiver ends respectively. Among the several properties of SC-FDMA, there are the followings:

- SC-FDMA is a multiple access scheme that can achieve an interference free transmission by allocating different subcarriers to different users.
- If the length of the cyclic prefix (CP) is longer than the length of the channel impulse response (CIR), SC-FDMA can guarantee orthogonality among users in multipath channel.
- SC-FDMA has a low PAPR compared to OFDM, thus providing better coverage and longer battery life.
- Channel equalization can be performed in the frequency domain using a single-tap equalizer per subcarrier with zero forcing (ZF) or minimum mean square error

(MMSE) criterion.

The specific application of SC-FDMA within LTE appears in Technical Specifications (TS) and Technical Reports (TR) published by 3GPP. The physical layer specifications can be found in the TS 36.201 document [9]. Figure 2.1 shows the LTE uplink physical channel processing. LTE specifies two channel coding techniques: tail-biting convolutional coding and turbo coding. The output after channel coding consists of three separate bit streams with code rate 1/3. These bit streams are then interleaved separately and fed to a circular rate-matching buffer before being scrambled with a length-33 Gold sequence. Depending on the channel quality, the physical uplink can use QPSK, 16QAM or 64QAM modulation. After modulation, the output symbols are given to the SC-FDMA transmitter. The transform precoding step corresponds to a DFT operation with a DFT size corresponding to the number of scheduled subcarriers for transmission. The operation of resource element mapping assigns DFT outputs to subcarriers in the resource block used in the physical channel. Finally, the SC-FDMA signal generation corresponds to a sequence of four operations: IDFT, parallel-to-serial conversion, addition of cyclic prefix and digital-to-analog conversion. The SC-FDMA modulation technique will be discussed in more details in the next chapters. However, one important thing to note is that during the resource element mapping operation, multiple users are not allowed to share a common set of subcarriers and therefore the number of users that a SC-FDMA system can accommodate is limited by the number of subcarriers available in each SC-FDMA symbol. After SC-FDMA signal generation, the generated continuous signal modulates the frequency carrier assigned to the mobile terminal before being transmitted.

2.1 Thesis Objectives

The main objective of this thesis is to propose new ways of improving the spectral efficiency of SC-FDMA without requiring more resources in terms of bandwidth and with the minimum possible increase in terms of system complexity. As discussed in the previous section, the number of users that a SC-FDMA system can accommodate at the same time is limited by the number of subcarriers and therefore, the transmission rate is limited by the available bandwidth. In current LTE specifications, if a SC-FDMA system is operating at its full capacity with only one user occupying all the subcarriers and another user wants to join the transmission, the system redistributes the subcarriers

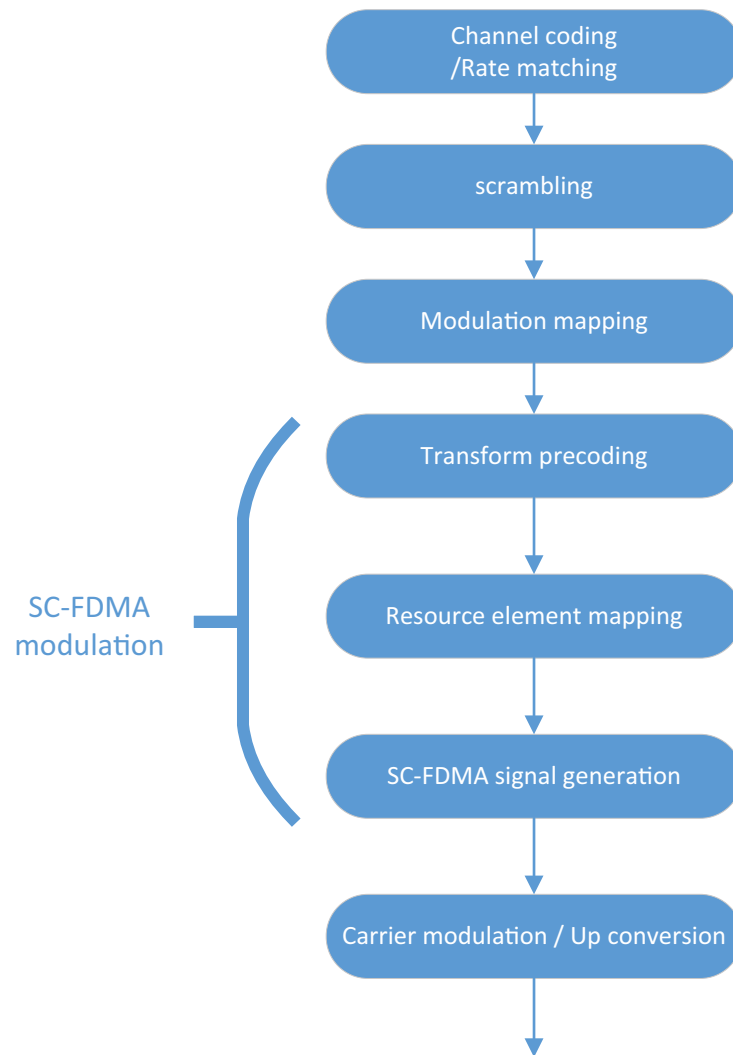


Figure 2.1: SC-FDMA physical channel processing.

between the users in such a way that every user transmits its data on half of the available subcarriers. For example, if there are 16 subcarriers per SC-FDMA symbol and only two users, the system will assign 8 subcarriers to every user. Now, if a third user comes, the system accommodates the three users by reassigning the subcarriers in such a way that two users transmit on 8 subcarriers (4 per user) and the third user transmits on 8 subcarriers. One thing to note is that it is preferable that the number of subcarriers assigned to each user is a power of 2 in order to facilitate efficient DFT implementation. Passing from one user to three users in a SC-FDMA system considerably decrease the number of subcarriers assigned to every source signal, thus decreasing the transmission rate of the mobile terminals. In order to keep the same rate, current LTE specifications suggest that every mobile terminal increases its modulation order. For example, if a user was initially transmitting on 16 subcarriers with QPSK modulation and another user wants to join the system, he will have to transmit on 8 subcarriers instead of 16 and change its modulation to 16QAM in order to keep the same transmission rate.

This technique of reassigning subcarriers between mobile terminals in order to accommodate more users is very straightforward. However, increasing the modulation order usually comes at the price of increasing the bit error rate (BER), which may lead in some cases to a poor system performance. Also, going to a higher modulation is not always possible in practice because it may introduce a considerable complexity to the system and the maximum allowed modulation order for SC-FDMA transmission is limited by the 3GPP LTE specifications to 64QAM. One other possible solution of accommodating more users in a SC-FDMA system while keeping the same transmission rate is to increase the number of subcarriers per SC-FDMA symbol. However, assigning more bandwidth to the system is not always possible. Therefore, new alternatives should be found in order to enable a SC-FDMA system to accommodate more users without increasing the bandwidth or going to a higher modulation order while keeping the same transmission rate for each mobile terminal.

The objective of this work is to design and evaluate the performance of different techniques that can be implemented at the receiver of a SC-FDMA system to allow for multiuser detection at the base station. The proposed algorithms should be able to considerably increase the spectral efficiency of the system without requiring more bandwidth or going to a higher modulation order. These algorithms should also be easy to implement in practice without requiring a considerable increase in the overall system complexity. The proposed techniques will be implemented and simulated in several SC-FDMA systems in order to study their performance and reliability.

2.2 Scientific Methods Employed

This thesis aims to provide a mathematical description of different multiuser detection techniques algorithms that can be used at the multi-antenna receiver of a SC-FDMA system in order to increase its spectral efficiency. The results presented in this thesis have been produced via extensive computer simulations using the system model developed and implemented during the course of the project. The objective is to test and evaluate the proposed algorithms as well as the corresponding SC-FDMA systems over fading channels in terms of bit error rate and spectral efficiency. The obtained results will be compared to those obtained with a conventional SC-FDMA system in order to determine the difference in terms of performance and evaluate the overall improvements to the system. The proposed SC-FDMA link level simulator is a state of the art, which corresponds to the current 3GPP LTE specifications and includes detailed implementation of SC-FDMA physical channel processing.

2.3 Thesis Contributions

The main contribution of this research project is the design and analysis of multiuser detection techniques to be implemented at the receiver of a SC-FDMA system in order to improve its spectral efficiency. As discussed previously, the current SC-FDMA systems that are specified in 3GPP LTE are limited in terms of transmission rate by the number of subcarriers available for transmission given that distinct users should be assigned different sets of subcarriers. To overcome this limitation, a new technique with multireceive antennas and multiuser detection is proposed. In the proposed system, signals of multiple users are superimposed over the channel and can be distinguished at the receiver by employing frequency domain equalizers as well as diversity combining techniques. Therefore, it is possible to assign the same set of subcarriers to multiple users. The proposed techniques can achieve a better performance than conventional SC-FDMA systems without requiring more bandwidth or increasing the modulation order. The proposed system offers a number of attractive features such as:

- The possibility of transmitting multiple source signals on the same set of subcarriers.
- A higher achievable throughput than conventional SC-FDMA systems.
- No need for increased bandwidth or more complex modulation.

- A relatively low computational complexity.
- Same benefits as conventional SC-FDMA, such as low PAPR.
- Similar transmitter and receiver structure as conventional SC-FDMA systems.
- Can be utilized to mitigate inter-cell interference (ICI) in the cell edges, where the same resource is reused in the neighbouring cell to increase the total throughput.

It the next chapter, it is shown that the proposed technique offers many advantages over conventional SC-FDMA with respect to power/spectral efficiency. Such power/spectral efficiency can provide considerable performance improvements in future wireless communication networks.

Chapter 3

Single Carrier Frequency Division Multiple Access

3.1 Introduction

Single Carrier Frequency Division Multiple Access (SC-FDMA) is a new multiple access technique used to transmit several signals simultaneously. The main idea is to assign the signals to mutually exclusive sets of sub-carriers. Given that broadband channels experience frequency-selective fading and that the fading characteristics of the terminals in different locations are statistically independent, this technique can employ channel dependent scheduling to achieve multi-user diversity by assigning to each terminal the subcarriers that provide the best transmission characteristics at the terminal location. In 2008, SC-FDMA was adopted by 3GPP for the uplink transmission from the mobile terminals to the base station in the long term evolution (LTE) of cellular systems.

The next section of this chapter starts by a brief overview of single carrier and multi-carrier systems. Section 3.3 introduces SC-FDMA signal processing operations. Section 3.4 describes two different approaches to assigning mobile terminals to subcarriers: localized FDMA (LFDMA) and interleaved FDMA (IFDMA). Section 3.5 presents a study of the peak power characteristics of a SC-FDMA signal. Finally, section 3.6 describes the relationship of SC-FDMA to OFDMA.

3.2 Single Carrier and Multi-carrier Systems

3.2.1 Single Carrier Systems

Single carrier systems transmit data sequentially on a single frequency band and information is carried by one single radio frequency carrier. Figure 3.1 presents a single carrier modulated signal. Although this technique is very simple to implement, it has a very bad performance in the presence of a multipath channel, which may create inter-symbol interference (ISI) and considerably affect the transmission quality. In addition, every transmitted symbol is spread over all the bandwidth and this makes the system very sensitive to frequency selective channels. These two disadvantages of single carrier systems become more important in the presence of a large transmission bandwidth and this is one of the main reasons why this transmission technique is not adopted to new communication systems, which require large bandwidth to carry more information. Some other transmission techniques were proposed instead in order to satisfy the current transmission systems' requirement in terms of data throughput and reliability.

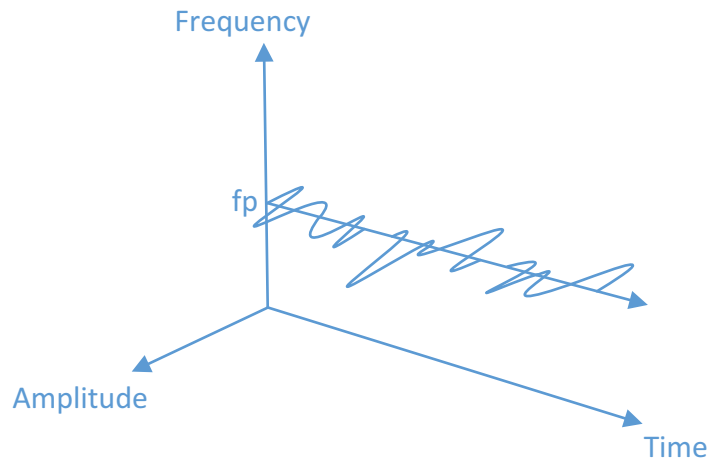


Figure 3.1: Single carrier modulated signal.

3.2.2 Multi-carrier Systems

Multi-carrier transmission systems, such as OFDM (Orthogonal Frequency Division Multiplexing), multiplex the data on multiple carriers and transmit them in parallel. Figure 3.2 shows a general multicarrier modulation system. This technique was proposed as an alternative to single carrier systems in order to reduce the effects of frequency selective

channel fading and provide faster data transmission. A simple example of multi-carrier modulation is shown in figure 3.3. OFDM uses orthogonal subcarriers, which overlap in the frequency domain. Because these overlapping subcarriers are orthogonal, the spectral efficiency is very high compared to conventional frequency division multiplexing (FDM), which requires guard bands between the adjacent sub-bands. Figure 3.4 shows the spectrum of ten orthogonal signals with minimum frequency separation.

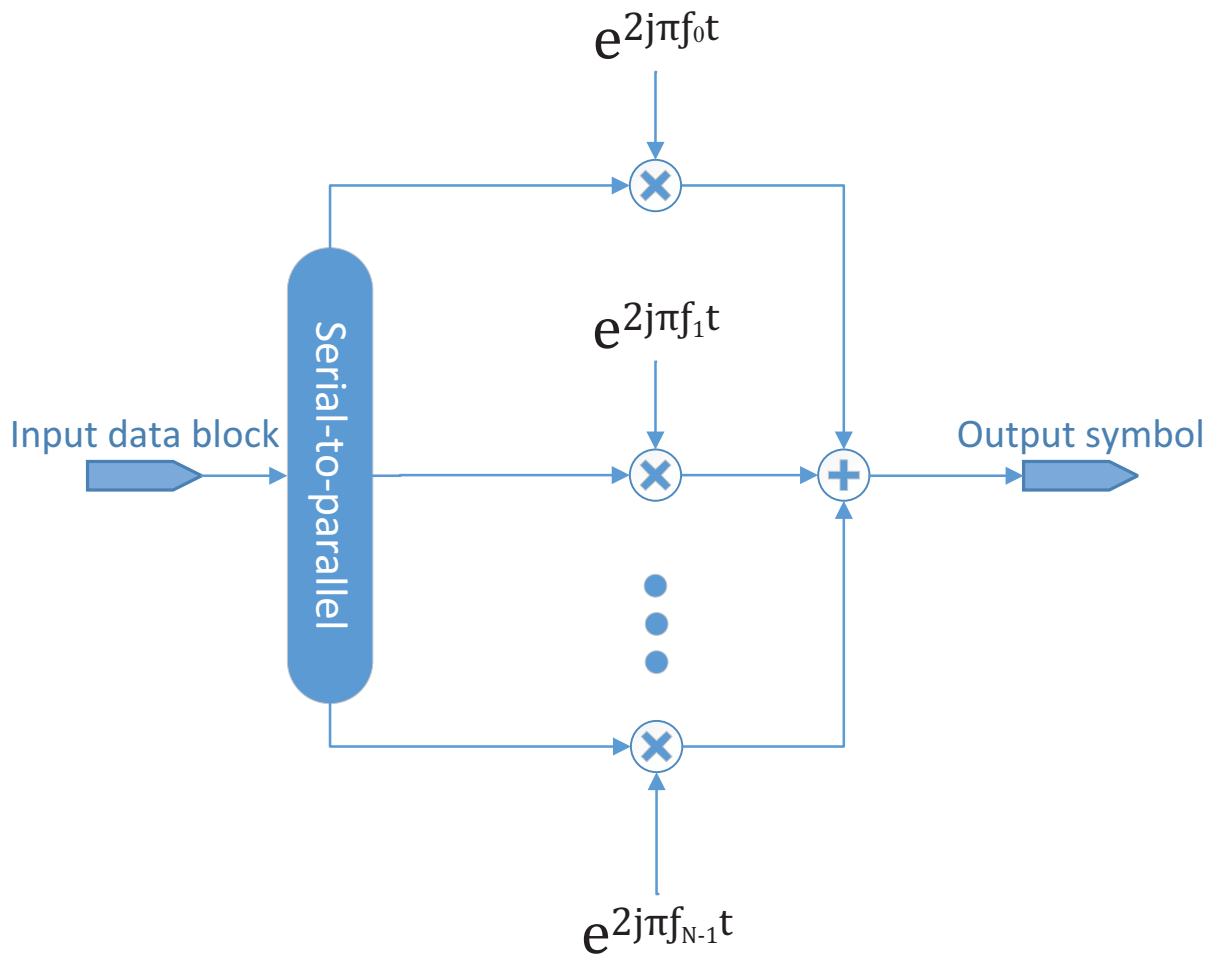


Figure 3.2: A general multi-carrier modulation system.

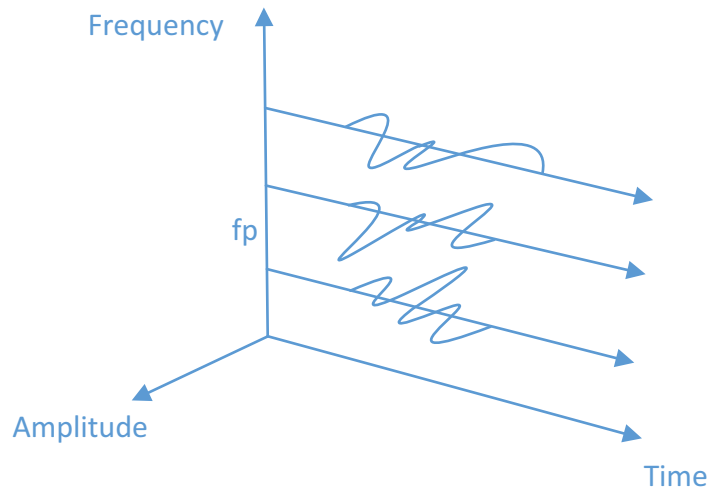


Figure 3.3: Multi-carrier modulated signal.

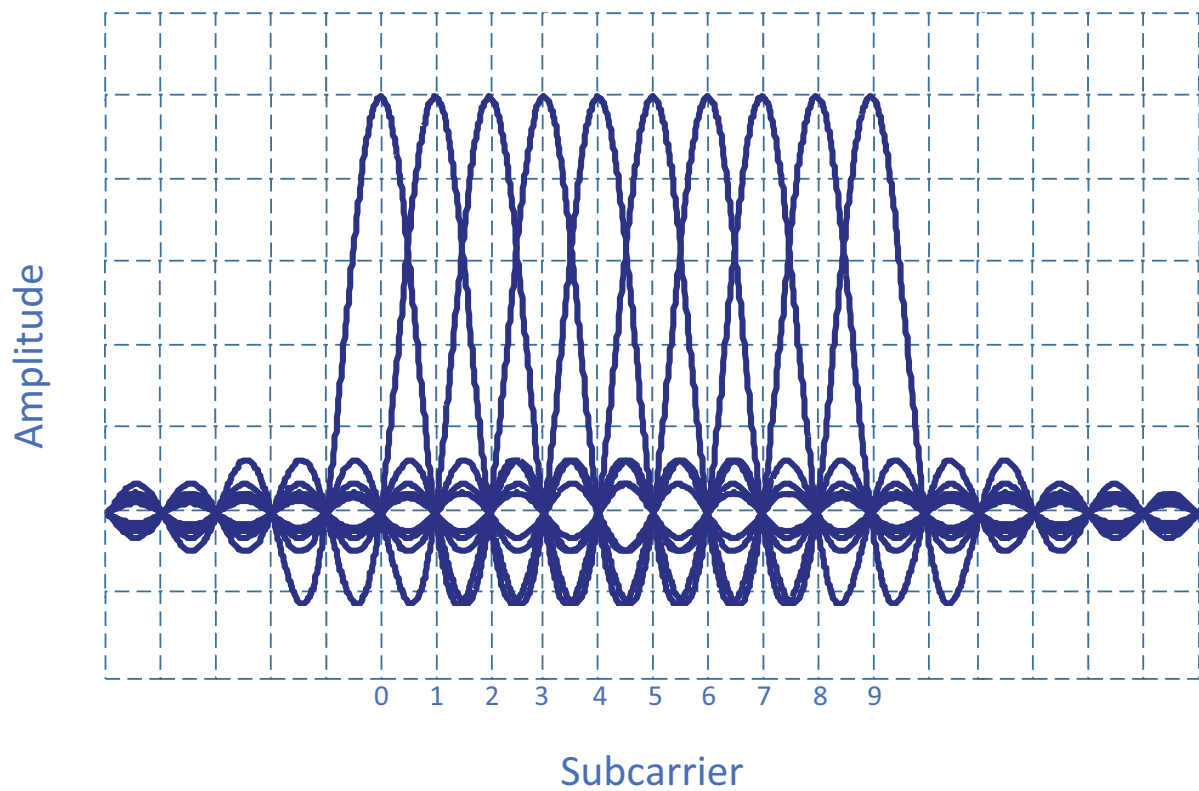


Figure 3.4: Orthogonal subcarriers in OFDM.

The basic idea is to divide a high-speed digital signal into many slower speed signals and transmit each slower signal in a separate frequency. The symbol duration in each

slower signal is long enough to eliminate inter-symbol interference. As shown in figure 3.5, even though fast fading is frequency selective across the entire signal band, it is effectively flat on each low-speed signal because the subcarrier bands are very narrow.

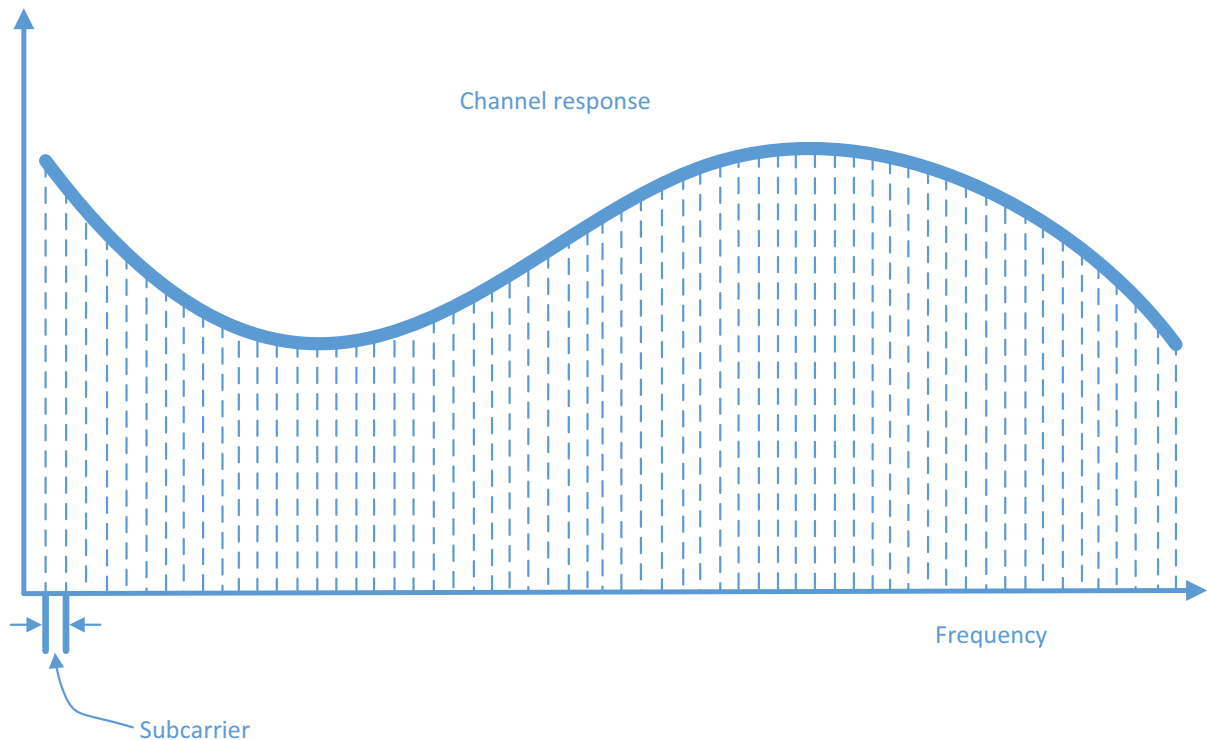


Figure 3.5: Channel response and the subcarriers in the frequency domain.

Discrete Fourier Transform (DFT) and Inverse Discrete Fourier Transform (IDFT) are at the heart of OFDM implementation. Usually, they are realized by Fast Fourier Transform (FFT) and Inverse Fast Fourier Transform (IFFT). Figure 3.6 shows the basic element of an OFDM transmitter and receiver. The binary bits are the output of the channel coder. The modulator typically performs quadrature amplitude modulation (QAM) to transform the binary bit symbols into a sequence of multilevel modulation symbols. Then, an IDFT is performed to N of these modulation symbols at a time in order to send each modulation symbol to one of the N frequency sub-bands. This group of N modulation symbols sent together at the same time is called an OFDM symbol. At the receiver side, an N -point DFT is performed on the received N modulation symbols in order to prepare the signal for channel equalization. Channel equalization compensates for linear distortion introduced by multipath propagation and the original binary bits are reproduced by the demodulator.

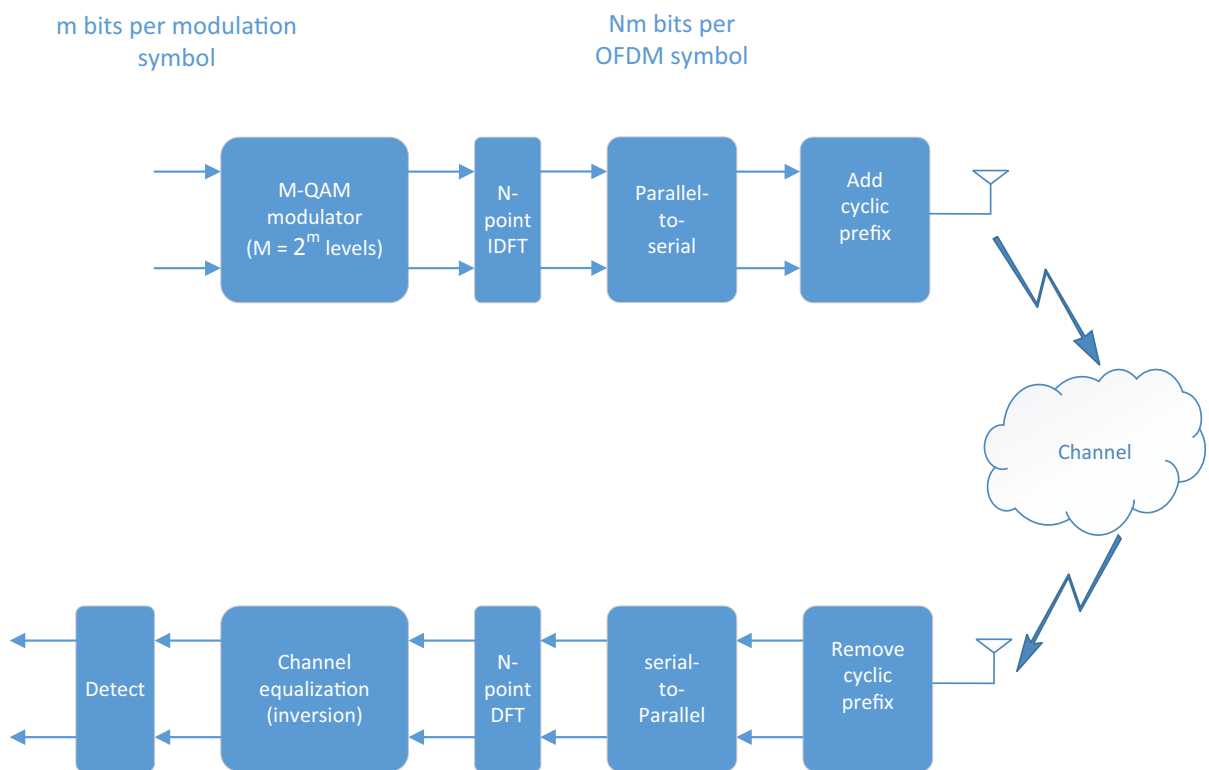


Figure 3.6: OFDM signal processing.

The main advantages of OFDM are the spectral efficiency (due to the fact that it uses overlapping orthogonal subcarriers) and the considerable reduction in inter-symbol interference. However, the principal weakness of OFDM is the high peak-to-average power ratio (PAPR). In fact, it's inevitable to have some high amplitude peaks in the transmitted signal because many of the sub-carriers are being transmitted in phase. This imposes the need for powerful amplifiers.

3.2.3 Single Carrier FDE

Besides multi-carrier systems, there is a new single-carrier technique, which is also very practical for mitigating the effects of frequency selective fading. Single carrier modulation with frequency domain equalization (SC-FDE) associates the single-carrier modulation technique with frequency domain equalizers in order to combat the effect of frequency selective fading. The main difference between SC-FDE and conventional single-carrier transmission systems is the per block processing that it implements. In fact, SC-FDE modulation symbols are not sent sequentially through the channel as it the case of single-carrier systems but are instead grouped into blocks before being transmitted. Figure 3.7 shows the block diagram of a SC-FDE system. At the transmitter side, each group of $\log_2 C$ information bits is mapped to a complex symbol belonging to a C -ary complex constellation. Then, each N symbols are grouped together to produce a data block. Next, a cyclic prefix (CP) is added to each data block before transmission through the channel. Adding a cyclic prefix consists simply of cyclically extending the transmitted block by inserting at its beginning a copy of its last symbols. This prevents inter-block interference. Also, it makes the illusion of periodicity in the system, which makes the channel filtering looks like a circular convolution and matches it to the DFT based frequency domain equalizer. Of course, this comes at the price of bandwidth and energy loss due to the presence of redundant data. The receiver transforms the signal into frequency domain by applying N -points DFT. It then performs equalization in frequency domain and an IDFT is used to transform back the single-carrier signal to time domain in order for the detector to recover the original modulation symbols.

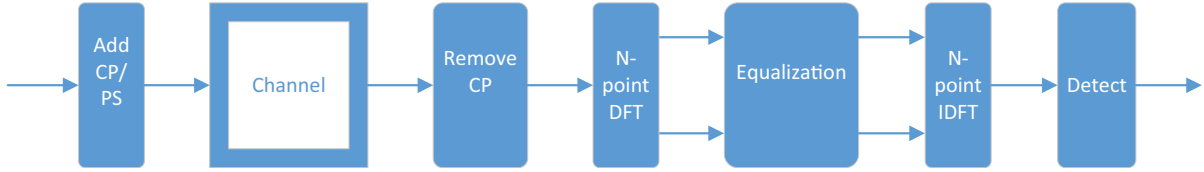


Figure 3.7: SC-FDE signal processing.

Channel equalization is essentially an inverse filtering technique that compensates for linear distortion introduced by multipath propagation channels. From a linear time invariant system perspective, linear filtering is a convolution operation in time domain and a multiplication operation in frequency domain. Figure 3.8 shows the basic operation of time domain equalization and frequency domain equalization. For broadband channels, time domain equalizers are not very practical because of the very long channel impulse response in time domain. However, frequency domain equalization can be easily implemented using modern digital signal processors. Also, for broadband channels, the complexity of frequency domain equalizers is much lower than of the equivalent time domain equalizers because the DFT size does not grow linearly with the length of the channel response. As it can be seen in figure 3.8, the main idea behind frequency domain equalization is to convert the time domain received signal y to a frequency domain signal Y . Dividing the frequency domain signal point by point by an estimate of the channel frequency response H results in channel equalization and an estimate of the transmitted signal x can be recovered by converting X back to time domain. It's important to note that in real systems, we do not compute $X = H^{-1} \cdot Y$ explicitly to avoid numerical instability in the case where the channel frequency response H is very small. However, there exist many alternative techniques that provide equivalent results with guaranteed system stability.

SC-FDE delivers a similar performance to OFDM with essentially the same overall complexity, even for a long channel response. In fact, both systems use the same communication components and the only difference is the location of the IDFT block. Thus, one can expect the two systems to have similar link level performance and spectral efficiency [10]. Comparatively with OFDM, SC-FDE systems have the advantage of operating at a low peak to average power ratio (PAPR) due to the single-carrier at the transmitter. They also offer a good robustness to spectral nulls given that it performs data detection in the time domain while OFDM performs data detection on a per-subcarrier basis in the frequency domain [11]. Also, SC-FDE systems are less sensitive to carrier frequency offsets and require less complexity at the transmitter. However, they need more

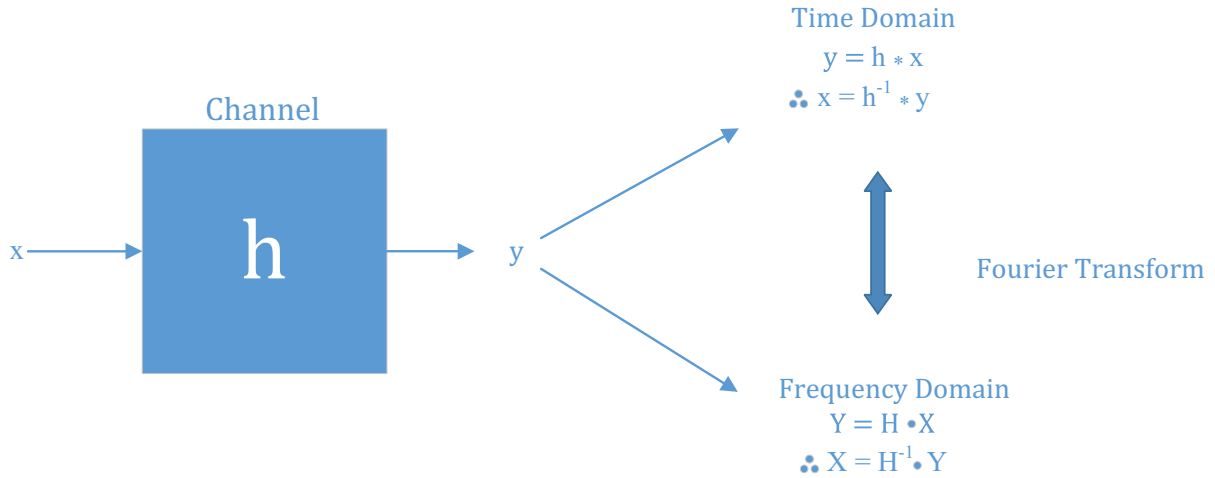


Figure 3.8: Time domain and frequency domain equalization.

complicated frequency equalizers due to the high signalling rates.

In summary, OFDM and SC-FDE systems try to address the problem of multipath propagation. Multipath propagation causes inter-symbol interference (ISI) in time domain and frequency selectivity in frequency domain. OFDM eliminates ISI by extending the symbol duration and compensate for the low data rate by using multiple orthogonal sub-carriers. On the other hand SC-FDE addresses the frequency selectivity issue by performing frequency domain equalization at the receiver while using a single carrier with a high data rate.

3.3 Single Carrier FDMA

Single Carrier Frequency Division Multiple Access (SC-FDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) are modified versions of the SC-FDE and OFDM schemes described in the previous section. In contrast with the techniques presented previously, multiple access techniques transmit multiple signals simultaneously by assigning these signals to mutually exclusive sets of sub-carriers. Because fading in broadband channel is frequency selective, FDMA techniques can employ channel dependent scheduling to achieve multi-user diversity.

The WiMAX cellular system uses OFDMA for both downlink and uplink while 3GPP prescribes OFDMA for downlink (from the base station to the mobile terminal) and SC-FDMA for uplink (from mobile terminal to the base station) in the long term evolution

(LTE) of cellular systems. Using SC-FDMA in the uplink transmission allow the power amplifiers at the mobiles terminals to be much simpler and power efficient than they would be with OFDMA transmission. However, due to the high signalling rate, frequency domain equalizers in the SC-FDMA links are far more complicated than the OFDMA equalizers. With SC-FDMA being only for the uplink, complicated equalizers are only needed at the base station and not at the mobile terminals.

3.3.1 SC-FDMA Signal Processing

A SC-FDMA transmitter and receiver structure is shown in figure 3.9. The input and output of the transmitter and receiver are complex modulation symbols obtained by binary phase shift keying (BPSK) modulation in the case of very weak channels and up to 64-level quadrature amplitude modulation (64QAM) in the case of very strong channels. The data block that is being sent consists of M complex modulation symbols generated at the source rate R_{source} symbols/second. The M point discrete Fourier Transform (DFT) takes M modulation symbols at a time and maps it to M out N orthogonal sub-carriers spread over a bandwidth $W_{channel}$ where:

$$W_{channel} = N \cdot f_0 [Hz] \quad (3.1)$$

Where $f_0 = 1/T_s$ Hz is the sub-carrier spacing with T_s being the symbol duration in seconds. The channel transmission rate is:

$$R_{channel} = \frac{N}{M} \cdot R_{source} [symbols/second] \quad (3.2)$$

The bandwidth spreading factor is denoted by Q and given by:

$$Q = \frac{R_{channel}}{R_{source}} = \frac{N}{M} \quad (3.3)$$

An SC-FDMA system can handle up to Q source signals with each signal occupying a set of M orthogonal subcarriers. After sub-carrier mapping, the N point inverse discrete Fourier Transform (IDFT) transmission block shown in figure 3.9 generates the time domain representation of the N sub-carriers symbols and the Parallel-to-serial block places it into a time sequence suitable for transmission. Then, the transmitter inserts a cyclic prefix (CP), which is a set of redundant symbols as described in section 2.3 in order to prevent inter-block interference due to multipath propagation. A linear filtering (also called pulse shaping) operation is also performed in order to reduce the

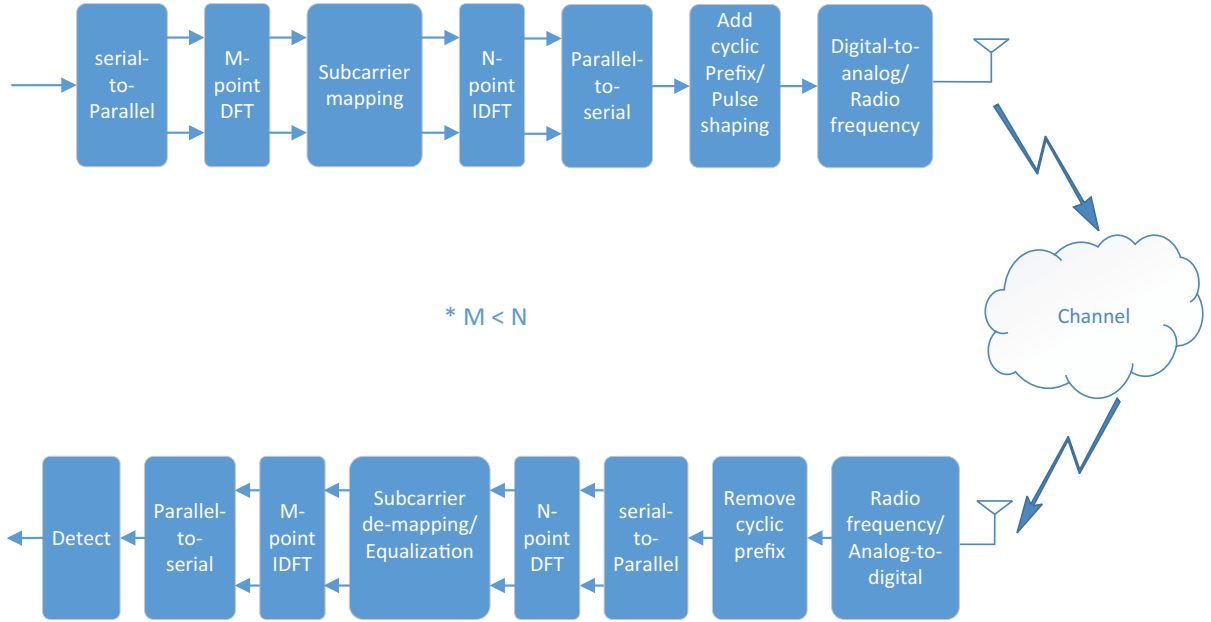


Figure 3.9: SC-FDMA transmitter and receiver structure.

out-of-band signal energy. Raised-cosine filter is one of the commonly used pulse-shaping techniques. Finally, a digital-to-analog converter is used in order to prepare the signal for transmission.

At the receiver side, the received signal undergoes the inverse operations. The N -points DFT transforms the signal to the frequency domain in order to recover the N sub-carriers. The de-mapping operation isolates the M frequency domain symbols of each source signal. Given that SC-FDMA uses a single-carrier modulation, it encounters an important inter-symbol interference (ISI) caused by linear distortion. Therefore, a frequency domain equalizer is used to eliminate this ISI. Using an M -point IDFT, the equalized symbols are transformed back to time domain where the detector is used to produce the received sequence of M complex modulation symbols.

3.4 SC-FDMA Subcarrier Mapping

As explained in the previous section, SC-FDMA systems use multiple access techniques in order to transmit different signals from different mobile users simultaneously. Each of these signals is assigned a set M out of N orthogonal subcarriers spread over the total available bandwidth. That is, in order to support as much users as possible, each of

these users is allocated a portion of the available bandwidth in such a way to reduce the interference with the other users as much as possible. There are two principal methods of assigning the M frequency domain modulation symbols to subcarriers in SC-FDMA systems: localized subcarrier mapping and distributed subcarrier mapping.

3.4.1 Localized Subcarrier Mapping Mode

The localized subcarrier mapping mode of SC-FDMA is referred to as localized FDMA (LFDMA). In this mode, the frequency domain modulation symbols are assigned to M adjacent subcarriers and the IDFT at the transmitter assigns zero amplitude to the remaining $N - M$ unoccupied subcarriers. Figure 3.10 shows an SC-FDMA system supporting three different terminals operating in the localized sub-carrier mode with $M = 4$ subcarriers allocated to each terminal and $N = 12$ total subcarriers. Given that the subcarriers in this mode are not spread all over the bandwidth, the system loses in terms of frequency diversity. However, this system is very robust to frequency offsets and guarantees the orthogonality between the signals of different users. Figure 3.11 shows the signals of the three terminals arriving at the base station. These signals are occupying mutually exclusive sets of orthogonal subcarriers.

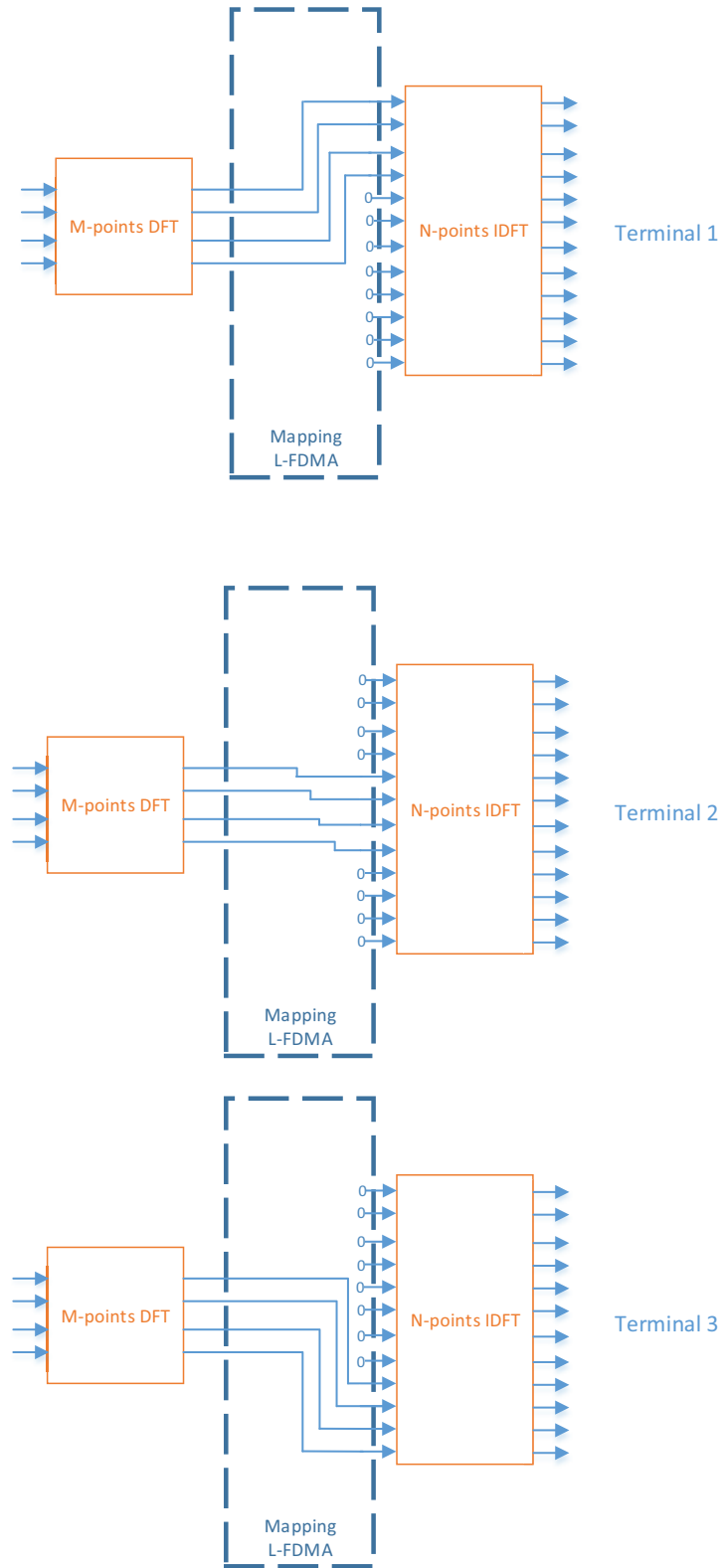


Figure 3.10: Localized subcarrier mapping (LFDMA).

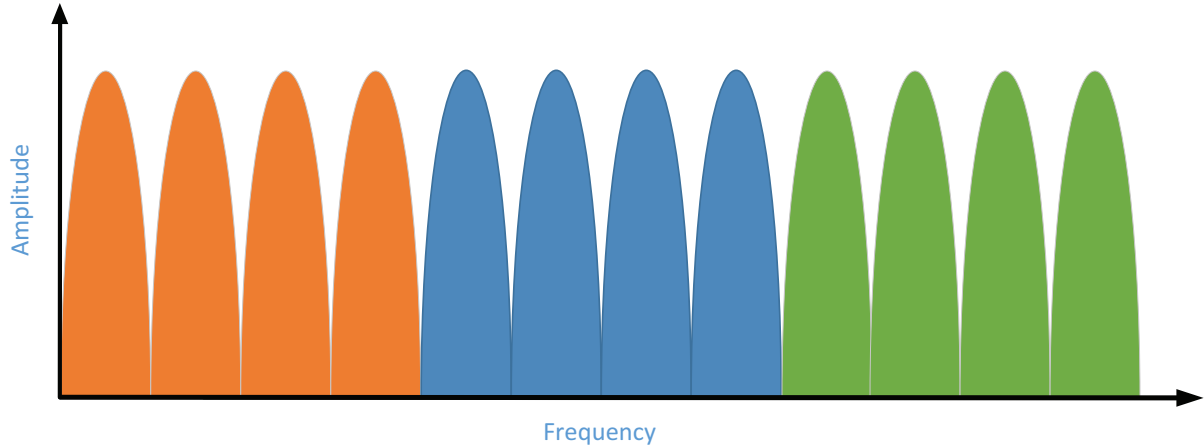


Figure 3.11: LFDMA signals received at the base station.

3.4.2 Distributed Subcarrier Mapping Mode

In the distributed subcarrier mapping mode, the M frequency domain symbols are equally spaced across the entire channel bandwidth and the remaining $N - M$ unoccupied subcarriers are assigned zero amplitude. This SC-FDMA subcarrier mapping mode is referred to as distributed FDMA (DFDMA). The special case of distributed mode with equal distance between occupied subcarriers is called interleaved FDMA (IFDMA). Figure 3.12 illustrates an example of an SC-FDMA transmitter operating in the IFDMA subcarrier mapping mode with three terminals, $M = 4$ allocated subcarriers per terminal and $N = 12$ total subcarriers. IFDMA is a special case of SC-FDMA that is very efficient because the transmitter can modulate the signal in the time domain without the use of DFT and IDFT. In fact, it can be shown that for IFDMA the combination of DFT and IDFT reduces to a complex modulation corresponding to a phase shift of each modulation symbol at the input of the transmitter [12]. However, IFDMA has the disadvantage of being very sensitive to frequency offsets which are often introduced by a bad synchronization between the transmitter and receiver oscillators and which may cause a loss of the signals orthogonality. Figure 3.13 shows the signals of the three terminals arriving at the base station and occupying mutually exclusive sets of subcarriers.

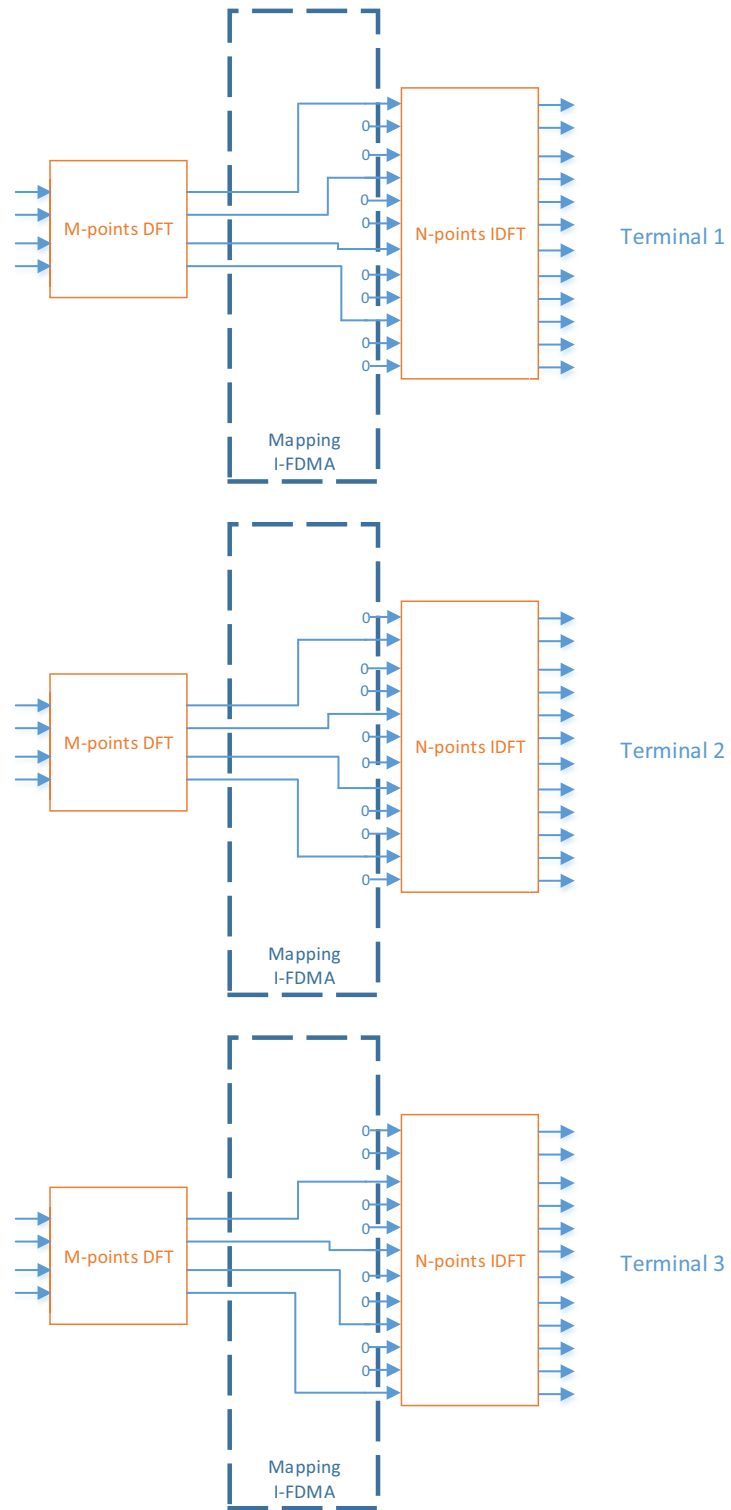


Figure 3.12: Interleaved subcarrier mapping (IFDMA).

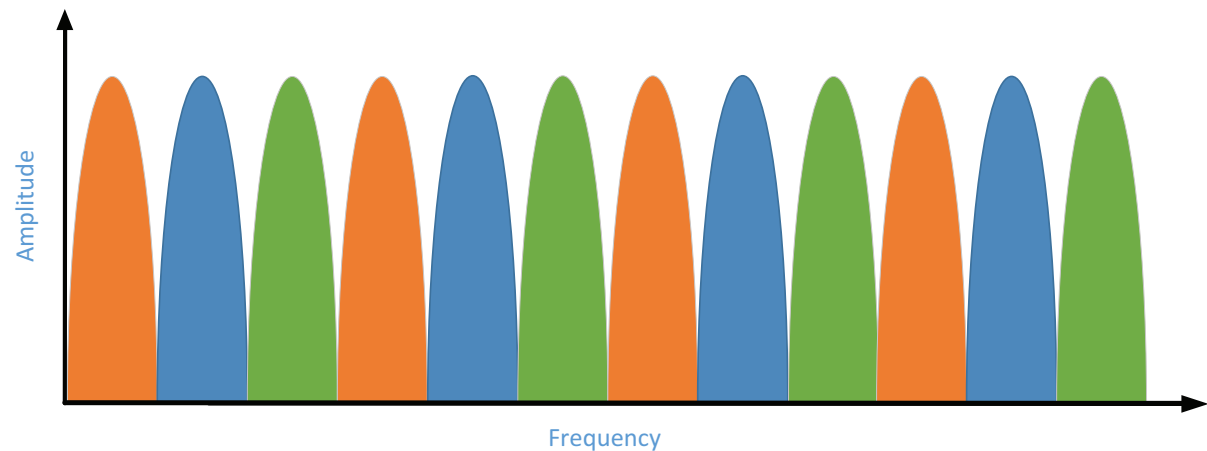


Figure 3.13: IFDMA signals received at the base station.

For LFDMA as well as DFDMA, the choice of subcarrier mapping can be done either by static scheduling or channel dependent scheduling (CDS). In the case of static scheduling, the same subcarriers are assigned to each user for the entire duration of the transmission. However, CDS assigns subcarriers to users according to the channel frequency response of each user. The idea is to map the transmitted signals of each terminal to a set of subcarriers that has favourable channel characteristics. Therefore, one user can be assigned different sets of subcarriers during the same communication or even be removed from the system if his transmission channel is very poor. In practice, this requires a scheduler at the base station that measures periodically the channel characteristics and assigns the more appropriate subcarriers to each terminal using an optimization algorithm to maximize the total throughput.

For both mapping methods, CDS provides frequency diversity because the transmitted signals are spread all over the bandwidth [13]. This performance improvement is significantly important for LFDMA because it provides a significant multi-user diversity to the system by spreading the assigned subcarriers while IFDMA signals are already spread all over the bandwidth even without CDS. However, CDS consumes system bandwidth because it requires terminals to transmit channel sounding signals that span the entire frequency band of the system and also requires the base station to transmit schedules to all the terminals sharing a channel. This is not the case of static scheduling where the assigned subcarriers are fixed for each terminal.

3.5 Peak Power Characteristics of SC-FDMA Signals

SC-FDMA is a multiple access technique that was chosen for the uplink transmission in the 3GPP LTE standard mainly because of its low peak-to-average power ratio (PAPR). PAPR is a performance measurement that is directly related to the energy consumed by the power amplifiers and is an indicative of the power efficiency of the transmitter. Figure 3.14 shows the relation between the input and output power of a typical power amplifier. As it can be seen on the curve, there is a very important point called the saturation point after which the output power stays constant even if the input power is increased. There is also an important point called the compression point that is reached when the power amplifier output is 1 dB less than the output power at saturation. In order to minimize the signal distortion and maximize the power efficiency, the power amplifier needs to operate as close as possible to the compression point while staying in the linear region [14]. A positive PAPR in dB means that a power backoff is needed in order to operate in the linear region of the power amplifier [15].

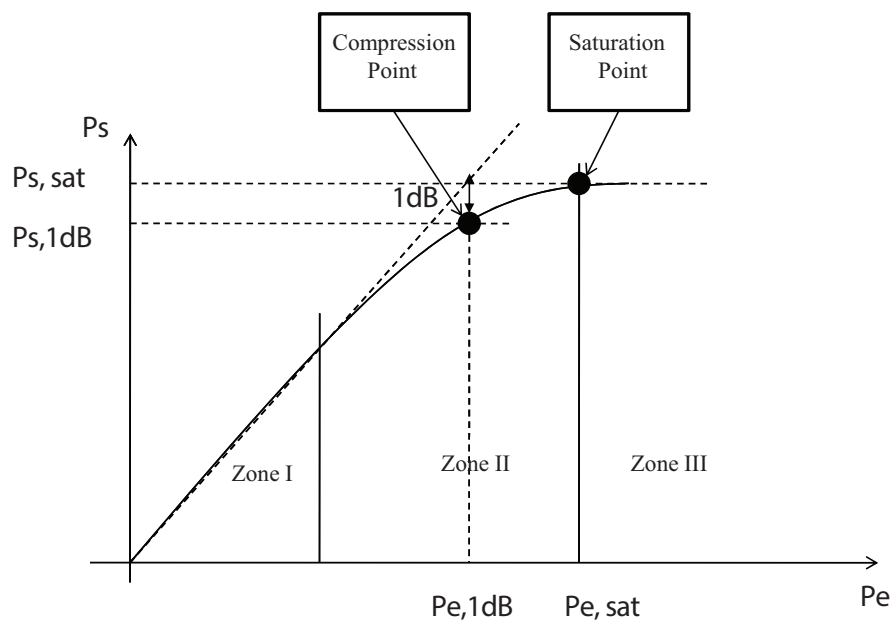


Figure 3.14: Input power vs. output power curve for a typical power amplifier [2].

The theoretical relationship between PAPR [dB] and the transmit power efficiency is

given by:

$$\eta = \eta_{\max} \cdot 10^{-\frac{PAPR}{20}} \quad (3.4)$$

where η denote the power efficiency and η_{\max} denotes the maximum power efficiency of the amplifier. Figure 3.15 shows this relationship for two typical classes of power amplifiers. For a class A power amplifier, η_{\max} is 50% and for class B amplifiers, it is 78.5% [16]. It can be seen from the figure that a high PAPR considerably decrease the transmit power efficiency. One of the most important advantages of SC-FDMA over OFDMA is the low PAPR and this is because of its single carrier structure. A low PAPR is very beneficial in the uplink communication because it reduces considerably the power consumption at the mobile terminal.

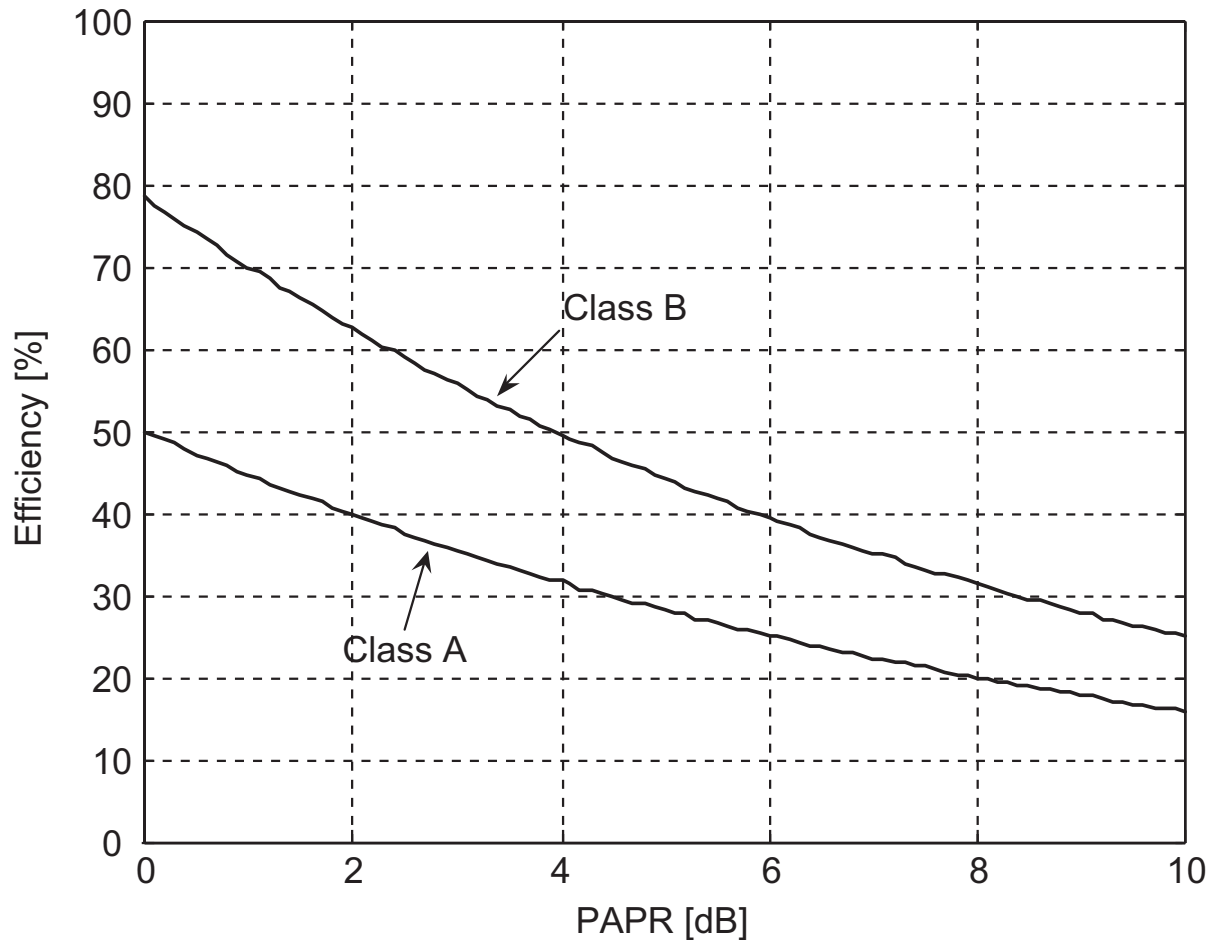


Figure 3.15: Power efficiency vs. PAPR for class A and class B power amplifiers [3].

Figure 3.16 shows a Monte Carlo simulation of the Complementary Cumulative Dis-

tribution Function (CCDF). CCDF is the probability that PAPR is higher than a certain $PAPR_0$. CCDFs of PAPR are evaluated for IFDMA, DFDMA, LFDMA and OFDMA systems using $N = 512$ total subcarriers, $M = 128$ input symbols and 16QAM modulation. For each system, three cases were considered: without pulse shaping (no PS), with raised-cosine pulse shaping (RC PS) and with a square-root raised-cosine pulse shaping. A pulse shaping filter is used to limit the effective bandwidth of the transmission and fit the signal in its frequency band. This is generally done in order to limit the inter-symbol interference caused by the channel. It can be clearly seen from the figure that all the mapping modes of SC-FDMA have lower PAPR than OFDMA. In fact, IFDMA has the lowest PAPR while LFDMA and DFDMA have similar levels of PAPR. It is also important to note that using a pulse shaping filter increases PAPR, thus degrading the power efficiency.

3.6 SC-FDMA and Orthogonal Frequency Division Multiple Access

Section two of this chapter introduced the notion of single carrier transmission and multi carrier transmission and described some of the similarities and differences between single carrier transmission and OFDM for one signal occupying the entire bandwidth. Similarly, one can describe the relationship between SC-FDMA and orthogonal frequency division multiple access (OFDMA) for the transmission of independent signals from different mobile signals to the same base station. In fact, OFDMA was one of the most important possible alternatives to SC-FDMA for the uplink transmission during the standardization of 3GPP LTE. This section presents a comparative study between SC-FDMA and OFDMA modulation in order to understand the similarities and differences between the two systems as well as their advantages and disadvantages.

OFDMA is a multiple access transmission technique based on OFDM. It is adopted by the 3GPP LTE standard for downlink transmission (from the base station to the terminals). Figure 3.17 shows that SC-FDMA and OFDMA transmitters and receivers perform very similar signal processing functions. It can be seen that SC-FDMA is essentially an OFDMA system with an added discrete Fourier transform (DFT) at the input of the receiver and a corresponding inverse discrete Fourier transform (IDFT) at the output of the transmitter. In fact, SC-FDMA is sometimes referred to as DFT-spread OFDMA because it expands the signal bandwidth to cover the entire bandwidth of the

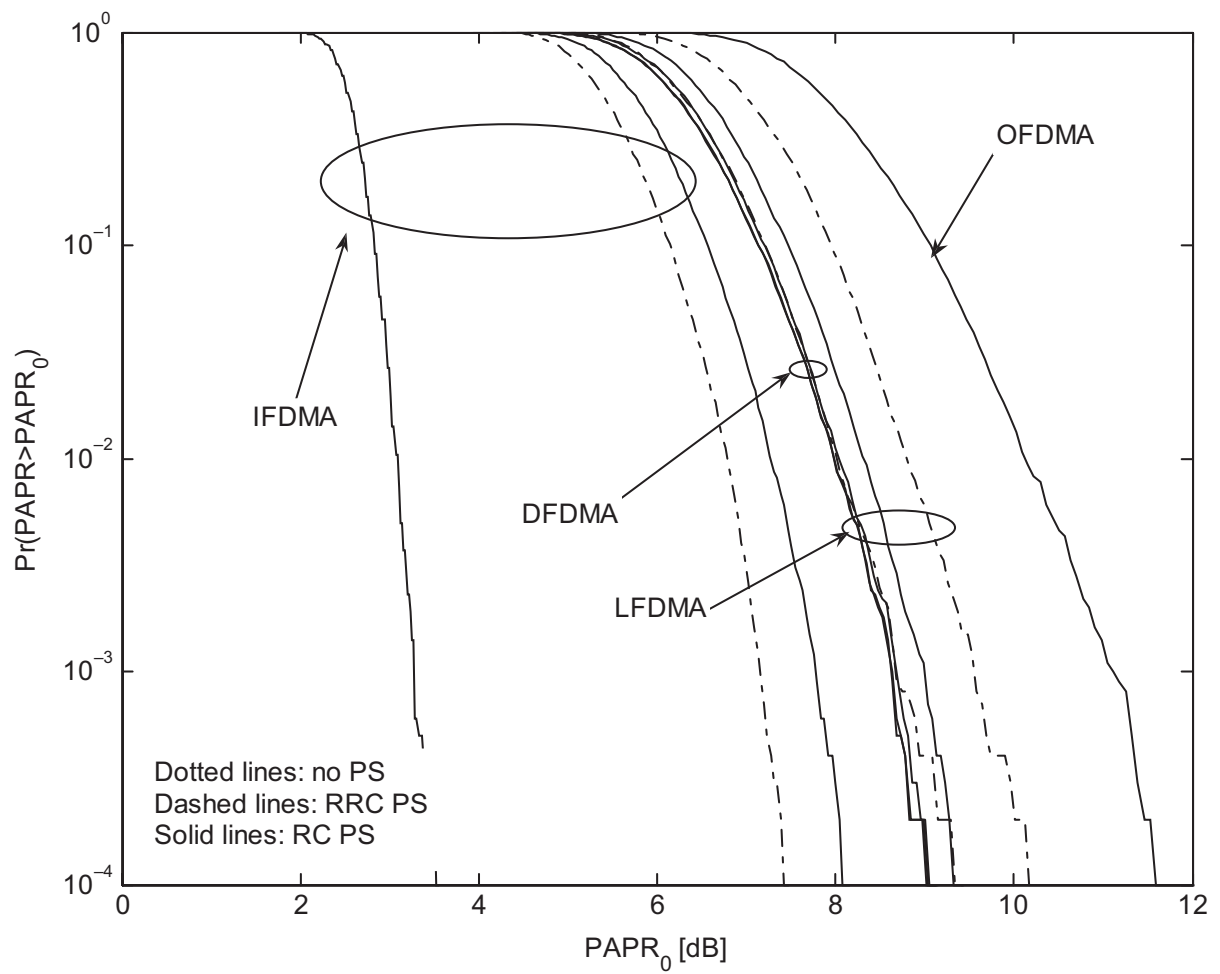


Figure 3.16: CCDF curves for different SC-FDMA and OFDMA systems [3].

channel. Because of these similarities, the two techniques have many common properties such as the transmission of data in blocks consisting of M modulation symbols. Also, they both divide the channel bandwidth into sub-bands and carry the information on different subcarriers. In addition, the two techniques perform channel equalization in the frequency domain and add a cyclic prefix to prevent from inter-block interference. Finally, the complexity of the two systems is fairly the same.

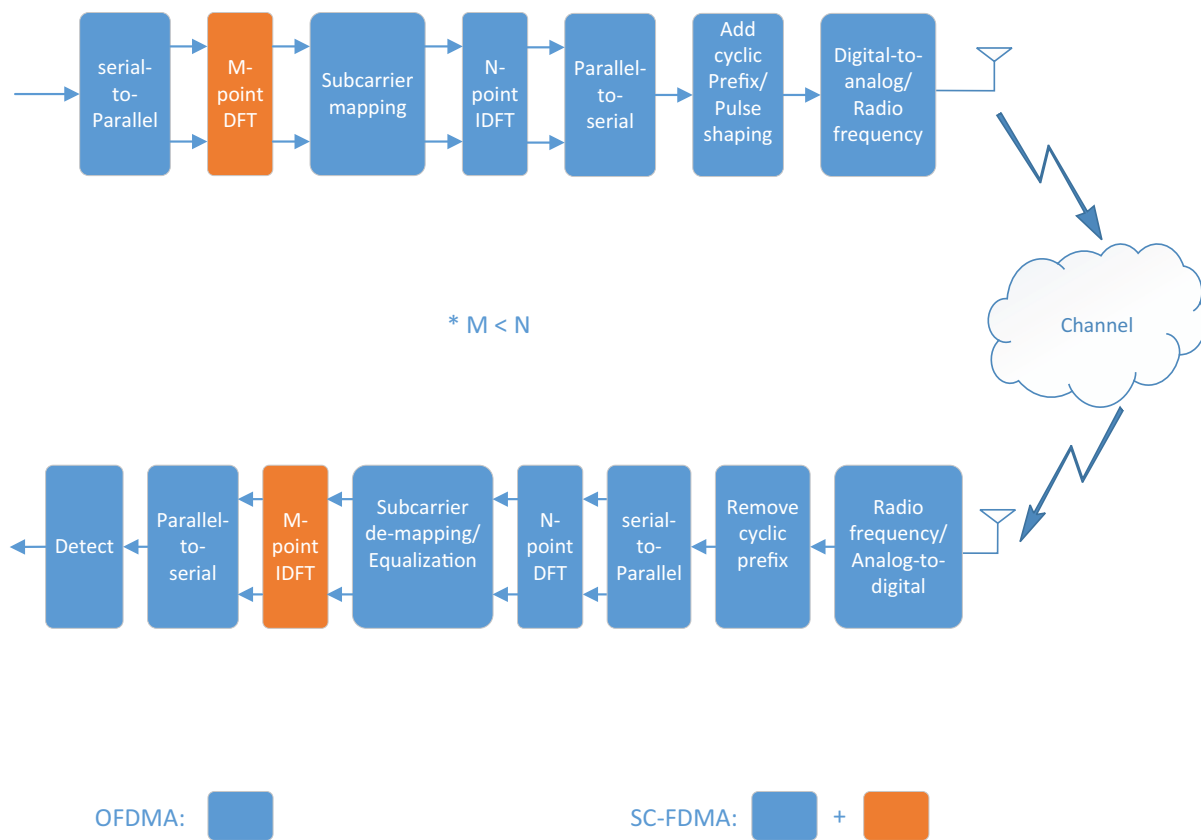


Figure 3.17: SC-FDMA and OFDMA transmitters.

However, these techniques have major differences that lead to different performances, one being that OFDMA transmits a multi carrier signal while SC-FDMA transmits a single carrier signal. Because of this, SC-FDMA has a lower peak-to-average power ratio (PAPR) than OFDMA and this is the main reason why SC-FDMA was chosen by 3GPP LTE for the uplink (from the terminal to the base station) transmission in order to reduce the power consumption at the transmitter and thus, the cost and weight of the mobile terminal. When there are, M symbols per block and N subcarriers, both techniques can transmit signals from $Q = N/M$ terminals simultaneously. However, the duration

of the modulated symbol is expanded in the case of OFDMA. In fact, if the modulated symbol duration is T seconds, the OFDMA symbol duration is $M \times T$ seconds. This time expansion provides the main benefit of OFDMA, which is the reduction of inter-symbol interference (ISI). On the other hand, the SC-FDMA modulated symbols are compressed and the duration of each symbol is T/Q seconds. This time compression leads to ISI, which needs to be cancelled at the base station using a frequency domain equalizer. Figure 3.18 shows that OFDMA performs equalization and data detection separately for each subcarrier. On the other hand, SC-FDMA performs a single equalization across the entire bandwidth and then uses the IDFT to transform the signals from each terminal to the time domain prior to symbol detection.

In addition to its low PAPR, one of the other advantages of SC-FDMA is that it effectively spreads each modulated symbol across the entire bandwidth and this makes it less sensitive to frequency-selective fading than OFDMA, which transmits modulated symbols in narrow sub-bands. However, OFDMA has also many advantages. For example, it is possible for an OFDMA system to adapt the symbol modulation and power for each individual subcarrier depending on the channel frequency response and this enables it to come close to the upper bound of the channel capacity limit [17].

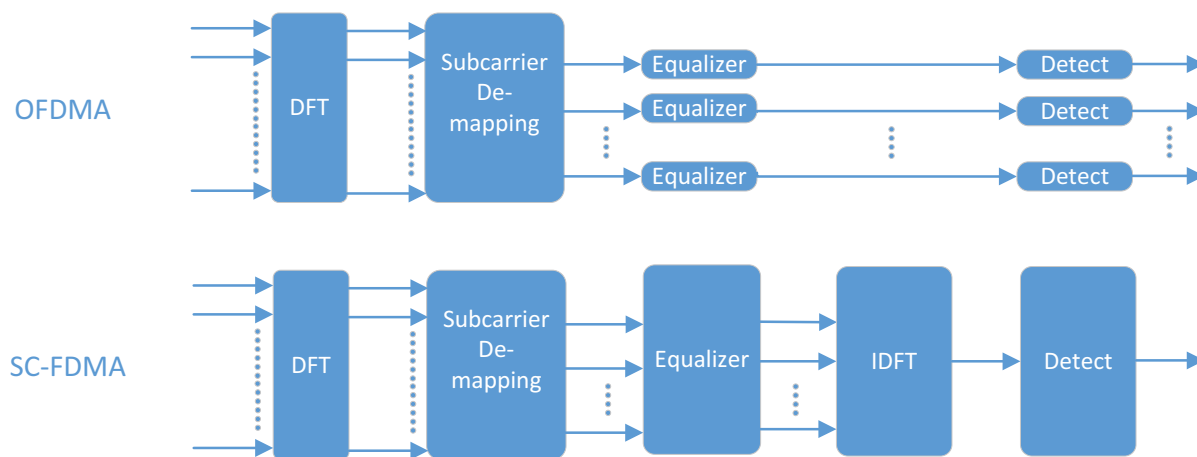


Figure 3.18: SC-FDMA and OFDMA detection and equalization steps.

3.7 Summary

Single Carrier Frequency Division Multiple Access (SC-FDMA) is a multiple access transmission technique that utilizes single carrier modulation, orthogonal frequency multiplex-

ing and frequency domain equalization. Because of its single carrier structure, SC-FDMA systems operate at a relatively low peak-to-average power ratio (PAPR). For this reason, SC-FDMA has been chosen by 3GPP LTE for the uplink communication where low peak power characteristics are greatly beneficial for the mobile terminals in terms of transmit power efficiency.

SC-FDMA has two different approaches to subcarrier mapping: localized and distributed. In localized subcarrier mapping, the data symbols occupy a set of consecutive subcarriers and frequency diversity can be achieved using channel dependent scheduling (CDS). For the case of distributed subcarrier mapping, the data symbols occupy a set of subcarriers spread over the entire bandwidth of the channel and this allows the system to achieve frequency diversity. SC-FDMA has a very similar structure to orthogonal frequency division multiple access (OFDMA) in that both systems use block-based processing, DFT-based frequency domain channel equalization and cyclic prefix. While the two systems are similar in terms of complexity, SC-FDMA has the advantage of operating at a lower PAPR but the disadvantage of being more sensitive to inter-symbol interference.

Chapter 4

Multi-receive Antenna SC-FDMA with Subcarrier Sharing and Multiuser Detection

4.1 Introduction

In this chapter, a modified version of the conventional SC-FDMA system discussed in the previous chapter is presented. The proposed technique can considerably improve the spectral efficiency of the system by allowing multiple source signals to be transmitted on the same set of subcarriers instead of mapping different source signals to different subcarriers as it was the case for the conventional SC-FDMA system. Although the system presented in this chapter is not a multiple input multiple output (MIMO) system, it is still based on some very important techniques related to MIMO transmission such as diversity combining and frequency domain equalization.

Section 4.2 of this chapter gives a general overview of MIMO transmission where multiple antenna elements at the transmitter and at the receiver are used in order to improve the communication link quality and/or communication capacity. This section also introduces the single input multiple output (SIMO) transmission, which is a special case of MIMO where there is only one transmit antenna. Section 4.3 presents three diversity combining techniques that can be used in a system that has multiple receive antennas in order to combine the different received signals in accordance with a criterion that will provide improved receiver performance. Section 4.4 discusses some important linear channel equalization techniques used to reduce the effect of the fading channels on

the received signals.

The diversity combining and channel equalization techniques presented in section 4.3 and 4.4 will be used in the spectrally efficient SC-FDMA system presented in section 4.5. In fact, the proposed system improves considerably the spectral efficiency by mapping multiple SC-FDMA symbols coming from independent source signals to the same subcarriers instead of allocating one subcarrier to each SC-FDMA symbol. At the receiver side, these signals are decorrelated using multiple receive antennas and some diversity combining and frequency equalization techniques. This section starts by presenting the mathematical description of the conventional SC-FDMA system using multiple receive antennas and then presents an SC-FDMA system with subcarrier sharing and multiuser detection that can increase the spectral efficiency of the conventional SC-FDMA without using more bandwidth or transmitting at a higher modulation order. This system will be simulated in chapter 5 in order to study its performance and reliability.

4.2 The Concept of MIMO SC-FDMA

Multiple input multiple output (MIMO) transmission is one of several forms of smart antenna technology. In recent years, this technique has attracted much attention in wireless communication because it offers significant increases in data throughput and transmission reliability without the need for additional bandwidth or increased transmit power. The main idea is to use multiple antenna elements at the transmitter and at the receiver to send and receive signals. By spreading the total transmit power over the antennas, MIMO systems can achieve a spatial diversity gain that improves communication reliability and/or a spatial multiplexing gain that improves spectrum efficiency.

4.2.1 Spatial Diversity Gain

As stated before, spatial diversity improves the reliability of communication in fading channels. In fact, the basic idea behind spatial diversity is to combat channel fading by having multiple copies of the same transmitted signal go through independently fading channel paths. At the receiver, these independently faded copies of the same transmitted signal are coherently combined to achieve a better reception. For a system with Nt transmit antennas and Nr receive antennas, the maximum diversity gain that can be achieved is $Nt \times Nr$. There are many well known diversity techniques that can be used to achieve spatial diversity such as space time coding [18] and smart antenna techniques

[19].

Depending on which end of the wireless link is equipped with multiple antennas, we may identify three types of space diversity:

- Transmit diversity, which involves the use of multiple antennas at the transmitter and a single antenna at the receiver.
- Receive diversity, which involves the use of a single antenna at the transmitter and multiple antennas at the receiver.
- Transmit and receive diversity, which involves the use of multiple antennas at the transmitter and multiple antennas at the receiver. Transmit diversity and receive diversity can be considered as a special case of this diversity form.

The case involving a single transmit antenna and multiple receive antennas is the one of interest for the subject of this thesis. Therefore, three receive diversity techniques will be presented in section 4.3 of this chapter.

4.2.2 Spatial Multiplexing Gain

While the main purpose of diversity gain is to combat fading, spatial multiplexing is a way to exploit fading in order to increase data throughput. In fact, if the path gains among the transmit and receive antenna pairs fade independently, multiple parallel spatial channels can be created. Therefore, data rate can be increased considerably by transmitting multiple streams of data through these spatial channels. The spatial multiplexing gain can be thought of as the total number of parallel channels (also known as degrees of freedom) available in the system to communicate. Telatar [20] showed that for a MIMO system with Nt transmit antennas and Nr receive antennas operating at a high SNR, the capacity of the channel increases linearly with $m = \min(Nt, Nr)$. Thus, there is m number of parallel channels in the system. Bell Labs Layered Space Time (BLAST) is one of the very well known spatial multiplexing techniques [21]. Although both diversity and multiplexing gains can be achieved simultaneously in a MIMO system, there is a fundamental trade-off between the two gains and increasing one gain comes at the price of lowering the other gain and vice versa.

4.2.3 Mathematical Description of a MIMO Channel

Figure 4.1 shows a MIMO channel with N_t transmit antennas and N_r receive antennas. In this configuration x_i represents the transmitted signal at the i th transmitter while y_j represents the received signal at the j th receiver. Also, h_{ji} is the channel complex gain between the i th transmitter and j th receiver. Such a system can be represented mathematically by the following equation:

$$\begin{bmatrix} y_1 \\ \vdots \\ y_{N_r} \end{bmatrix} = \begin{bmatrix} h_{11} & \cdots & h_{1N_t} \\ \vdots & \ddots & \vdots \\ h_{N_r 1} & \cdots & h_{N_r N_t} \end{bmatrix} \cdot \begin{bmatrix} x_1 \\ \vdots \\ x_{N_t} \end{bmatrix} + \begin{bmatrix} n_1 \\ \vdots \\ n_{N_r} \end{bmatrix} \quad (4.1)$$

This equation is usually written as following:

$$\mathbf{y} = \mathbf{H} \cdot \mathbf{x} + \mathbf{n} \quad (4.2)$$

where \mathbf{x} denotes the $N_t \times 1$ transmitted signal vector, \mathbf{y} denotes the $N_r \times 1$ received signal vector, \mathbf{n} denotes the $N_r \times 1$ zero-mean complex Gaussian noise vector and \mathbf{H} is the $N_r \times N_t$ complex matrix of channel gains h_{ji} .

4.2.4 The Special Case of SIMO Channel

Single input multiple output (SIMO) transmission is another form of smart antenna technology that can be considered as a special case of MIMO systems where the transmitter has only one transmit antenna. The idea is to use two or more antennas at the receiver as shown in figure 4.2 in order to reduce the trouble caused by multipath wave propagation and improve the system performance and communication reliability.

SIMO technology has widespread applications in digital television (DTV), Wireless Local Area Networks (WLANs) as well as mobile communications. The SC-FDMA system with multi-receive antennas and multi-user detection that will be proposed in section 4.5 can be seen as an SC-FDMA system with the capacity of accommodating multiple SC-FDMA signals that are being transmitted at the same time and at the same frequency with every SC-FDMA signal going through a SIMO channel. Figure 4.3 shows a block diagram of a SIMO SC-FDMA system. The mathematical description of this system will be presented in details in section 4.5. This system uses a single transmitter and multiple receivers and has a space diversity on the receive side, which is, as discussed in the previous section, known as receive diversity. Three receive diversity techniques are presented in the following section.

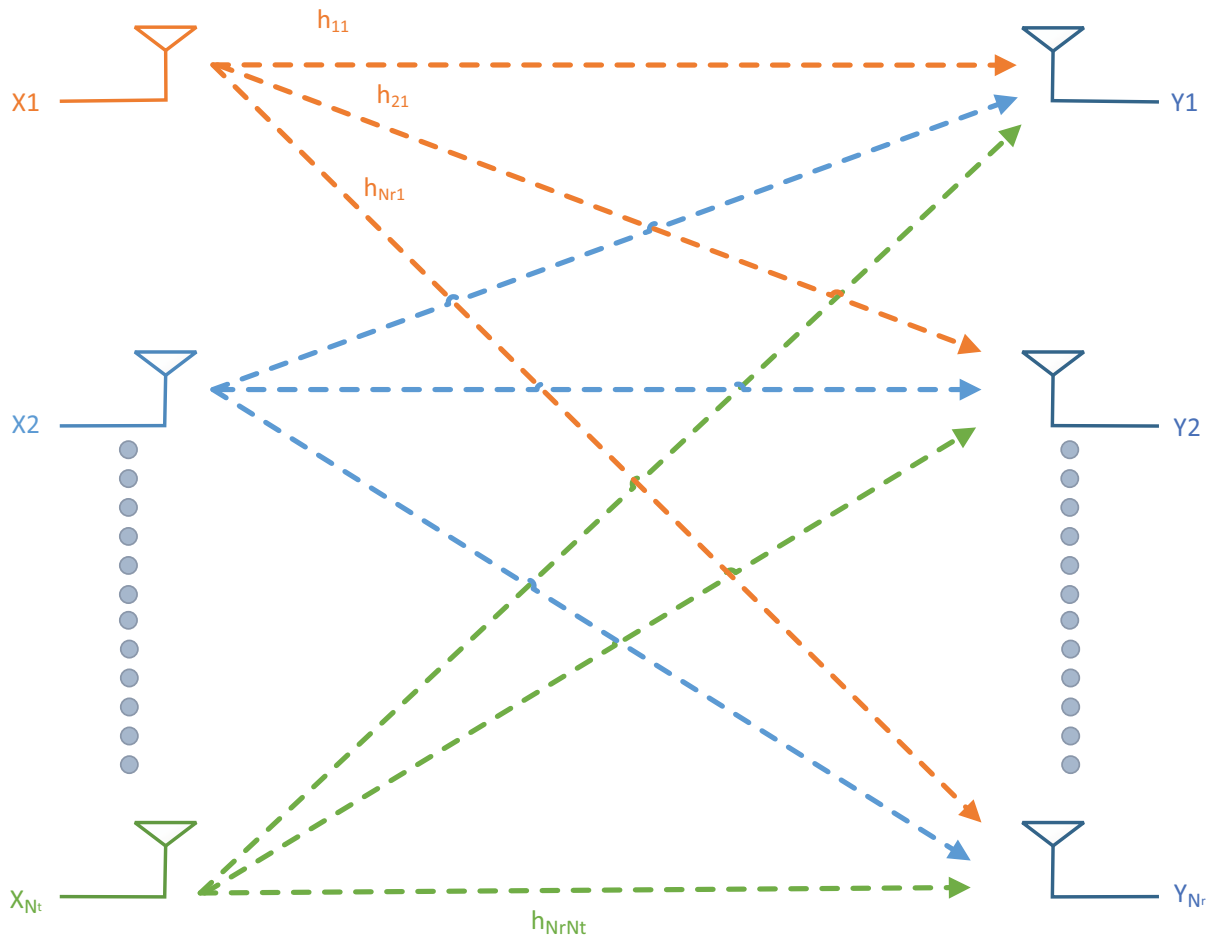


Figure 4.1: MIMO channel with N_t transmit antennas and N_r receive antennas.

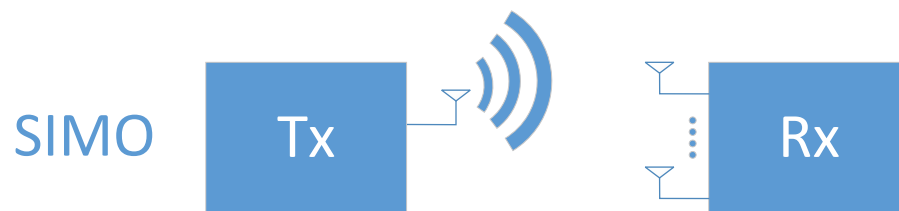


Figure 4.2: SIMO channel with one transmit antenna and N_r receive antennas.

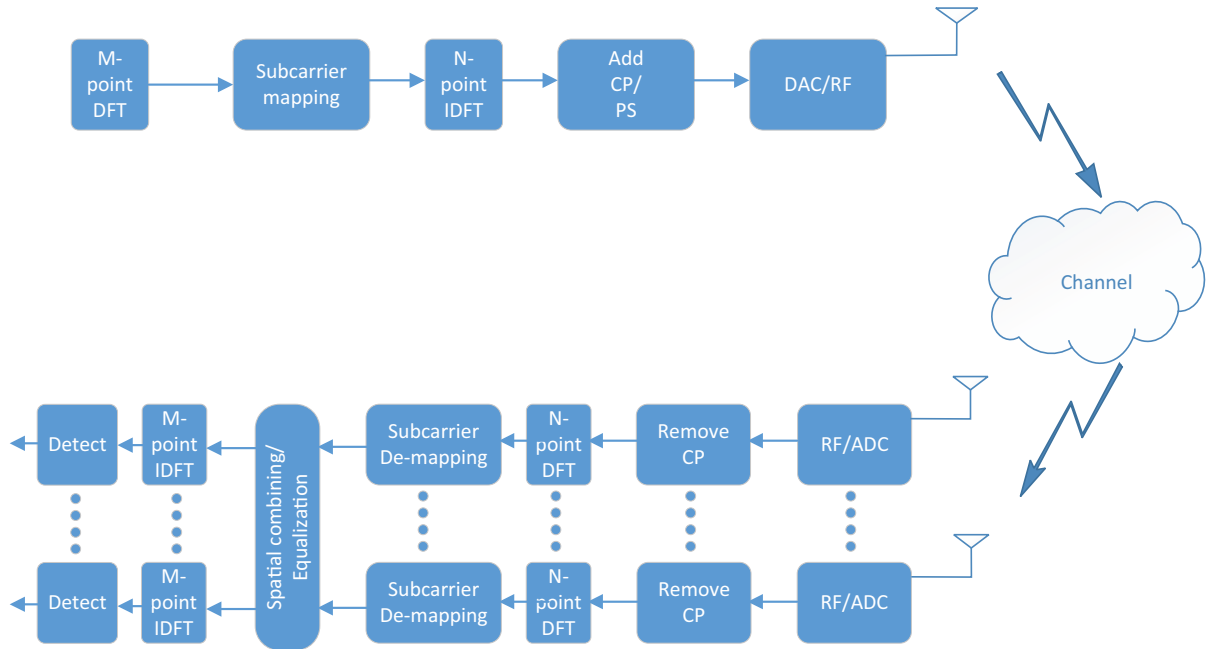


Figure 4.3: Block diagram of SIMO SC-FDMA.

4.3 Space Diversity on Receive Techniques

In space diversity on receive, only one transmitter and multiple receivers are used in the system. By adequately choosing the spacing between adjacent receive antennas, it is possible to create a set of fading channels that are essentially independent of each other, thus creating multiple independent paths for the signal. The idea is to combine the output of these independent channels in accordance with a criterion that will provide improved receiver performance. This section discusses three diversity combining techniques that can be used on the receive side, namely, selection combining, equal-gain combining and maximal-ratio combining.

4.3.1 Selection Combining

Conceptually, selection combining can be considered as the simplest form of space diversity on receive techniques. Figure 4.4 shows a block diagram of a selection combining structure consisting of N_r receive antennas and a logic circuit. At any given moment of time, the logic circuit, also called selector, selects the particular receiver output with the largest signal-to-noise ratio (SNR) as the received signal. Although selection combining is relatively straightforward to implement, this technique requires the receiver outputs

to be monitored continuously and such a selective procedure is rather cumbersome from a practical perspective. It is also not optimum from a performance point of view, in that it ignores the information available from all the channels except from the one that produces the strongest signal.

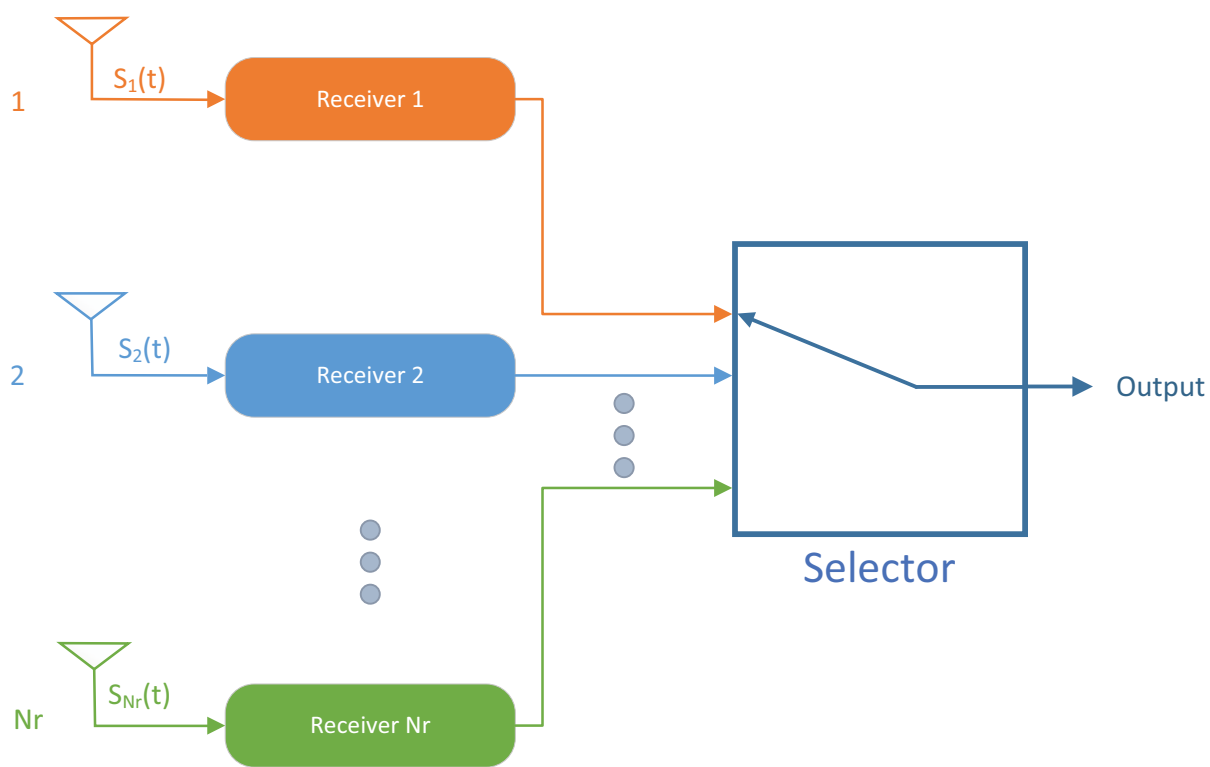


Figure 4.4: Selection combining.

4.3.2 Equal-gain Combining

Equal gain combining is another technique used to combine the signals received on multiple branches. The corresponding block diagram is shown in figure 4.5. In equal gain combining, the received signals from different branches are weighted with a complex weighting parameter W_k and then summed in order to produce the output signal. All the combining weights have equal magnitudes set to a constant value, thus the reason for the name equal-gain combining. However, co-phasing of all signals is needed in order to avoid signal cancellation and that is why these complex weighting parameters W_k have their phase angles set opposite to those of their respective multipath branches. This technique has the advantage of being relatively simple to implement and offers a

better performance than selection combining and can produce acceptable outputs from unacceptable inputs. However, the system performance degrades if there is a correlation between the individual branch signals (i.e. they are not perfectly independent).

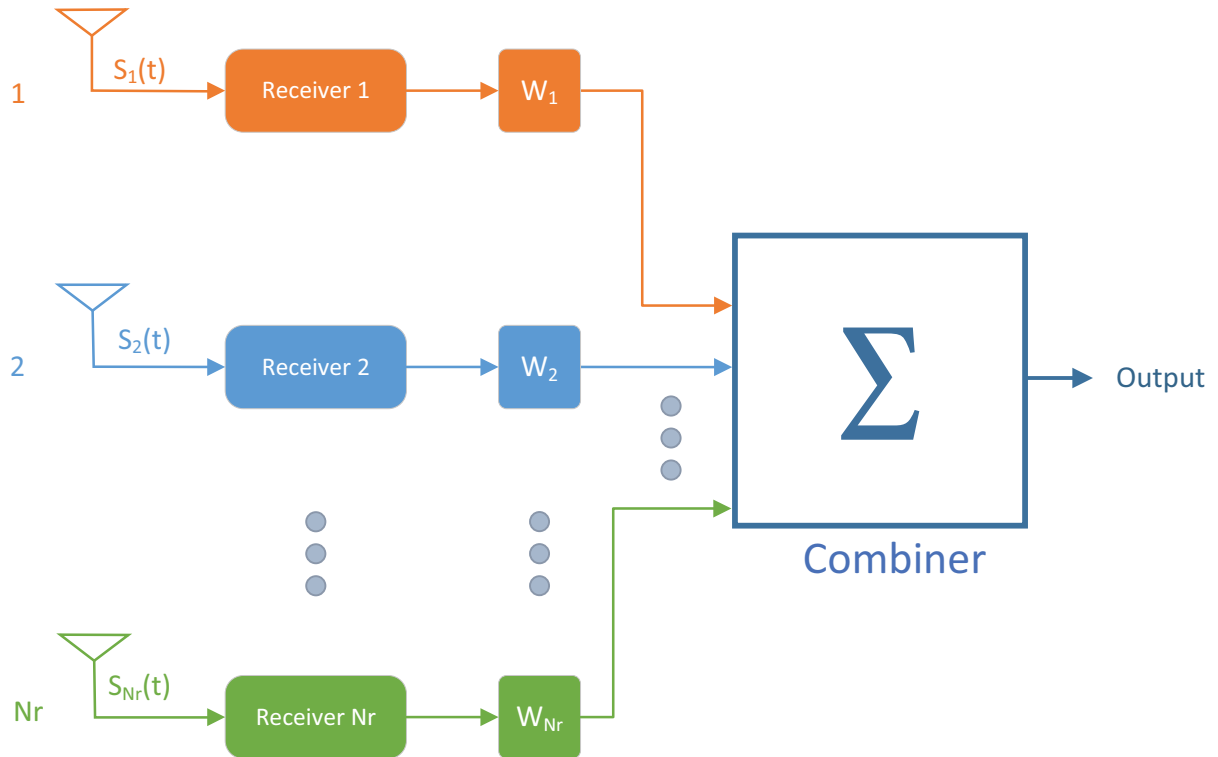


Figure 4.5: Equal-gain combining.

4.3.3 Maximal-ratio Combining

The equal gain combining just described is relatively straightforward to implement. However, from a performance point of view, it is not optimum. The maximal ratio combiner (MRC) can be thought of as a more advanced version of selection combiner where the complex weighting factors W_k are not set having equal magnitudes but are rather chosen to maximize the output signal-to-noise ratio. As shown in the block diagram of figure 4.6, the maximal-ratio combiner consists of N_r linear receivers followed by a linear combiner. The complex weighting parameters of the linear combiner are changed from instant to instant in accordance with variations in signals in the N_r diversity branches so as to maximize its output signal to noise ratio (SNR) at each instant of time. Therefore, the

combiner must boost the strong signal components and attenuate the weak (relatively noisy) components. In order to do this, each signal branch is multiplied by a complex weighting factor that has a magnitude proportional to the signal's amplitude and a phase that cancels the signal's phase to within some value that is identical for all the N_r diversity branches. In practice, this weighting operation is realized by a phase shifter followed by a signal attenuator at each branch. By doing this, branches with strong signal are further amplified, while weak signals are attenuated. The mathematical description related to this combining technique is discussed in details in section 4.5 where a maximal-ratio combiner is used at the receiver of a SC-FDMA system.

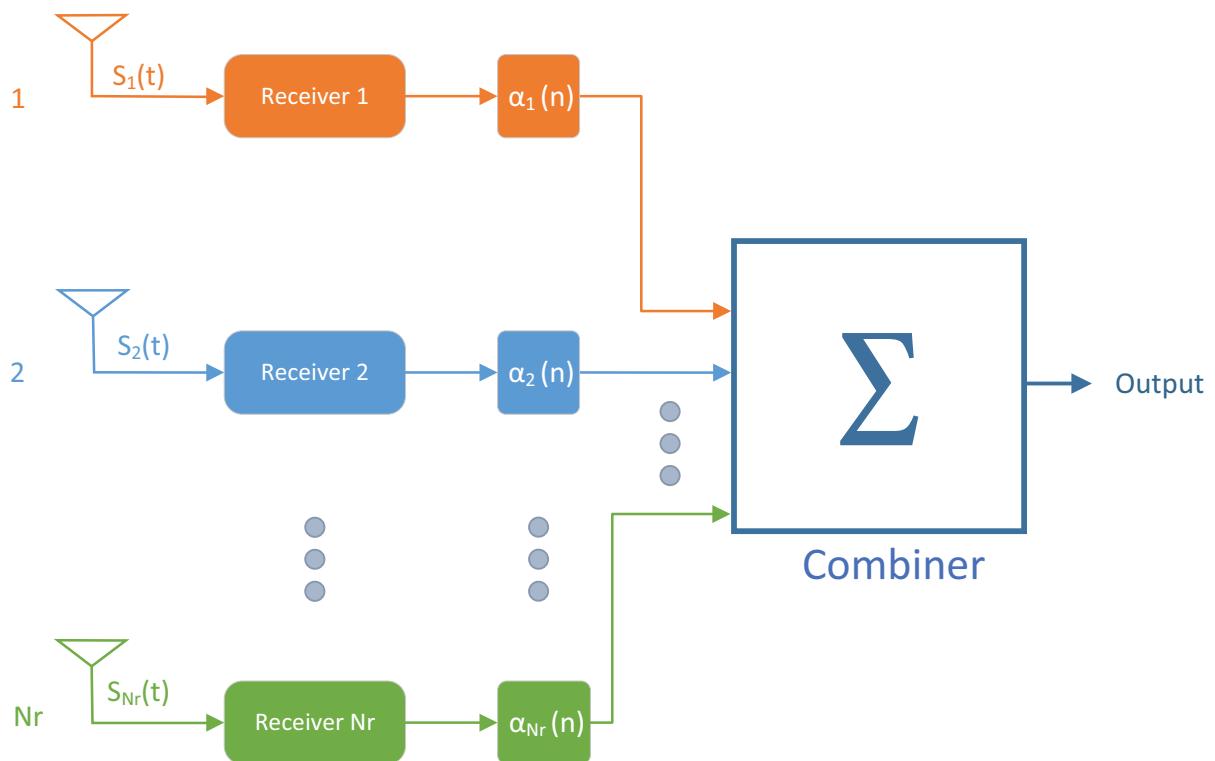


Figure 4.6: Maximal-ratio combining.

In summary, receive diversity is a special form of space diversity involving a single transmit antenna and multiple receive antennas. It is a very powerful technique used to overcome the effects of multipath fading by sending the same information over independent fading paths and combining the received signals in order to improve the receiver performance. Three receive diversity techniques were discussed: selection combining, equal gain combining and maximal ratio combining. In selection combining, only the branch with the strongest signal is used to define the received signal. While selection

combining is the simplest form of receive diversity, it has the disadvantage of not being able to exploit the full information content of all the receive diversity branches. Equal gain combining provides a better performance than selection combining because instead of choosing the signal from only one branch at a time, all the received signals are co-phased and summed with equal weighting in order to produce the output. Finally, maximal-ratio combining is a more advanced version of selection combining that is characterized by a set of time varying complex weighting factors, which are chosen to maximize the output signal-to-noise ratio of the combiner.

Among the three diversity combining techniques, maximal-ratio combining is the optimum one, in that it produces the largest possible value of instantaneous output signal-to-noise ratio. Overall, combiners complexity and performance varies significantly from type to type. In fact, while maximal-ratio combining provides the best performance, it is the most complex one. On the other hand, selection combining is easy to implement but gives a relatively bad performance. Finally, the equal gain combining performance and complexity is between these two techniques. Therefore, there exists a performance/complexity trade-off and one has to choose between these combining techniques according to his system requirements and characteristics.

4.4 Channel Equalization

As discussed in the previous chapter, channel equalization is a very important step in SC-FDMA transmission used to reduce the inter-symbol interference (ISI) arising from the delay spread or band-limitation of the channel by adjusting the pulse shape so that it does not interfere with the neighbouring pulses. This section presents one of the most important equalization schemes, which is linear equalization. Linear equalization is essentially a linear filtering process used to invert the channel transfer function in order to eliminate the effects of the channel from the received signal. Depending on the optimization criterion used for the calculation of the filter coefficients, linear equalizers can be classified in two main categories: zero-forcing (ZF) equalizers and minimum mean-square error (MMSE) equalizers. For both techniques, a training sequence is transmitted over the channel in order to help the receiver to calculate the channel frequency response, which is used for equalization.

4.4.1 Zero-forcing Equalization

A zero-forcing equalizer applies the inverse of the channel frequency response to the received signal in order to restore the signal after the channel. In fact, for a channel with a frequency response $H(f)$, the zero-forcing equalizer $Z(f)$ is constructed by applying the channel inversion $Z(f) = 1/H(f)$. Thus, the combination of channel and equalizer leads to a completely flat frequency response and linear phase $H(f) \cdot Z(f) = 1$. This corresponds to forcing the ISI to zero in the noise free case. A more detailed mathematical description is provided in section 4.5 where a zero-forcing equalizer is used for the proposed system.

Zero-forcing is very useful when the ISI is significant compared to noise. However, the ZF equalizer enhances the noise of the channel at the frequencies when the channel frequency response attains small values, since it performs channel inversion. Furthermore, in some cases, the channel may have zeroes in its frequency response and that cannot be inverted at all by zero-forcing since any gain multiplied by zero will still give zero. This problem is addressed in the linear minimum mean-square error equalization by making a small modification to the denominator of $Z(f)$ as discussed next.

4.4.2 Minimum Mean-square Error Equalization

Although the ZF equalizer eliminates ISI, noise enhancement in many applications can make the bit error rate (BER) performance undesirable. Minimum mean-square error (MMSE) equalization is a more balanced technique, which does not completely eliminate the ISI but instead minimize both the total power of the noise and ISI components in the output. The MMSE equalizer $Z(f)$ in this case is constructed by applying the channel inversion $Z(f) = 1/(H(f) + k)$ where k is a parameter related to the channel response and signal-to-noise ratio. In MMSE equalization, the filter parameters are updated by minimizing the variance of the error signal:

$$e[k] = \hat{d}[k] - d[k] \quad (4.3)$$

where $d[k]$ is the desired signal at time k and $\hat{d}[k]$ is the estimated signal after equalization. By this means, the ISI is removed as much as possible. In fact, MMSE equalization ensures an optimum trade-off between residual ISI and noise enhancement. Usually, MMSE equalizers achieve a significantly lower BER than ZF equalizers at low to moderate SNRs. However, MMSE equalizers introduce more complexity to the system and in many practical situations, a ZF equalization is sufficient to provide an acceptable performance.

4.5 Spectrally Efficient SC-FDMA with Multiuser Detection

As was discussed in chapter 2, the conventional Single Carrier Frequency Division Multiple Access (SC-FDMA) is a multiple access technique that is capable of transmitting multiple source signals simultaneously by assigning signals to mutually exclusive sets of sub-carriers. In particular, it was shown that if there is a total of N available subcarriers spread over the entire bandwidth and if each source signal occupies M out of these N subcarriers, then the maximum number of source signals that an SC-FDMA system can accommodate is:

$$Q = \frac{N}{M} \quad (4.4)$$

and the channel transmission rate is:

$$R_{channel} = \frac{N}{M} \cdot R_{source} \text{ [symbols/sec]} \quad (4.5)$$

where R_{source} is the source rate in symbols/seconds. With the current SC-FDMA systems, the only two ways to increase the transmission rate $R_{channel}$ is to allocate more bandwidth to the communication system or to increase the modulation order (for example going from 16QAM to 64QAM). However, allocating more spectrum to the system is not always possible in practice and going to a higher modulation order has an associated power penalty and introduces a considerable complexity to the system. Furthermore, according to the 3GPP LTE technical specifications, there are only three supported data modulation schemes, which are QPSK, 16QAM and 64QAM [22]. Therefore, these two options are not always feasible. In this section, a new SC-FDMA system is presented. This system has the advantage of being able to increase the transmission rate without increasing the bandwidth or going to a higher modulation order. The basic idea is that instead of transmitting the SC-FDMA source signals on mutually exclusive sets of sub-carriers, it is possible to transmit two or more independent source signals on the same set of subcarriers and use some diversity combining and equalization techniques at the receiver to recover the transmitted signals. For example, if each source signal that is being transmitted consists of M complex modulation symbols, it is possible to transmit two source signals on the same set of M subcarriers instead of each signal occupying a different set of M subcarriers. This corresponds to doubling the spectral efficiency without allocating more resources. In fact, if there is a total of N available subcarriers,

the number of source signals that the new SC-FDMA system can accommodate is:

$$Q = 2 \cdot \frac{N}{M} \quad (4.6)$$

and the new channel transmission rate is:

$$R_{channel} = 2 \cdot \frac{N}{M} \cdot R_{source} \text{ [symbols/sec]} \quad (4.7)$$

This spectrally efficient SC-FDMA system is discussed in details in this section and the simulation results as well as the system model are presented in the next chapter. In order to fully understand this new SC-FDMA system that has multiple source signals transmitted on the same set of subcarriers, it is essential to start first by providing a mathematical description of the conventional SC-FDMA in order to understand the modifications that are being made to this system to make it more spectrally efficient. Section 4.5.1 presents a conventional SC-FDMA system with maximal-ratio combining at the receiver. Sections 4.5.2 presents modified versions of this system that can increase the spectral efficiency of the system by transmitting N_t source signals on the same set of subcarriers.

4.5.1 Conventional SC-FDMA System with MRC at the Receiver

This section presents a conventional SC-FDMA transmission system using maximal-ratio combining at the receiver. This system was already discussed previously and the corresponding block diagram is shown in figure 4.7. The system has one transmitter and N_r receivers. $\mathbf{x} = [x(1), x(2), \dots, x(N)]$ represents the transmitted block of length N symbols, A_{cp} represents the addition of cyclic prefix to the block and $\mathbf{n}_j = [n_j(1), n_j(2), \dots, n_j(N)]$, $1 \leq j \leq N_r$ represents a complex Gaussian noise added to the transmitted block \mathbf{x} at the j th receiver antenna. The block R_{cp} indicates the cyclic prefix removal step while F and F^{-1} are respectively the N -point DFT and IDFT. Finally, \hat{W} illustrates the frequency domain equalizer, which is the most important block of the system responsible for producing the equalized received SC-FDMA block $\hat{\mathbf{x}} = [\hat{x}(1), \hat{x}(2), \dots, \hat{x}(N)]$ that is required to be as close possible to the originally transmitted block \mathbf{x} .

A maximal-ratio combiner (MRC) is used in this system in order to combine all the received signals from different channels and generate an output that should be as close as

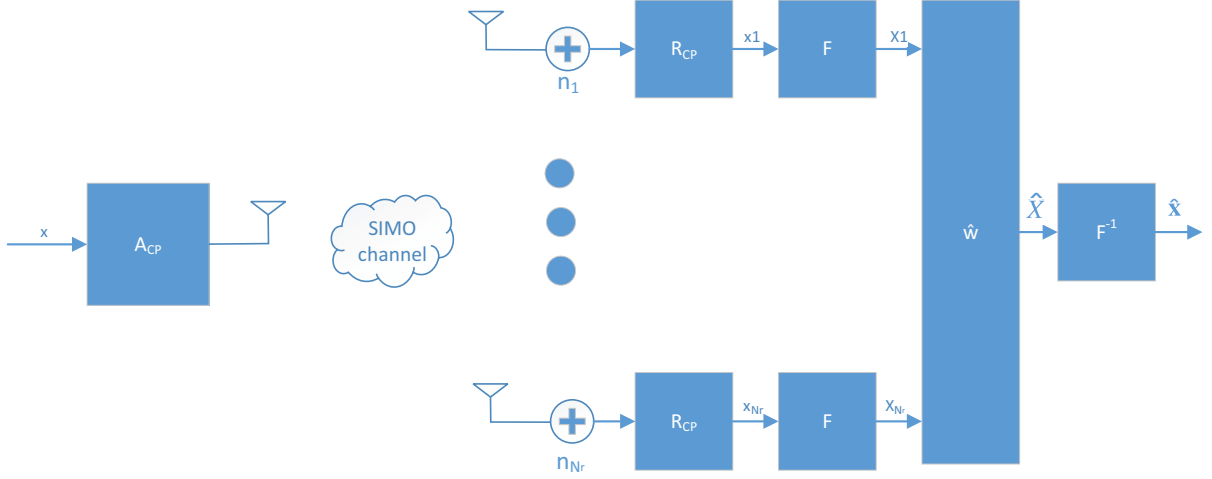


Figure 4.7: Conventional SC-FDMA with MRC at the receiver.

possible to the original input. Each SC-FDMA transmitted block consists of a set of N subcarriers containing a total of N modulation symbols represented in the frequency domain by the vector $\mathbf{X} = [X(1), X(2), \dots, X(N)]$. Let $\mathbf{H}_j = [H_j(1), H_j(2), \dots, H_j(N)]$, $1 \leq j \leq N_r$ denotes the channel frequency response between the transmitter and the j th receiver. At the j th receiver, after removing the cyclic prefix, an N -point DFT operation converts the received block of symbols into frequency domain, thus generating N frequency domain symbols denoted by $\mathbf{X}_j = [X_j(1), X_j(2), \dots, X_j(N)]$. Each symbol $X_j(i)$, $1 \leq i \leq N$ of this received block can be expressed as:

$$X_j(i) = X(i) \cdot H_j(i) + \eta_j(i) \quad (4.8)$$

where $X(i)$ and $\eta_j(i)$ are respectively the frequency domain representation of the transmitted symbol $x(i)$ and the noise $n_j(i)$. The next step is to use the maximal-ratio combining technique in order to combine the N_r received signals $X_j(i)$ and produce a unique output $\hat{X}(i)$, which should be as close as possible to the originally transmitted signal $X(i)$. As discussed in section 4.3, every received signal must be multiplied by a MRC weighting factor. Therefore, let's start by multiplying every received symbol $X_j(i)$ by the complex conjugate of its corresponding channel frequency response $H_j^*(i)$. The sum of all these components is denoted by $U(i)$ and given by:

$$U(i) = X_1(i) \cdot H_1^*(i) + X_2(i) \cdot H_2^*(i) + \dots + X_{N_r}(i) \cdot H_{N_r}^*(i) \quad (4.9)$$

where $*$ denotes complex conjugations. Substituting equation (4.8) in equation (4.9)

gives:

$$U(i) = [X(i) \cdot H_1(i) + \eta_1(i)] \cdot H_1^*(i) + [X(i) \cdot H_2(i) + \eta_2(i)] \cdot H_2^*(i) + \dots + [X(i) \cdot H_{N_r}(i) + \eta_{N_r}(i)] \cdot H_{N_r}^*(i) \quad (4.10)$$

Expanding the above equation leads to the following expression:

$$U(i) = X(i) \cdot H_1(i) \cdot H_1^*(i) + \eta_1(i) \cdot H_1^*(i) + X(i) \cdot H_2(i) \cdot H_2^*(i) + \eta_2(i) \cdot H_2^*(i) + \dots + X(i) \cdot H_{N_r}(i) \cdot H_{N_r}^*(i) + \eta_{N_r}(i) \cdot H_{N_r}^*(i) \quad (4.11)$$

Knowing that $H_j(i) \cdot H_j^*(i) = |H_j(i)|^2$, equation (4.11) can be written as:

$$U(i) = X(i) \cdot [|H_1(i)|^2 + |H_2(i)|^2 + \dots + |H_{N_r}(i)|^2] + \eta_1(i) \cdot H_1^*(i) + \eta_2(i) \cdot H_2^*(i) + \dots + \eta_{N_r}(i) \cdot H_{N_r}^*(i) \quad (4.12)$$

Therefore, the final expression for $U(i)$ can be written as following:

$$U(i) = X(i) \cdot \sum_{j=1}^{N_r} |H_j(i)|^2 + \sum_{j=1}^{N_r} \eta_j(i) \cdot H_j^*(i) \quad (4.13)$$

The expression of $U(i)$ as it appears in equation (4.13) suggests that the received symbol $X(i)$ can be approximated by $\hat{X}(i)$ as following:

$$\hat{X}(i) = \frac{U(i)}{\sum_{j=1}^{N_r} |H_j(i)|^2} = X(i) + \frac{\sum_{j=1}^{N_r} \eta_j(i) \cdot H_j^*(i)}{\sum_{j=1}^{N_r} |H_j(i)|^2} \quad (4.14)$$

For notation purposes, let:

$$Z(i) = \frac{\sum_{j=1}^{N_r} \eta_j(i) \cdot H_j^*(i)}{\sum_{j=1}^{N_r} |H_j(i)|^2} \quad (4.15)$$

Therefore, the frequency domain estimation of the i th transmitted SC-FDMA symbol $X(i)$ calculated using maximal-ratio combining is given by:

$$\hat{X}(i) = X(i) + Z(i) \quad (4.16)$$

In order for the output symbol $\hat{X}(i)$ to be as close as possible to the transmitted symbol $X(i)$, the expression of $Z(i)$ involving the noise added at each receive antenna needs to be as close as possible to zero. It is clear from equation (4.15) that $Z(i)$ can

be minimized by maximizing the denominator $\sum_{j=1}^{N_r} |H_j(i)|^2$. Therefore, one can expect that a better estimate of the transmitted signal can be obtained by increasing the number of receiving antennas N_r . This scenario is studied in the next chapter.

Following the above derivations, let $\mathbf{X} = [X(1), X(2), \dots, X(N)]$ denotes the transmitted SC-FDMA block of N symbols in frequency domain. The received block of symbols $\mathbf{X}_j = [X_j(1), X_j(2), \dots, X_j(N)]$ at the j th receive antenna can be expressed as:

$$\mathbf{X}_j = \mathbf{X} \cdot \mathbf{H}_j + \eta_j \quad (4.17)$$

Where η_j is the noise vector at the j th receive antenna whose entries are i.i.d complex Gaussian:

$$\eta_j = [\eta_j(1), \eta_j(2), \dots, \eta_j(N)] \quad (4.18)$$

and \mathbf{H}_j represents an $N \times N$ diagonal matrix whose entries are the channels frequency responses as seen by j th receive antenna:

$$\mathbf{H}_j = \begin{bmatrix} H_j(1) & 0 & \dots \\ 0 & \ddots & 0 \\ \vdots & 0 & H_j(N) \end{bmatrix} \quad (4.19)$$

Therefore, the output of the SC-FDMA receiver using maximal-ratio combining on the N_r received signals \mathbf{X}_j is calculated by the following equation:

$$\hat{\mathbf{X}} = \frac{\sum_{j=1}^{N_r} \mathbf{X}_j \cdot \mathbf{H}_j^*}{\sum_{j=1}^{N_r} |\mathbf{H}_j|^2} \quad (4.20)$$

After calculating this frequency domain signal $\hat{\mathbf{X}}$, the system performs an IDFT to recover the signal $\hat{\mathbf{x}}$, which is the estimated time domain version of the transmitted block \mathbf{x} . This $\hat{\mathbf{x}}$ will be then given to the detector in order to estimate the input bits. The system simulation results are presented and discussed in the next chapter.

4.5.2 SC-FDMA system with N_t source signals occupying the same set of sub-carriers

In the previous section, a maximal-ratio combiner was used in a conventional SC-FDMA system with one transmitter and multiple receive antennas in order to recover the transmitted signal from N_r received signals \mathbf{x}_j . In fact, the source signals were assigned a

different set of subcarriers and each SC-FDMA transmitted symbol had its own subcarriers. In other words, if the available bandwidth is divided into a total of N sub-carriers, the conventional SC-FDMA system can transmit a maximum of N symbols at a time. The new SC-FDMA system that is proposed in this section can transmit simultaneously N_t source symbols on the same number of sub-carriers. This is realized by mapping every N_t signals to the same set of sub-carriers. By doing this superposed mapping, it is possible to send $N_t \times N$ symbols simultaneously on a bandwidth containing only N_t sub-carriers. This technique has the advantage of increasing the spectral efficiency without increasing the bandwidth or going to a higher modulation order. However, sending N_t signals at the same time and on the same sub-carriers will create a very strong interference and the SC-FDMA system should have the ability at the receiver to remove this interference and recover the signals.

Figure 4.8 shows a block diagram of the proposed SC-FDMA system with N_t transmitted signals occupying the same sub-carriers and multiple receive antennas. This configuration consists of N_t transmit antennas sending multiple SC-FDMA signals \mathbf{x}_k , $1 \leq k \leq N_t$ on the same set of N sub-carriers and N_r antennas at the receiver. At the output of the receiver, each signal $\tilde{\mathbf{x}}_k$ represents the estimation of \mathbf{x}_k . As seen previously, A_{CP} and R_{CP} blocks indicate the cyclic prefix addition and removal steps while F and F^{-1} are the N -point DFT and IDFT. Also, \mathbf{n}_j indicates the complex Gaussian noise vector added to the received signal at the j th receiver.

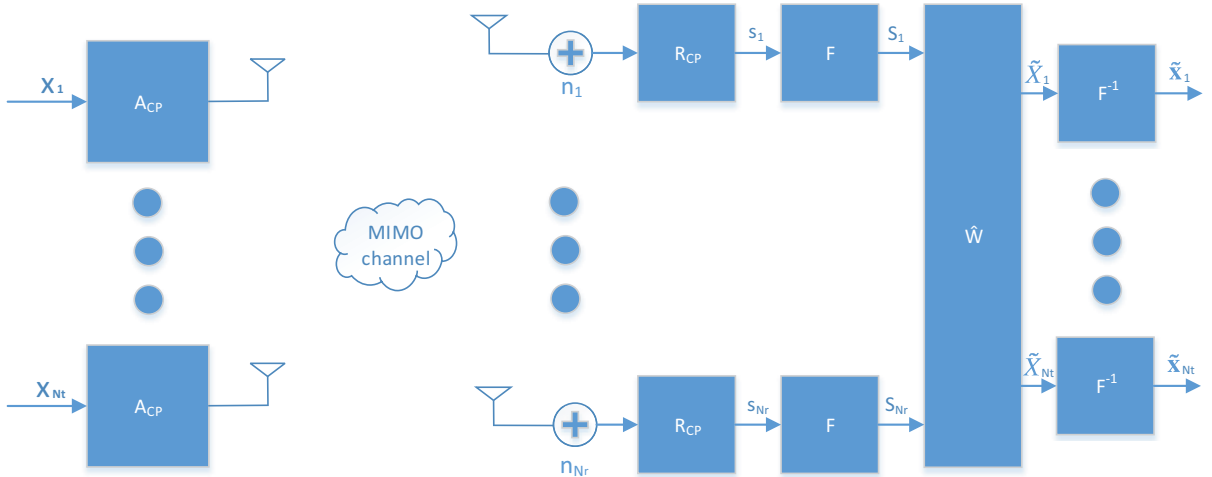


Figure 4.8: SC-FDMA system with N_t transmitted signals occupying the same set of sub-carriers.

Up to this point, this system seems very similar to the conventional SC-FDMA system

presented in the previous section. However, the major difference is that there are N_t independent SC-FDMA signals being transmitted at the same time and on the same sub-carriers instead of only one. Therefore, each receive antenna will receive a signal \mathbf{s}_j that contains all the transmitted signals \mathbf{x}_k . Hence, a special technique should be implemented at the receiver in order to decorrelate and detect the N_t transmitted signals.

Let $\mathbf{H}_{\mathbf{kj}} = [H_{kj}(1), H_{kj}(2), \dots, H_{kj}(N)]$, $1 \leq k \leq N_t$ and $1 \leq j \leq N_r$ denote the frequency response of the wireless channel between the transmitter k and the j th receiver. The received signal at the j th receive antenna consisting of N SC-FDMA symbols can be expressed in the frequency domain as $\mathbf{S}_j = [S_j(1), S_j(2), \dots, S_j(N)]$. Each symbol $S_j(i)$, $1 \leq i \leq N$ of this received block can be expressed as:

$$S_j(i) = \eta_j(i) + \sum_{k=1}^{N_t} X_k(i) \cdot H_{kj}(i) \quad (4.21)$$

where $X_k(i)$ and $\eta_j(i)$ are respectively the frequency domain representations of the transmitted symbol $x_k(i)$ and the noise $n_j(i)$.

By comparing equation (4.21) with equation (4.8), its possible to see that the received signal at the j th receiver for the SC-FDMA system discussed in this section is much more complicated than the expression of the received signal in the case of conventional SC-FDMA. This is because the received signal contains now N_t independent source signals that were sent from different transmitters. The objective now is to recover these N_t transmitted signals $X_k(i)$ by combining the received signals $S_j(i)$, $1 \leq j \leq N_r$ from all the receive antennas. Following the same reasoning as in the previous section, lets define a new variable U_k such that:

$$U_k(i) = \sum_{j=1}^{N_r} S_j(i) \cdot H_{kj}^*(i), \quad 1 \leq i \leq N \quad (4.22)$$

where $*$ denotes complex conjugation. Substituting $S_j(i)$ as it appears in equation (4.21) into (4.22) gives the following expression for U_k :

$$\begin{aligned} U_k(i) = & X_k(i) \cdot \sum_{j=1}^{N_r} |H_{kj}(i)|^2 \\ & + \sum_{\{t \mid 1 \leq t \leq N_t, t \neq k\}} \left(X_t(i) \cdot \sum_{j=1}^{N_r} H_{tj}(i) \cdot H_{kj}^*(i) \right) + \sum_{j=1}^{N_r} \eta_j(i) \cdot H_{kj}^*(i) \end{aligned} \quad (4.23)$$

Given that the objective is to estimate $X_k(i)$, it is a reasonable decision to start by following a similar procedure to the one presented in the previous section and divide $U_k(i)$ by $\sum_{j=1}^{N_r} |H_{kj}(i)|^2$. Using this technique, the frequency domain estimation of $X_k(i)$ is calculated as following:

$$\hat{X}_k(i) = \frac{U_k(i)}{\sum_{j=1}^{N_r} |H_{kj}(i)|^2} \quad (4.24)$$

This gives the following estimation:

$$\hat{X}_k(i) = X_k(i) + \sum_{\{t \mid 1 \leq t \leq N_t, t \neq k\}} \left(X_t(i) \cdot \frac{\sum_{j=1}^{N_r} H_{tj}(i) \cdot H_{kj}^*(i)}{\sum_{j=1}^{N_r} |H_{kj}(i)|^2} \right) + \frac{\sum_{j=1}^{N_r} \eta_j(i) \cdot H_{kj}^*(i)}{\sum_{j=1}^{N_r} |H_{kj}(i)|^2} \quad (4.25)$$

Just for notation convenience, let:

$$\rho_{tk}(i) = \frac{\sum_{j=1}^{N_r} H_{tj}(i) \cdot H_{kj}^*(i)}{\sum_{j=1}^{N_r} |H_{kj}(i)|^2} \quad (4.26)$$

and

$$Z_k(i) = \frac{\sum_{j=1}^{N_r} \eta_j(i) \cdot H_{kj}^*(i)}{\sum_{j=1}^{N_r} |H_{kj}(i)|^2} \quad (4.27)$$

The frequency domain estimation of the i th transmitted symbol $X_k(i)$ calculated using the same technique as in the previous section is given by:

$$\hat{X}_k(i) = X_k(i) + \sum_{\{t \mid 1 \leq t \leq N_t, t \neq k\}} (X_t(i) \cdot \rho_{tk}(i)) + Z_k(i) \quad (4.28)$$

As it will be shown in the simulation results of the next chapter, using a maximal-ratio combiner at the receiver in the case of a conventional SC-FDMA system with multiple receive antenna is a very efficient technique to recover the transmitted signal. However, using this same technique in a system that has multiple independent source signals occupying the same sub-carriers to estimate the transmitted signals is completely inefficient and useless. In fact, estimating the transmitted signals $X_k(i)$ using only a maximal-ratio combiner as proposed in equation (4.28) is not sufficient to recover the transmitted signals. This is because the new SC-FDMA system has multiple source signals that are being transmitted on the same set of sub-carriers instead of the conventional system where different source signals are mapped to different set of sub-carriers. As it can be

seen from equation (4.21), each received SC-FDMA symbol $S_j(i)$ at the j th receiver is a combination of the N_t transmitted signals $X_k(i)$ with an additional noise. Using a maximal-ratio combiner, the frequency domain estimations of these signals calculated by equation (4.28) will not only have a component related to noise but also other component related to the interference from the other signals. Therefore, the estimated signals $\hat{X}_k(i)$ will have a very big margin of error because MRC can reduce the errors due to the noise introduced by the components $Z_k(i)$ but it cannot reduce the errors $X_t(i) \cdot \rho_{tk}(i)$ caused by the interfering signals. Therefore, equations (4.28) need to be modified in order to provide a better estimate of the transmitted signals.

Given that the error terms $X_t(i) \cdot \rho_{tk}(i)$ are very important and cannot be neglected, the SC-FDMA system needs to have the ability to eliminate these terms in order to recover the transmitted signals. Writing equation (4.28) in a matrix form gives the following expression:

$$\begin{bmatrix} \hat{X}_1(i) \\ \hat{X}_2(i) \\ \hat{X}_3(i) \\ \vdots \\ \hat{X}_{N_t}(i) \end{bmatrix} = \begin{bmatrix} 1 & \rho_{2,1}(i) & \rho_{3,1}(i) & \cdots & \rho_{N_t,1}(i) \\ \rho_{1,2}(i) & 1 & \rho_{3,2}(i) & \cdots & \rho_{N_t,2}(i) \\ \rho_{1,3}(i) & \rho_{2,3}(i) & 1 & \cdots & \rho_{N_t,3}(i) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_{1,N_t}(i) & \rho_{2,N_t}(i) & \cdots & \rho_{N_t-1,N_t}(i) & 1 \end{bmatrix} \begin{bmatrix} X_1(i) \\ X_2(i) \\ X_3(i) \\ \vdots \\ X_{N_t}(i) \end{bmatrix} + \begin{bmatrix} Z_1(i) \\ Z_2(i) \\ Z_3(i) \\ \vdots \\ Z_{N_t}(i) \end{bmatrix} \quad (4.29)$$

For notation convenience, let:

$$A = \begin{bmatrix} 1 & \rho_{2,1}(i) & \rho_{3,1}(i) & \cdots & \rho_{N_t,1}(i) \\ \rho_{1,2}(i) & 1 & \rho_{3,2}(i) & \cdots & \rho_{N_t,2}(i) \\ \rho_{1,3}(i) & \rho_{2,3}(i) & 1 & \cdots & \rho_{N_t,3}(i) \\ \vdots & \vdots & \vdots & \ddots & \vdots \\ \rho_{1,N_t}(i) & \rho_{2,N_t}(i) & \cdots & \rho_{N_t-1,N_t}(i) & 1 \end{bmatrix} \quad (4.30)$$

Equation (4.30) suggests that it is possible to eliminate the terms related to interference by multiplying both sides of the equation by A^{-1} . As discussed in section 4.4.1, this technique is called zero forcing and it should provide a much better estimate of the transmitted signals given that the errors due to interference are being forced to zero. Let $\tilde{X}_k(i)$ denote the new frequency domain estimations of the transmitted signals $X_k(i)$. Therefore, these new estimations are given by the following equation:

$$\begin{bmatrix} \tilde{X}_1(i) \\ \vdots \\ \tilde{X}_{N_t}(i) \end{bmatrix} = A^{-1} \begin{bmatrix} \hat{X}_1(i) \\ \vdots \\ \hat{X}_{N_t}(i) \end{bmatrix} \quad (4.31)$$

Substituting $\begin{bmatrix} \hat{X}_1(i) & \cdots & \hat{X}_{N_t}(i) \end{bmatrix}^T$ in (4.31) by its corresponding expression as given in equation (4.29) gives the following:

$$\begin{bmatrix} \tilde{X}_1(i) \\ \vdots \\ \tilde{X}_{N_t}(i) \end{bmatrix} = \begin{bmatrix} X_1(i) \\ \vdots \\ X_{N_t}(i) \end{bmatrix} + A^{-1} \begin{bmatrix} Z_1(i) \\ \vdots \\ Z_{N_t}(i) \end{bmatrix} \quad (4.32)$$

The calculation of the estimated $\tilde{X}_k(i)$ given by equation (4.32) doesn't involve the interfering signals. Therefore the new estimations are expected to have a much smaller error margin compared to the estimations given by equation (4.28), which were calculated using only a maximal-ratio combiner.

As it will be shown in the next chapter, calculating the estimated signals $\tilde{X}_k(i)$ using the technique proposed above is much more efficient and reliable than estimating the transmitted signals using only a maximal ratio-combiner as it was the case for calculating $\hat{X}_k(i)$. This procedure is very efficient because it reduces considerably the contribution of the interfering signals to the estimation error and allows the system to increase its spectral efficiency without increasing the system complexity. In fact, by using this estimation technique, it is possible to send N_t independent source signals simultaneously on the same bandwidth without increasing the modulation order and still detect each signal at the receiver and recover it separately while keeping the same data rate. Chapter 5 will present a simulation of the proposed system and study the effects of increasing the spectral efficiency on the transmission power.

4.6 Summary

In this chapter, a new SC-FDMA transmission technique was proposed. This technique can improve the spectrum efficiency of the conventional SC-FDMA system without any important increase in the overall system complexity and without the need for additional bandwidth. It is based on the use of multiple antennas at the receiver with some diversity combining techniques and frequency domain equalization. The first sections of this chapter discussed some important techniques that are used in the proposed system.

Some concepts related to multiple input multiple output (MIMO) transmission were first introduced. As its name implies, MIMO systems use multiple antenna elements at the transmitter and the receiver to send and receive signals. By spreading the total transmit power over the antennas, MIMO systems can achieve a spatial diversity gain that improves communication reliability and/or a spatial multiplexing gain that improves spectrum efficiency. Channel equalization is also a very important step in SC-FDMA transmission used to reduce the effects of fading channels on the transmitted signals. One of the most frequently used channel equalization techniques is called linear equalization. Depending on the optimization criterion that is chosen, linear equalizers can be classified in two main categories: zero-forcing equalizers and minimum mean-square error equalizers. While a zero-forcing equalizer completely eliminates ISI, it causes an important noise enhancement in many applications and can lead to a bad bit error rate (BER) performance in certain cases. On the other side, minimum mean-square error equalization is a more balanced technique, which does not completely eliminate the ISI but instead minimize both the total power of the noise and ISI components in the output.

The second part of this chapter presented a mathematical description of the proposed SC-FDMA system. In fact, it was shown that the proposed technique increases the transmission rate without the need for additional bandwidth or going to a higher modulation order and this is realized by transmitting multiple source signals on the same subcarriers instead of mapping each source signal to a different set of subcarriers as it is currently the case with the current SC-FDMA systems. First of all, a conventional SC-FDMA system with multiple receive antennas and maximal-ratio combining was presented. After that, a detailed description of an SC-FDMA system with subcarrier sharing and multiuser detection was proposed. This modified version of the conventional SC-FDMA can increase the spectral efficiency of the system by transmitting up multiple SC-FDMA symbols on the same subcarrier and using a decorrelation technique at the receiver to recover the transmitted signals. Although this technique can be applied to SC-FDMA systems transmitting N_t source signals on the same subcarriers, each increase in channel capacity would require the system to use more power at the transmitter, as it will be shown in the next chapter. Therefore, one has to make a trade-off between channel capacity and transmission power.

Chapter 5

System Model and Simulations

5.1 Introduction

The previous chapter presented the mathematical description of a new technique that allows a conventional SC-FDMA system, which can usually transmit only one modulation symbol per subcarrier, to transmit more than one modulation symbol from different users on the same subcarrier. The main advantage of this technique is that it can considerably improve the spectrum efficiency of the system by allowing more source signals to be transmitted simultaneously without increasing the number of subcarriers or going to a higher modulation order. In this chapter, several simulations of SC-FDMA systems are presented in order to evaluate their performances and make comparative studies.

Sections 5.2 starts by giving a general overview of the SC-FDMA system model that was used for computer simulations. It presents two channels models described by 3GPP technical specifications and make a quick comparison between them. This section also describes the transmission model by presenting the main blocks of the SC-FDMA link level simulator. Finally, the main simulation assumptions and parameters are given at the end of the section.

Section 5.3 presents link level simulations of several SC-FDMA systems for different cases and scenarios. It first starts by simulating a conventional SC-FDMA system (with different users occupying different sets of subcarriers) using a localized as well as an interleaved subcarrier mapping mode. The objective is to study and compare the performance of these two subcarrier mapping techniques. This section also studies the effect of increasing the number of antennas at the receiver on the overall system performance.

Section 5.4 provides a link level simulation of a spectrally efficient SC-FDMA system

which can transmit modulation symbols from two different users on the same set of subcarriers using the multiuser detection technique presented in the previous chapter. The first four scenarios in this section describe different alternatives to add a third user to an SC-FDMA system while keeping the same performance as a conventional system with only two users. In the last scenario, a fourth user is added to the system. The main objective is to study the effect of adding more users to the system on the overall performance. While SC-FDMA systems in section 5.4 can transmit up to two modulation symbols on the same subcarrier, the SC-FDMA systems presented in section 5.5 can handle up to three source symbols on a single subcarrier, resulting in improved spectral efficiency. In fact, the scenario presented in this section simulates an SC-FDMA system with six independent users where every three users are transmitted on the same set of subcarriers. The performance of this system is compared with the conventional system presented in section 5.3, which can only accommodate two users at the same time. One important thing to mention is that although all simulations are realized on a conventional SC-FDMA system with initially two users per SC-FDMA symbol, the same technique can be applied to any SC-FDMA system with any number of users per SC-FDMA symbol without any additional operations or increase in complexity.

5.2 Overview of the SC-FDMA System Model

In order to have a realistic link level simulation, the SC-FDMA system should be modeled as accurately as possible. This section provides a detailed description of the SC-FDMA model that was used for Matlab simulations. It starts by describing the multipath channel as modeled by 3GPP LTE and presents the channel model that was chosen for simulation. It also presents the transmission model and summarizes the simulations assumptions and parameters. It must be noted that all these models and assumptions are in accordance with the 3GPP LTE technical specifications [23].

5.2.1 Channel Model

For the multipath channel, let's consider first the ITU Pedestrian A and ITU Vehicular A channels [23] with additive white Gaussian noise (AWGN). The delay profiles of these two channels are summarized in tables 5.1 and 5.2. As it can be noticed, the pedestrian channel has a relatively short channel delays while the vehicular channel has longer delays. This is the case because the pedestrian channel assumes that the mobile terminal

is moving at around 4 km/h while the vehicular channel assumes much higher speeds (approximately 100 km/h). Consequently, the vehicular channel has much more severe selectivity in the frequency domain as shown in figures 5.1 and 5.2, which illustrates the frequency domain responses of these two channels.

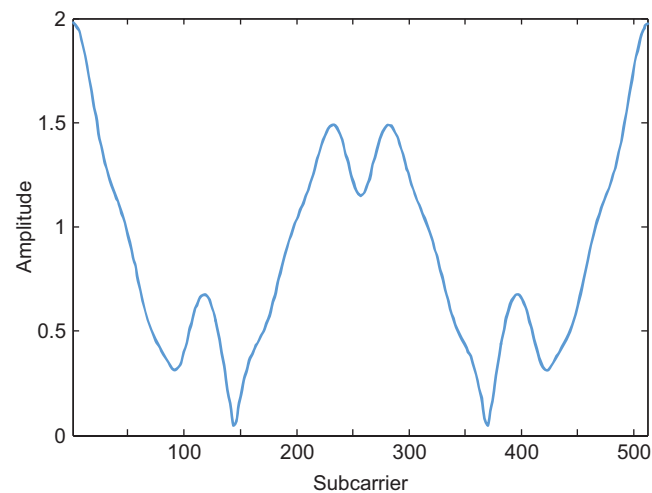


Figure 5.1: Frequency domain channel response of ITU Vehicular A channel.

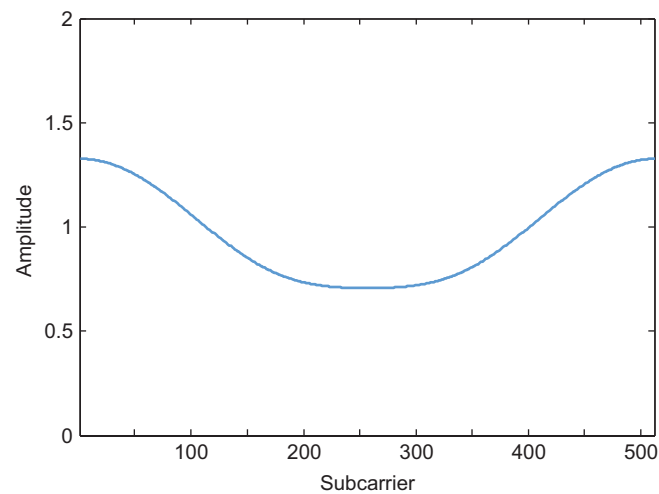


Figure 5.2: Frequency domain channel response of ITU Pedestrian A channel.

Channel Model		Path 1	Path 2	Path 3	Path 4	Path 5	Path 6
Ped. A	Delay (nsec)	0	110	190	410	—	—
	Power (dB)	0	-9.7	-19.2	-22.8	—	—
Veh. A	Delay (nsec)	0	310	710	1090	1730	2510
	Power (dB)	0	-1.0	-9.0	-10.0	-15.0	-20.0

Table 5.1: Channel delay profiles of ITU Pedestrian A and Vehicular A channels.

System bandwidth	5 MHz
Sampling rate	5 mega-samples per second
Data modulation format	16QAM
Pulse shaping	None
Cyclic prefix	20 samples
Transmitter IFFT size	64
SC-FDMA input block size	32 symbols
SC-FDMA input FFT size	32
Channel estimation	Perfect
Channel coding	None
Detection	Hard decision
Number of iterations	$> 10^3$
Number of antennas at the receiver	4

Table 5.2: Simulation assumptions and parameters.

5.2.2 Transmission Model

Figure 5.3 shows the flow of the link level simulation for the SC-FDMA system. The input bits to be transmitted are mapped onto a constellation of complex symbols using 16QAM modulation. The M -point DFT operation converts these complex symbols in to precoded complex symbols. The precoded symbols are then mapped on subset of different allocated subcarriers per user, i.e., M out of N subcarriers in which the total system bandwidth is divided. The mapping can be interleaved FDMA (IFDMA), which is an equally distributed subcarrier mapping, or localized FDMA (LFDMA). At the receiver, after removing cyclic prefix, an N -point DFT operation converts the received signal in to frequency domain in order to perform subcarrier de-mapping and equalization. After going back to time domain using an M -point IDFT, the generated signal is given to the detector. The outputs of the detector are the estimated input bits.

5.2.3 Simulation Assumptions and Parameters

Table 5.2 summarizes the simulation parameters and assumptions used for all the simulations in this chapter, except when specifically mentioned. The system's sampling rate is set to 5 mega-samples per second, the channel delay was quantized to the nearest multiples of 200 nsec ($= 1/5 \times 10^6$). The simulated system employs 16-QAM modulation and 64 symbol FFT blocks with a Pedestrian A channel and 4 antennas at the receiver. Also, the length of the cyclic prefix is chosen as $4\mu s$ (20 samples), considering the maximum channel delay of the Vehicular A channel, which is $2.51\mu s$ and a hard decision detector is used at the receiver. Furthermore, it assumed that the two subcarrier mapping schemes (i.e. IFDMA and LFDMA) operate with static scheduling (i.e., no channel-dependent scheduling). The SC-FDMA system performance is evaluated by calculating the bit error rates (BER) for different energy per bit to noise power spectral density ratios (E_b/N_0).

5.3 Link Level Simulation of Conventional SC-FDMA

This section presents a simulation of the conventional SC-FDMA system presented in section 4.5 of the previous chapter. In this configuration, every source signal occupies a different set of subcarriers. The system uses a single transmitter with multiple receive antennas and a maximal-ratio combiner (MRC) is used at the receiver in order to combine all the received signals from different channels and generate an output that should be as close as possible to the original input. The system is realized for LFDMA and IFDMA

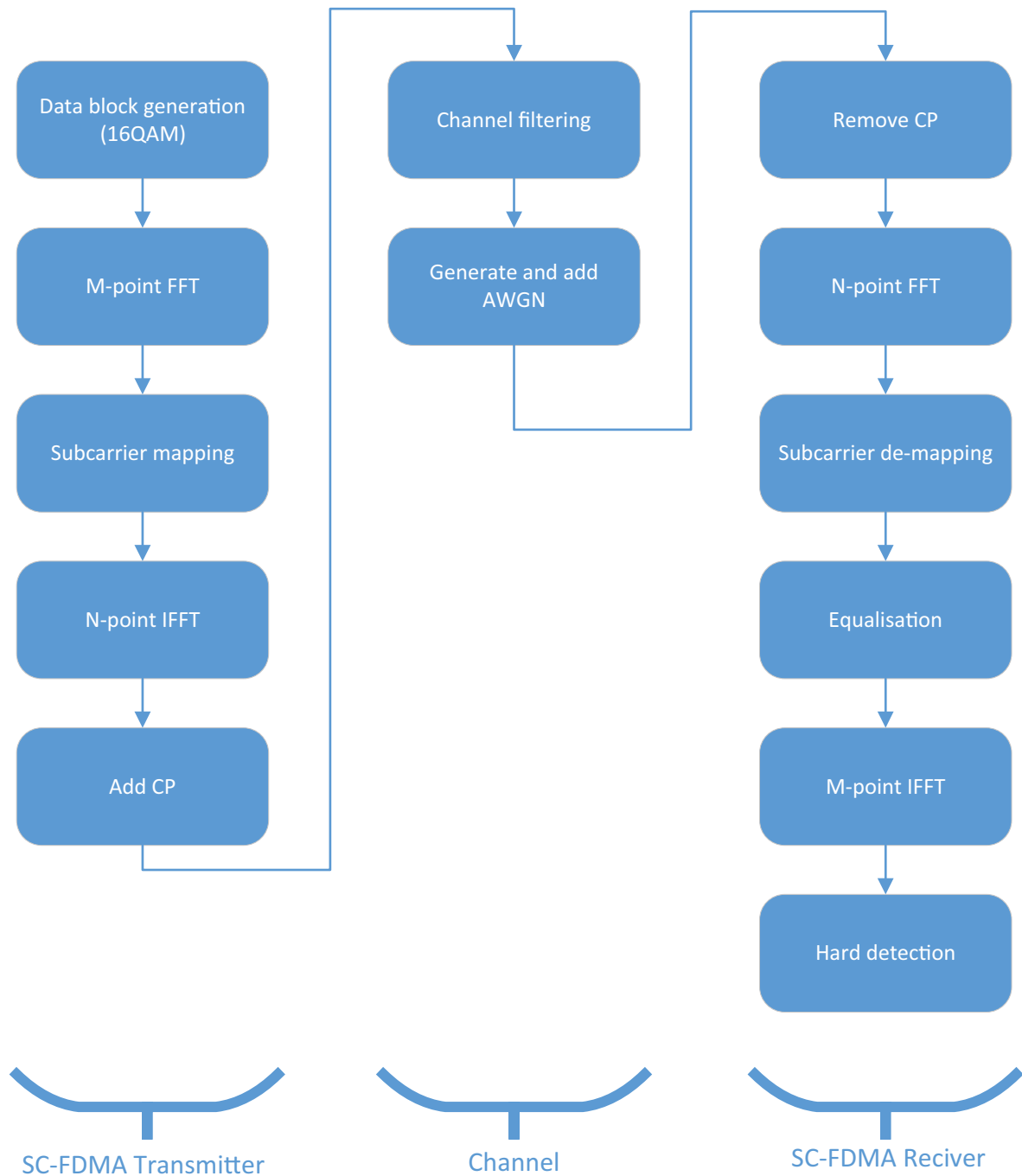


Figure 5.3: Block diagram of SC-FDMA link level simulator.

sub-carrier mapping and for different numbers of receive antennas in order to study the effect of these mapping schemes as well as the number of antennas at the receiver on the overall system performance.

5.3.1 Localized Mode

In localized subcarrier mapping, the frequency domain modulation symbols of each source signals are assigned to mutually exclusive sets of adjacent subcarriers and the transmitter assigns zeroes to the remaining subcarriers. The simulated system uses a single transmitter and 4 receive antennas with two users per SC-FDMA block. Each user is allocated 32 adjacent subcarriers out of the 64 available. Figure 5.4 illustrates the subcarrier mapping that is used in this configuration for the simple case where there is a total of 8 subcarriers with 4 allocated to each user. In this mode, it is expected that the system does not have a good frequency diversity given that the subcarriers in this mode are not spread all over the bandwidth. However, this system should be very robust to frequency offsets.



Figure 5.4: Localized subcarrier mapping for $N = 8$ total subcarrier and $M = 4$ subcarrier per user.

Figure 5.5 gives the BER performance of the system using maximal ratio combining and 4 receive antennas for the Vehicular A Channel. As shown in this figure, the two curves of BER vs. E_b/N_0 corresponding to users 1 and 2 are practically the same which means that the SC-FDMA system provides the same overall performance to each user independently of the location of the assigned subcarriers. Also, the curve indicates that for a typical value of $BER = 10^{-3}$, the required E_b/N_0 is approximately 17.5 dB.

Figure 5.6 shows the BER vs. E_b/N_0 for the same system but this time using a Pedestrian A channel. It can be seen that in order to provide a BER of 10^{-3} , the SC-FDMA system needs an $E_b/N_0 = 12$ dB, which is much less than the required power to operate at the same BER when the mobile terminal is moving at a vehicle speed. This difference in performance is justified by the fact that the frequency selectivity is much severe in the case of the vehicular channel due to the fast moving nature of the transmitter. However, the system performance of user 1 and 2 is practically the same. It

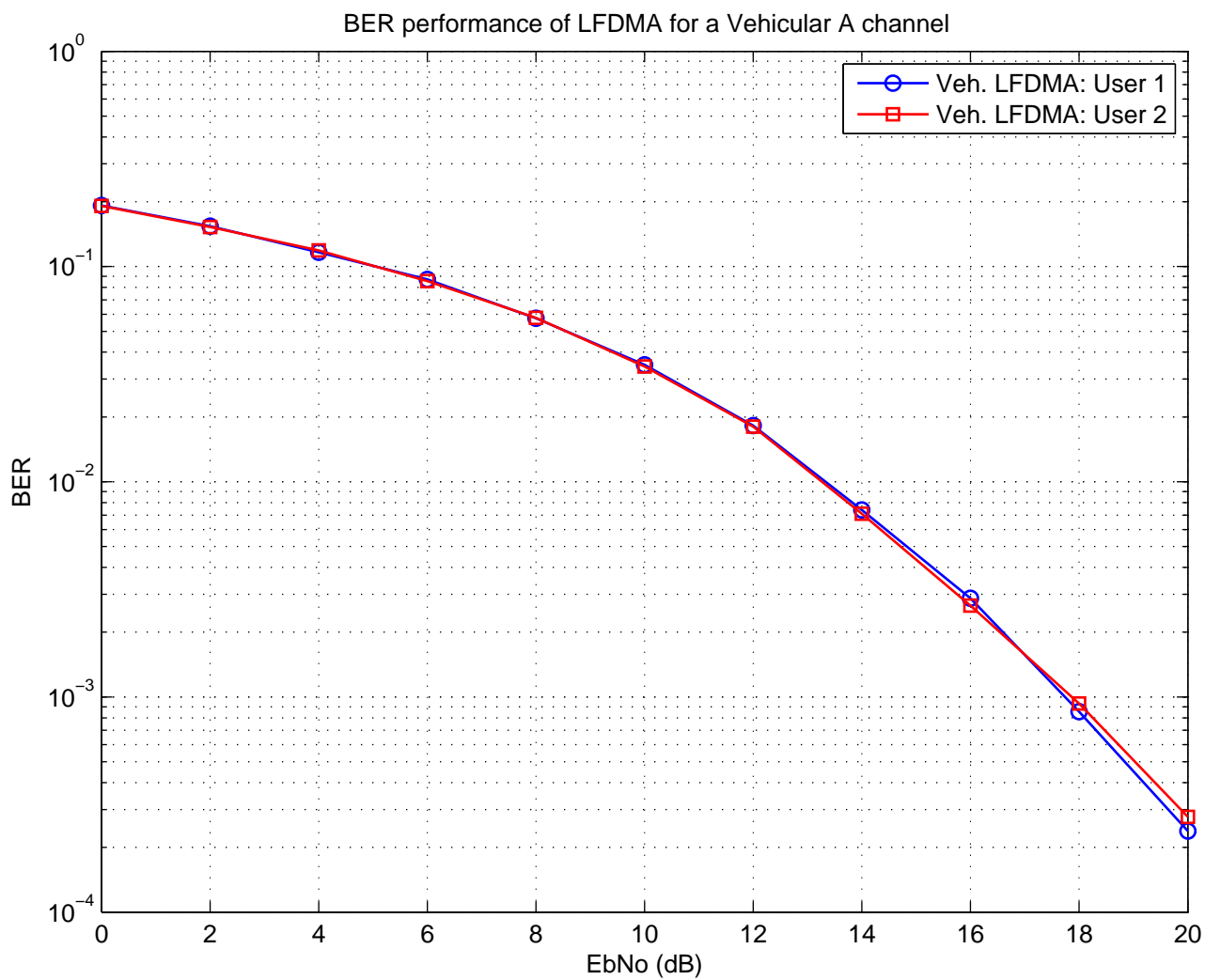


Figure 5.5: BER performance of conventional SC-FDMA in localized subcarrier mapping mode for a Vehicular A channel.

is important to mention that the BER vs. E_b/N_0 curves for users 1 and 2 are very similar for the Pedestrian A channel as well as the Vehicular A channel because the channels frequency responses of these two channels are symmetric as it was shown in figures 5.1 and 5.2. Therefore, when the spectrum is divided into two sets of adjacent subcarriers, the source signals that are mapped to these subcarriers undergoes very similar frequency selectivity and the system performs in a similar manner for the two users. This is a special case because the channels frequency responses are symmetric and the spectrum is divided into two equal parts. However, the performance of LFDMA usually varies depending on which part of the spectrum the transmitted signals occupies. This is not the case of IFDMA as it will be shown later in this section.

5.3.2 Interleaved Mode

In the interleaved FDMA (IFDMA) mode, the subcarriers allocated to the source signal are equally spaced across the entire bandwidth. Figure 5.7 illustrates an example of this mapping mode with $N = 8$ subcarriers and $M = 4$ allocated to each user. It is expected that the SC-FDMA system operating in this mode will have good frequency diversity given that the subcarriers allocated to each source signal are spread all over the bandwidth.

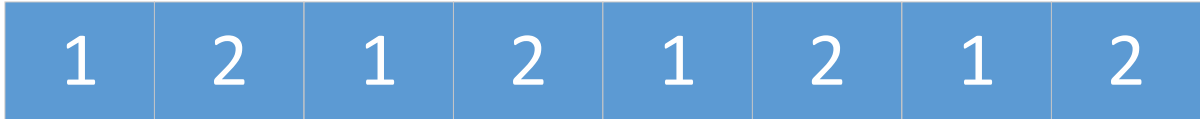


Figure 5.7: Interleaved subcarrier mapping for $N = 8$ total subcarrier and $M = 4$ subcarrier per user.

As it was the case for LFDMA, the simulated system has a single transmitter and 4 receive antennas. It can accommodate two users with 32 subcarriers each for a total of 64 subcarriers per SC-FDMA block. A maximal ratio combiner is used at the receiver to recover the transmitted signals. Figure 5.8 shows the system performance curve for the case of Vehicular A channel. As it can be seen, the E_b/N_0 is approximately 16.5 dB for a BER of 10^{-3} and the system performs similarly for the two users.

Figure 5.9 shows the BER vs. E_b/N_0 curve of the same system but this time using a Pedestrian A channel. It can be seen that at $E_b/N_0 = 11$ dB, the BER is approximately 10^{-3} . Once again, it is very clear that the SC-FDMA system operating on a pedestrian channel has a much better performance than the system with a vehicular channel and

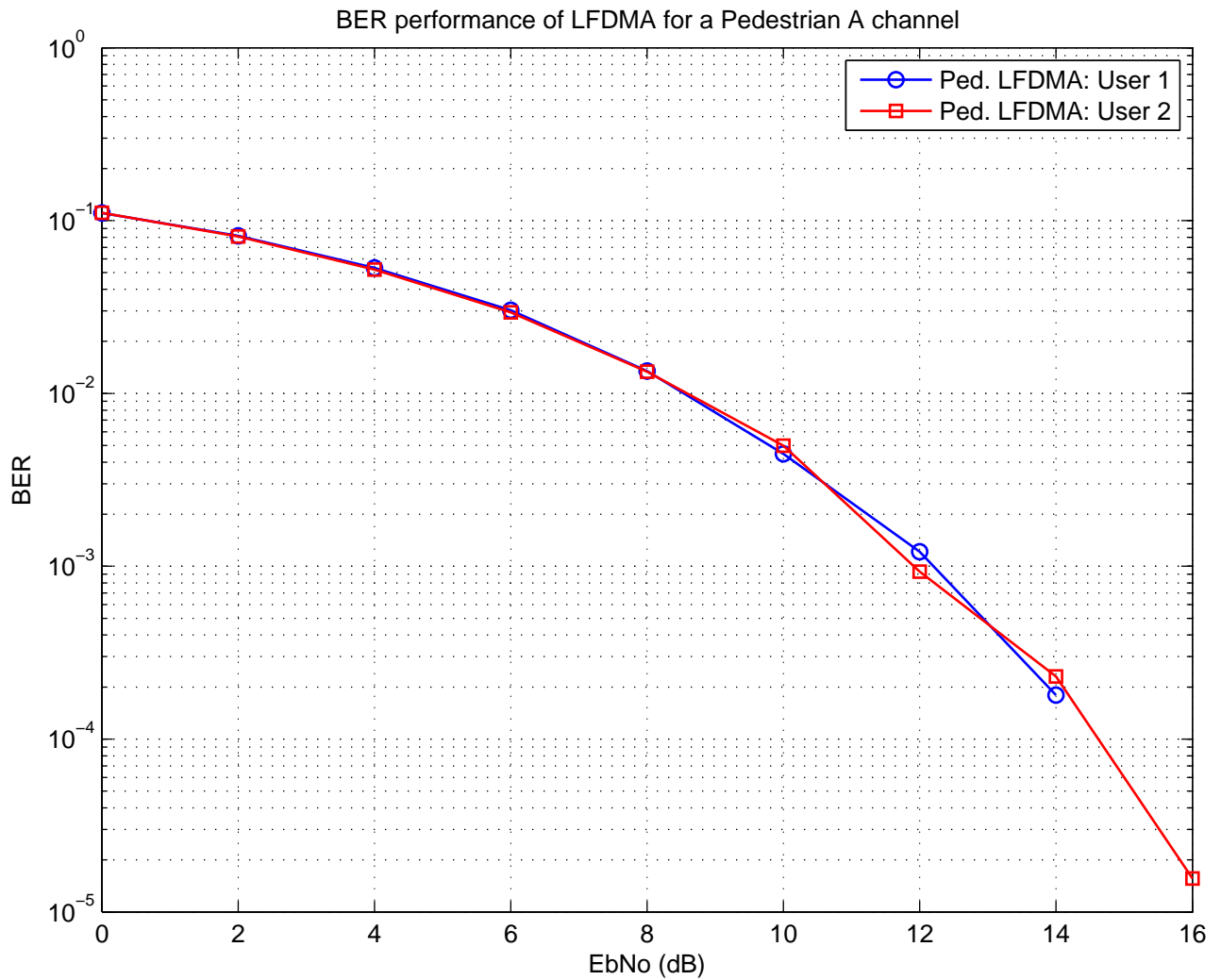


Figure 5.6: BER performance of conventional SC-FDMA in localized subcarrier mapping mode for a Pedestrian A channel.

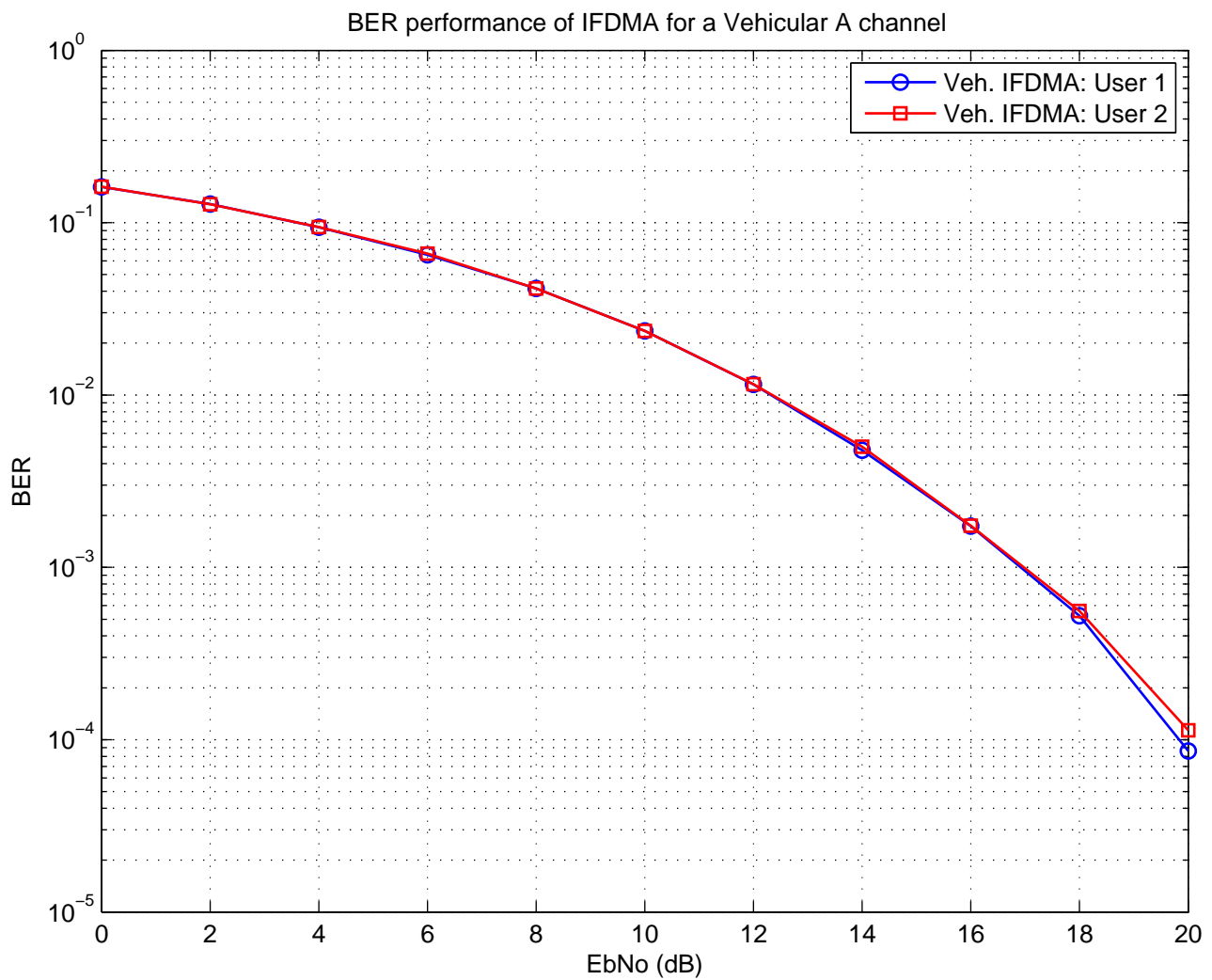


Figure 5.8: BER performance of conventional SC-FDMA in interleaved subcarrier mapping mode for a Vehicular A channel.

this is due to the severe frequency selectivity found in the second system. Also, the performance curves of user 1 and 2 are practically the same and due to the fact that the corresponding subcarriers are spread similarly over the entire bandwidth.

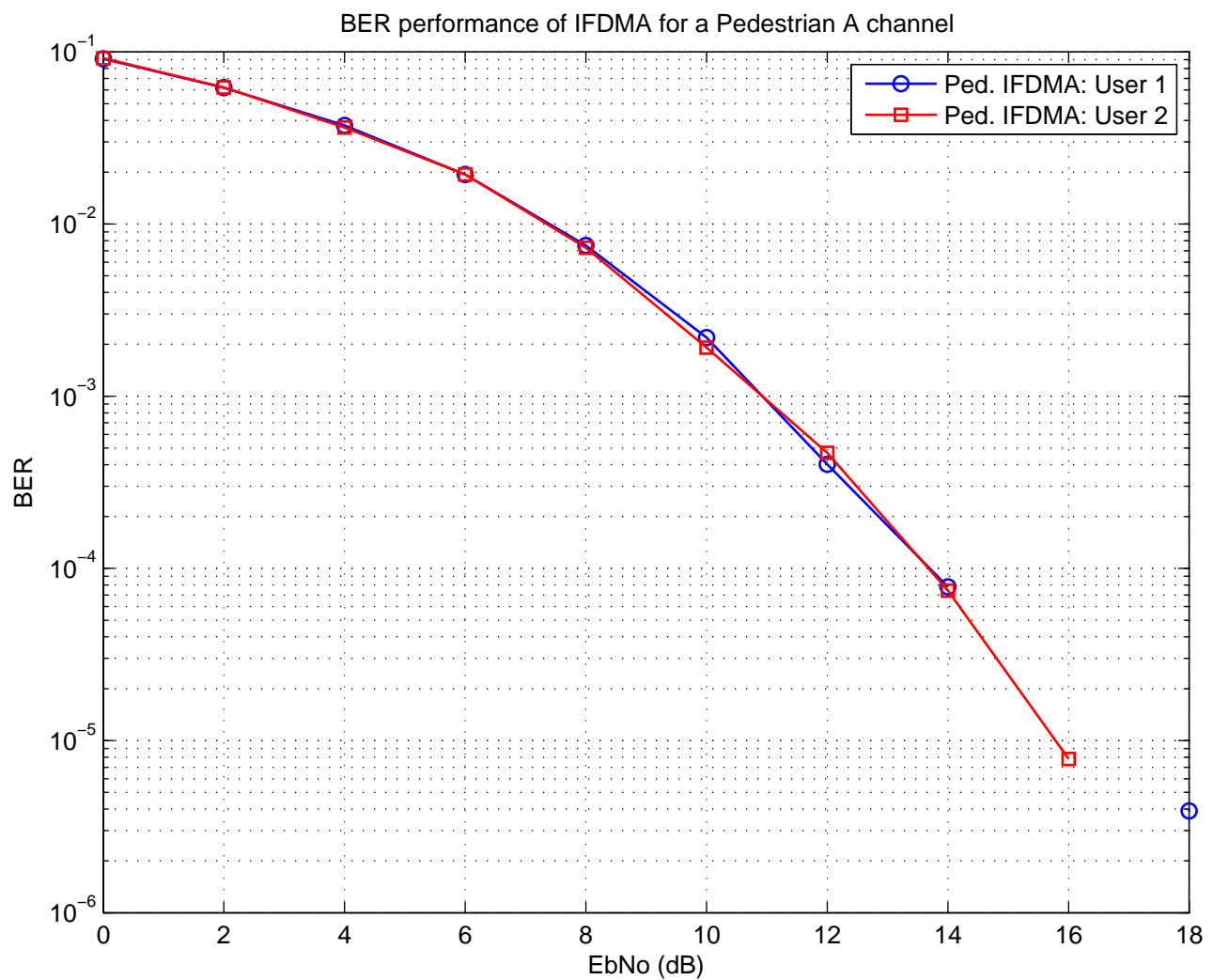


Figure 5.9: BER performance of conventional SC-FDMA in interleaved subcarrier mapping mode for a Pedestrian A channel.

5.3.3 Comparison Between Localized and Interleaved Subcarrier Mapping

Figure 5.10 shows the BER performance of two SC-FDMA systems using LFDMA and IFDMA subcarrier mapping for a pedestrian channel. It can be clearly seen that the system using interleaved mapping has a better performance than the system with localized mapping and this is due to the fact that IFDMA provides a good frequency diversity to the system since the source signals are spread over the entire bandwidth. On the other side, LFDMA performance may vary significantly depending on the subband location of the transmitted signal. In order to understand the effect of the subcarrier location on the overall system performance, let's consider an SC-FDMA system with 512 total subcarriers and 16 subcarriers per user in the case of a Pedestrian A channel. As it is shown in figure 5.11, the channel frequency response may vary significantly depending on the location of the assigned subcarriers. For example, assigning the subband 0 (subcarriers 1 to 16) to a user may give a very different performance than assigning subband 15 (subcarriers 240 to 256) to the same user and this is because the channel is not perfect and its frequency response is not constant over the entire bandwidth.

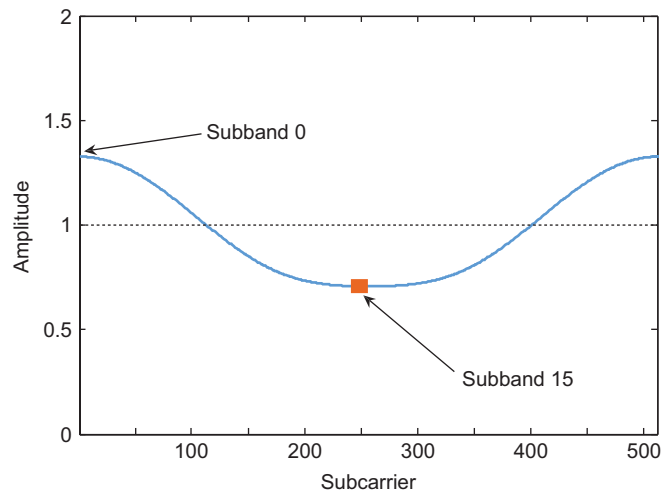


Figure 5.11: Illustration of localized subbands 0 and 15 for a Pedestrian A channel.

Figure 5.12 shows the BER performance of this SC-FDMA system operating in localized mode. It can be seen that the performance varies depending on which part of the spectrum it occupies. In localized subband 0, the channel gain is higher than the average and accordingly the BER performance is much better. In localized subband 15, the

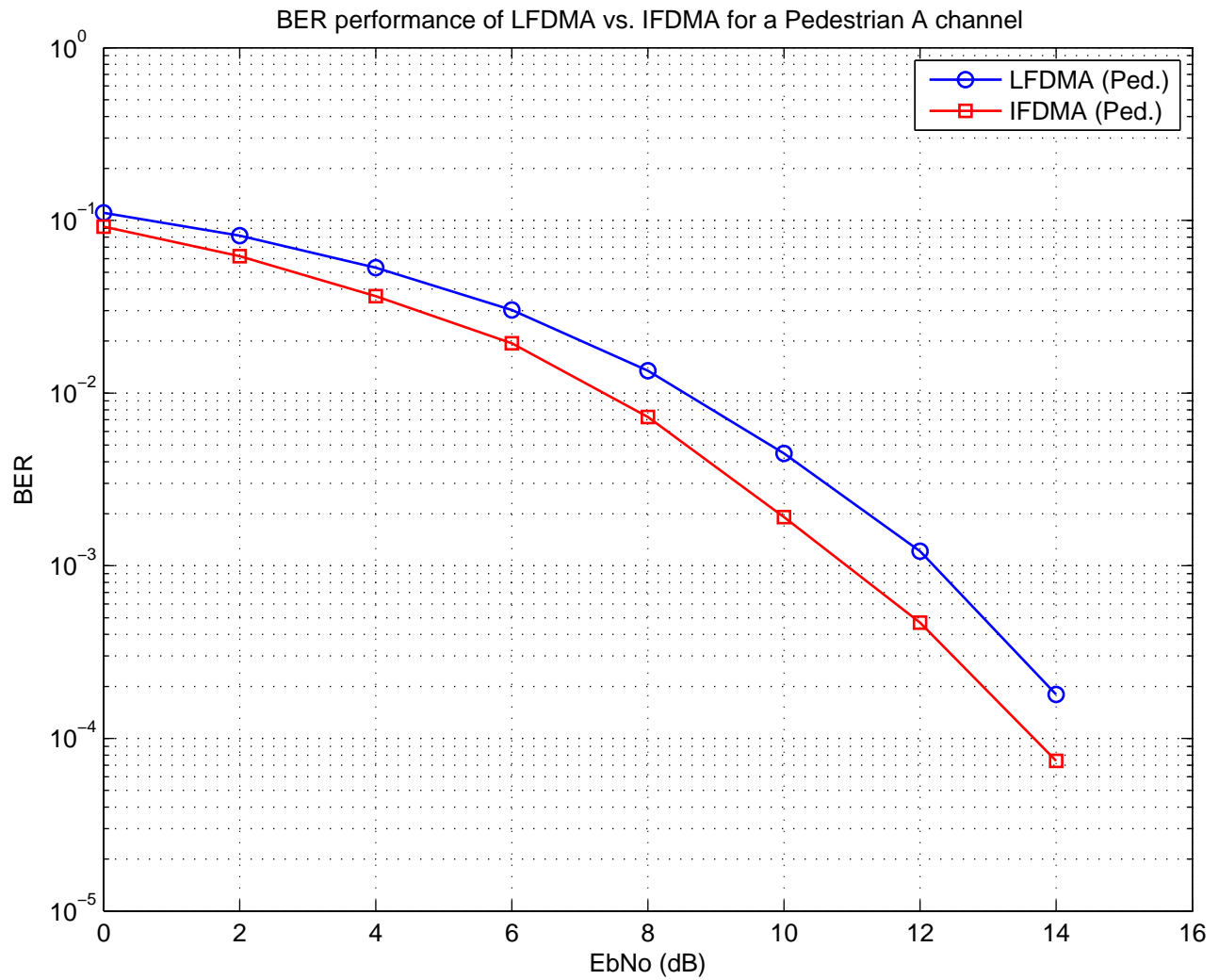


Figure 5.10: BER performance of LFDMA vs. IFDMA for a Pedestrian A channel.

channel gain is lower and the performance is less accordingly. The effect of the subband location on the system performance is not present in the case of interleaved mapping and this is because in this mapping mode, every user is assigned a set of subcarriers that are spread over the entire bandwidth. Therefore, the overall performance is the same for all the users independently of which subcarriers are assigned to everyone. Figure 5.13 shows the BER performance of the same SC-FDMA system but this time using IFDMA. As it can be seen, the system performance does not depend on the subband location. It is important to mention that it is for figures 5.12 and 5.13 only that the the simulated SC-FDMA system has 512 total subcarriers and 16 subcarriers per user. For all the other simulations, the total number of subcarriers is 64 from which 32 are assigned to each user. In fact, it was decided to increase the SC-FDMA subcarriers size and decrease the number of subcarriers assigned to each user to better see the effect of frequency selectivity on the system's performance.

In summary, localized subcarrier mapping lacks frequency diversity and it should use channel-dependent scheduling as discussed in chapter 3 to overcome this limitation. On the other hand, with multipath channels, the performance of interleaved subcarrier mapping does not depend on the location of the subband because of the inherent frequency diversity.

5.3.4 The Effect of Increasing the Number of Receive Antennas on the System's Performance

Equation (4.15) in chapter 4 suggested that the performance of an SC-FDMA system using maximal-ratio combining at the receiver could be significantly improved by increasing the number of antennas at the receiver. Figure 5.14 shows a simulation of an SC-FDMA system operating with interleaved (IFDMA) subcarrier mapping. The BER performance versus E_b/N_0 is plotted for different numbers of receive antennas. As expected from the derived equations in chapter 4, this figure shows that the performance of the SC-FDMA system is considerably improved when the number of receive antennas is increased. In fact, with only 2 antennas at the receiver, an E_b/N_0 of approximately 17 dB is required in order to have a BER of 10^{-3} . However, with 10 antennas at receiver, the same SC-FDMA system requires only 6 dB in order to achieve the same bit error rate. This confirms the conclusion derived from chapter 4, which suggests that the performance of a maximal-ratio combiner depends considerably on the number of antennas at the receiver.

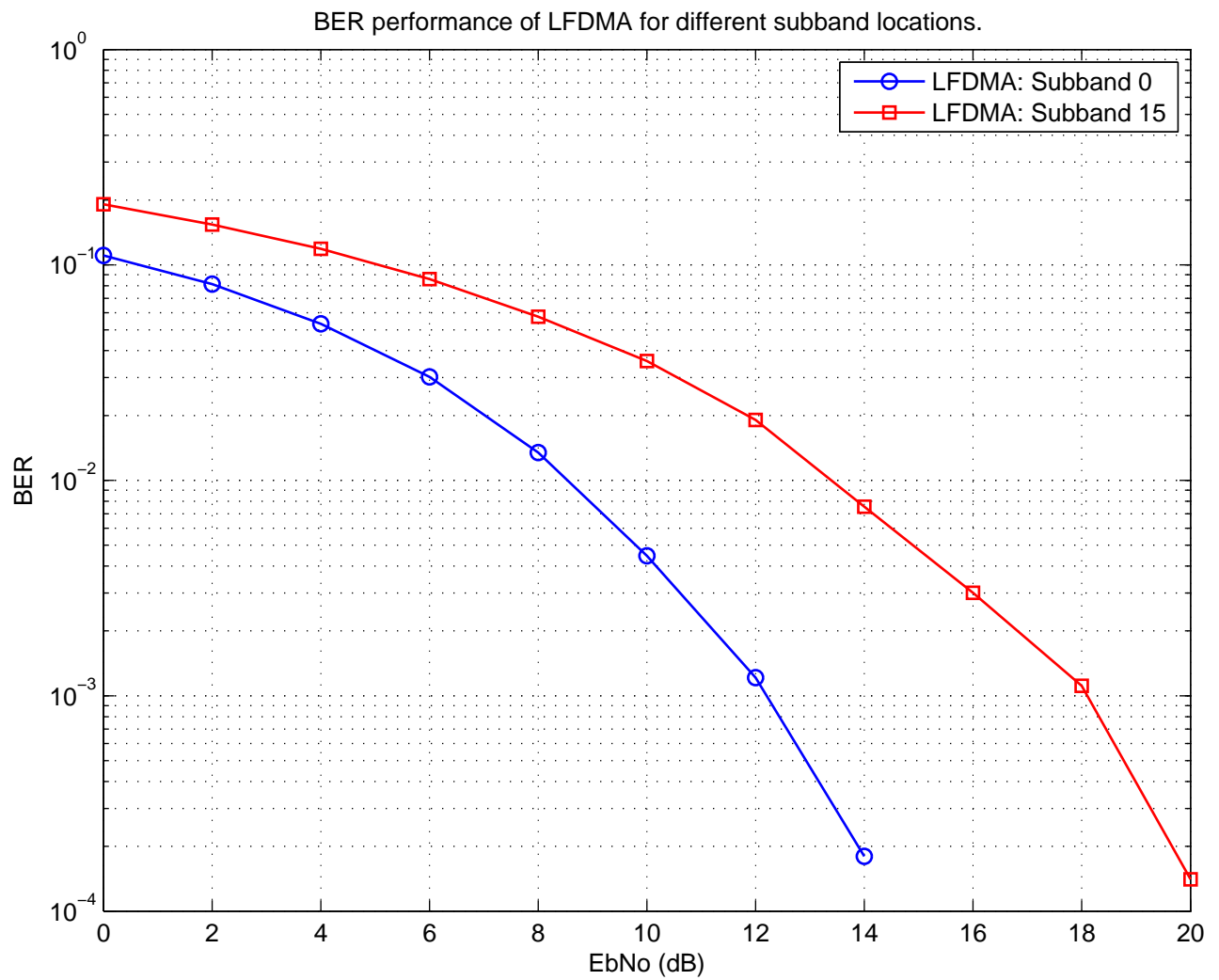


Figure 5.12: BER performance of LFDMA for different subband locations.

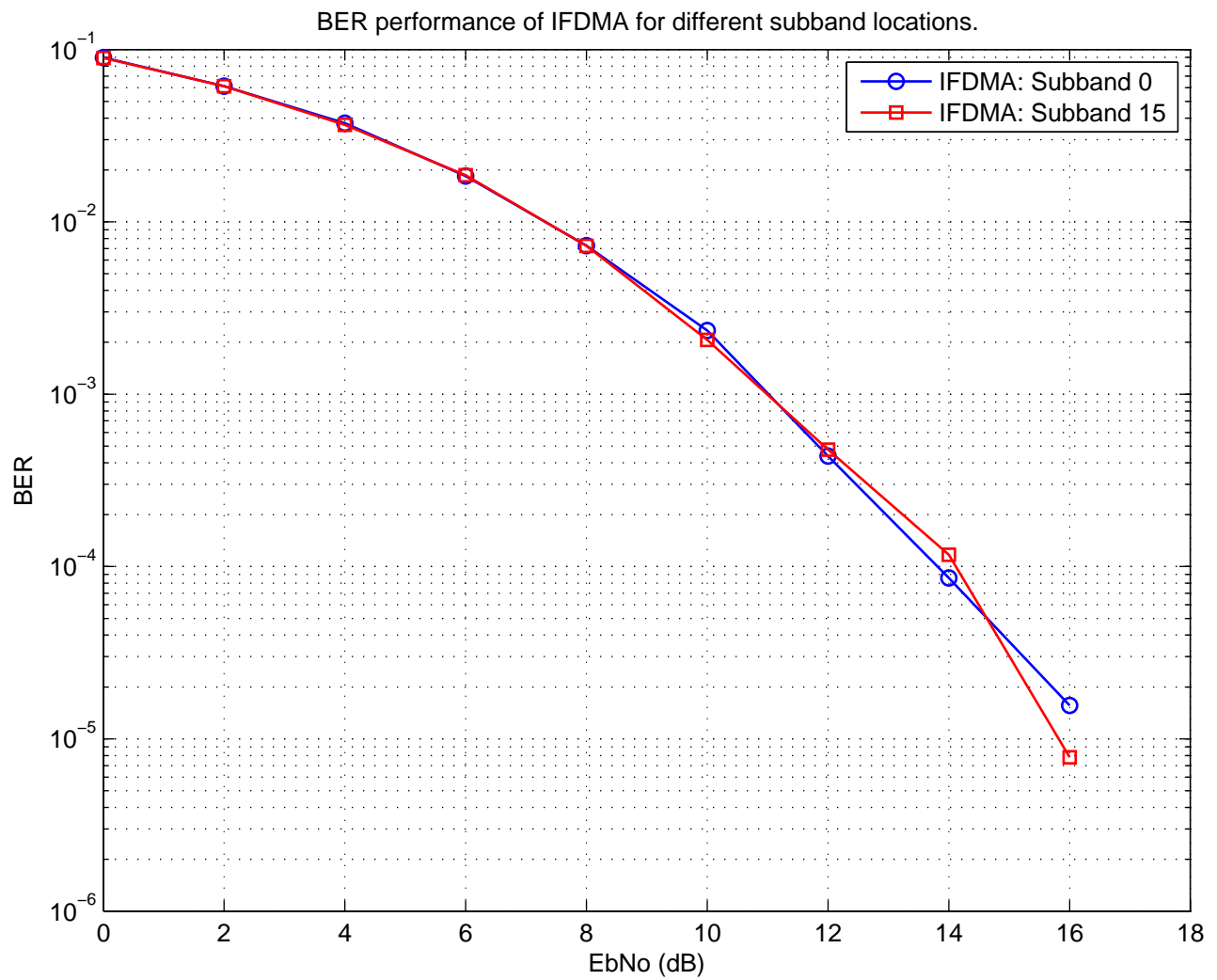


Figure 5.13: BER performance of IFDMA for different subband locations.

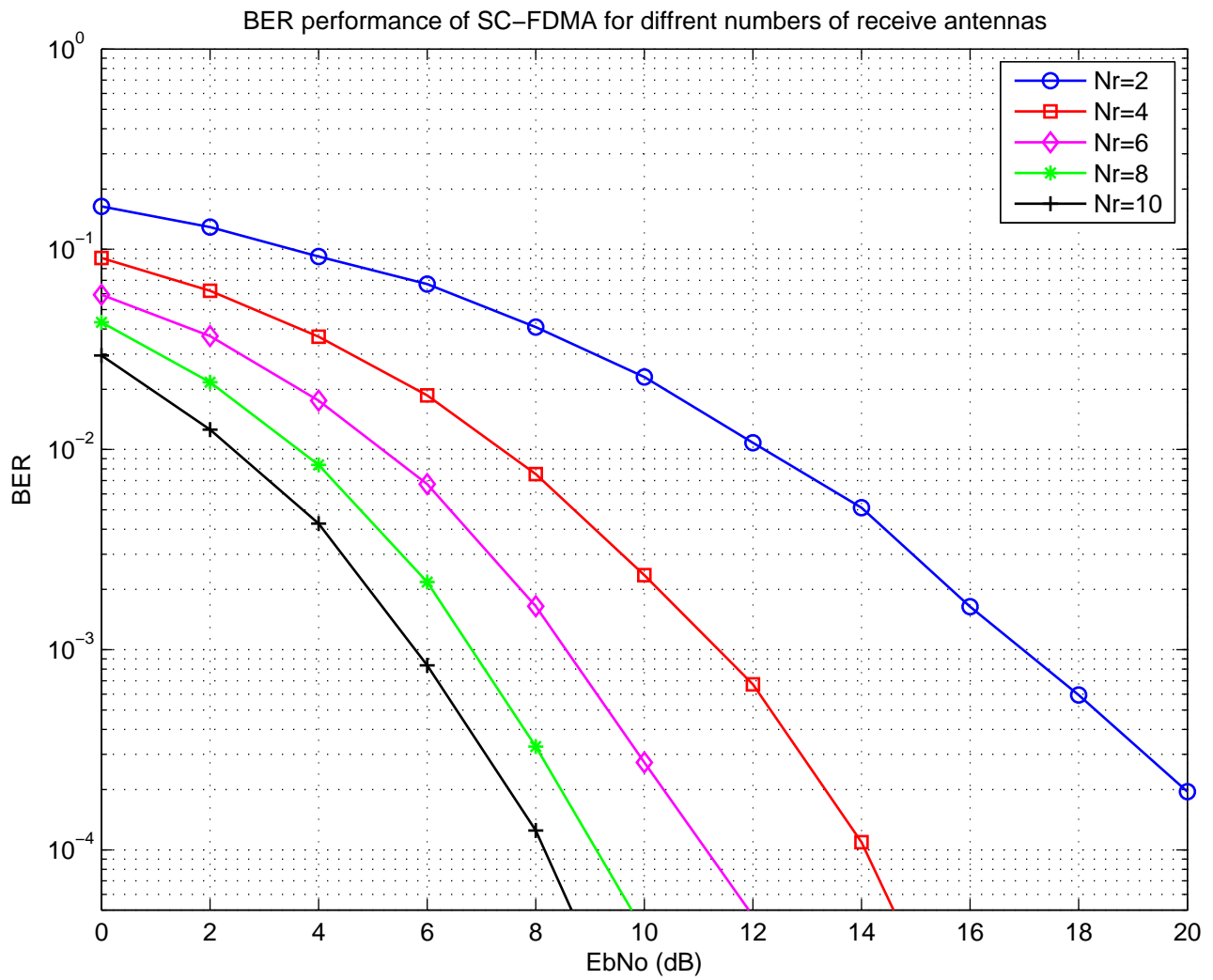


Figure 5.14: BER Performance of an SC-FDMA system using different numbers of receive antennas N_r .

5.4 Link Level Simulation of Spectrally Efficient SC-FDMA with two Transmit Symbols on the same Subcarrier

This section studies the case where an SC-FDMA system is operating at its full capacity (i.e. all the subcarriers are occupied) and a new user arrives and wants to start transmitting. With the current SC-FDMA specifications, it is possible to accommodate the new user by redistributing the subcarriers between all the users. For example, let's consider the case of a system operating with 64 subcarriers per SC-FDMA symbol. If initially there are two users transmitting, the system will allocate 32 subcarriers to each user. However, if another user comes, the system accommodates the three users by reassigning the subcarriers in such a way that two users transmit on 32 subcarriers (16 per user) and the third user transmits on 32 subcarriers. It is important to mention that every time a new user comes, the system has to split the subcarriers allocated to one of the users by two. It always has to split the subcarriers by two because it is more efficient for taking the discrete Fourier transform (DFT). Now, given that the number of subcarriers allocated to every source signal has decreased, the system increases the modulation order in order to keep the same transmission rate. For example, a source signal transmitting on 32 subcarriers with QPSK modulation will have to go to 16QAM modulation if it is assigned only 16 subcarriers in order to keep the same data rate.

This subcarrier mapping technique mentioned above is straightforward. However, it is not always possible in practice because going to a higher modulation order usually comes at the price of increasing the BER. Also, the system is limited by the 3GPP LTE specifications, which indicate that the maximum allowed modulation order for SC-FDMA transmission is 64QAM. This section presents an alternative solution where two users are assigned the same set of subcarriers and a multiuser detection technique as described in section 4.5 is used to recover the transmitted source signals. This technique allows the SC-FDMA system to accommodate multiple users while keeping the same data rate without increasing the bandwidth or going to a higher modulation order. In other words, if a source signal is being transmitted on 32 subcarrier with 16QAM modulation and another user comes, the SC-FDMA system will allocate the same 32 subcarriers to both users and the two of the them will keep using the same modulation technique without decreasing their data rate. This new transmission technique was explained in details in chapter 4. This section presents the simulation of different SC-FDMA systems

in order to study the performance of the proposed technique for different transmission scenarios.

5.4.1 First Simulation Scenario

The first simulated scenario is that of an SC-FDMA system with three users where the third user transmits on the same subcarriers as the second one. In this simulation, each SC-FDMA symbol consists of 64 subcarriers where 32 subcarriers are allocated to user 1 and the other 32 are allocated to users 2 and 3 jointly. Figure 5.15 illustrates an example of this mapping scheme for $N = 8$ subcarriers per SC-FDMA symbol.



Figure 5.15: An example of the first scenario subcarrier mapping for $N = 8$ total subcarrier and $M = 4$ subcarrier per user.

The system uses the technique described in section 4.5.2 in order to recover the transmitted signals. In fact, it applies maximal-ratio combining (MRC) followed by zero-forcing (ZF) equalization in order to separate the modulation source symbols coming from different users. This MRC+ZF technique is applied to all the subcarriers including the ones that contain data from user 1 only. Figure 5.16 shows the BER curves of this system as well as the conventional SC-FDMA where there are only two users occupying different sets of subcarriers mapped using the interleaved mode (IFDMA) as discussed in section 5.3.2.

At a typical BER of 10^{-3} , it can be seen from figure 5.16 that the difference between the two systems in terms of E_b/N_0 is approximately 2 dB. Therefore, it is possible to add a third user to an SC-FDMA system using the technique described in the first scenario. However, the E_b/N_0 should be increased by approximately 2 dB comparatively to the conventional SC-FDMA in order to keep the same BER while accommodating three users instead of only two.

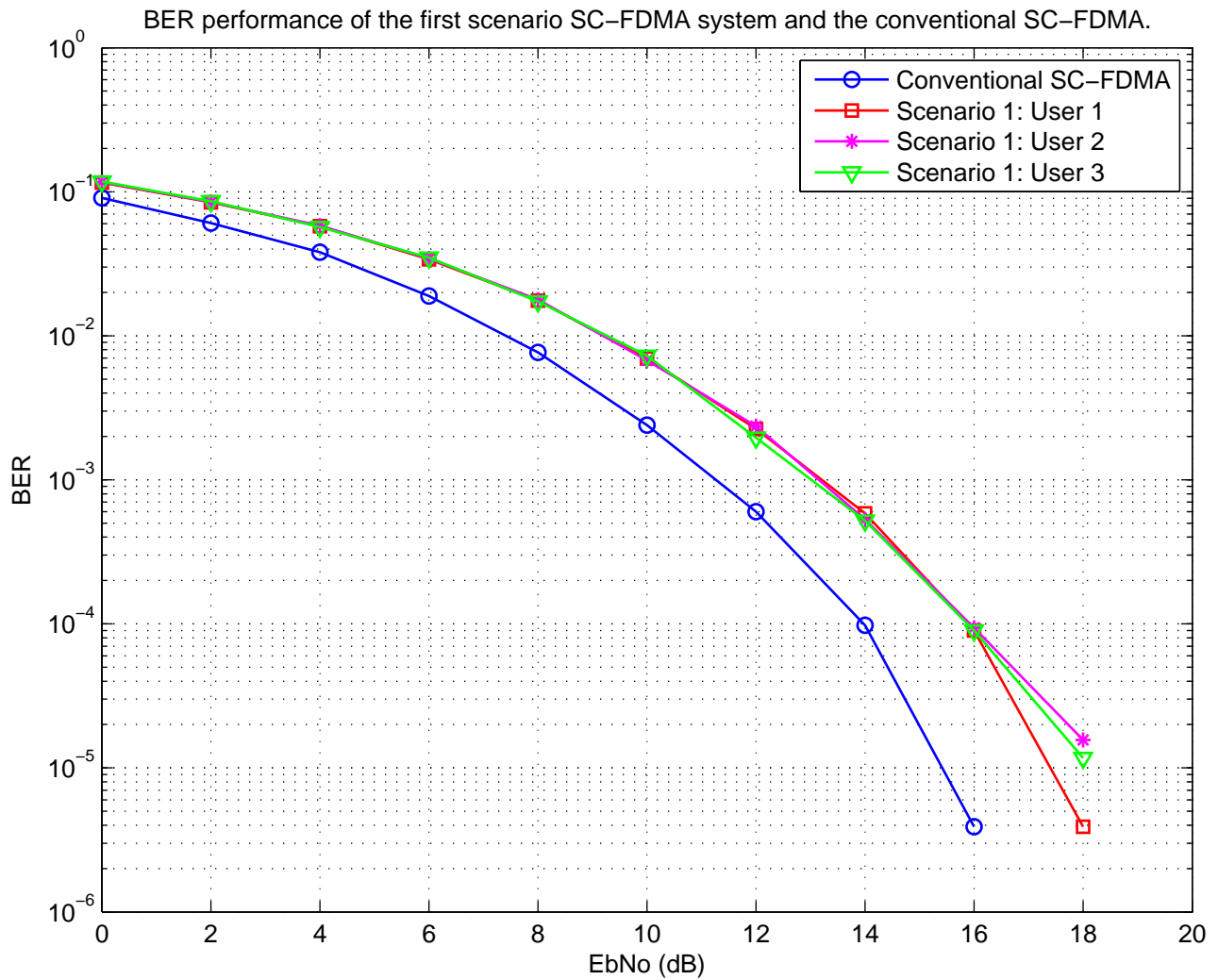


Figure 5.16: BER vs. E_b/N_0 of the first scenario SC-FDMA system and the conventional SC-FDMA.

5.4.2 Second Simulation Scenario

As discussed in chapter 4, the method of maximal-ratio combining followed by zero forcing (MRC+ZF) is very efficient when there is more than one source signal on the same set of subcarriers given that it has the ability to eliminate the interference coming from the other users. However, this method also increases the noise level in the system. Therefore, for the cases where there are no interfering signals, using a maximal-ratio combiner only (as it is the case for conventional SC-FDMA) has a better performance than using MRC+ZF. The SC-FDMA system simulated in this scenario takes advantage of this fact by applying MRC+ZF only on the subcarriers where there are several source signals. For the subcarriers that are allocated to only one source signal, it uses the same method of maximal-ratio combining as for conventional SC-FDMA. Applying this method should decrease the noise level in the system and hence, give a better performance than the SC-FDMA system presented in section 5.4.1. Figure 5.17 illustrates an example of the mapping scheme used in this scenario with $N = 8$ total subcarriers per SC-FDMA symbol. As it can be seen, this mapping scheme is exactly the same as the mapping presented in the previous scenario. However, the main difference this time is that the transmitted signals are recovered using MRC+ZF for the subcarriers containing two source signals and using only MRC for the subcarriers that contain only one source signal. This was not the case for the previous scenario where MRC+ZF method was applied to all the subcarriers.

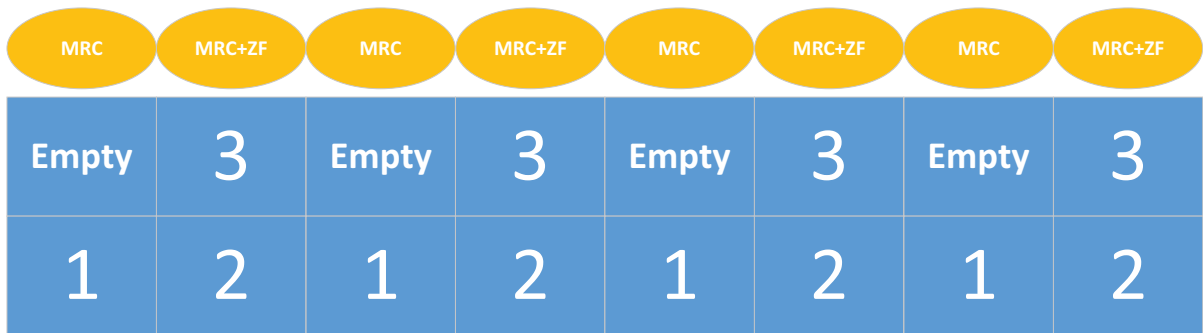


Figure 5.17: An example of the second scenario subcarrier mapping for $N = 8$ total subcarrier and $M = 4$ subcarrier per user.

Figure 5.18 shows the BER curve of the SC-FDMA system simulated in scenario 1 vs. scenario 2. As it can be seen from this figure, the BER performance of scenario 1 is the same for all the three users and this is the case because the method of MRC+ZF was

applied to all the SC-FDMA subcarriers, even those containing only one source signal. Thus, an equal amount of noise level was added to all the source signals and this led to the same BER performance after signal detection. However, the curves of scenario 2 show that the BER performance of user 1 is better than the BER performance of users 2 and 3. In fact, the BER performance of user 1 is exactly the same as the BER of conventional SC-FDMA and this is because the same method of MRC was used for both cases. Thus, at a BER of 10^{-3} , the difference in terms of E_b/N_0 between user 1 and the other two users is approximately 2 dB. For user 2 and 3, the BER curves are still the same as in the first scenario given that the same method was used.

Figure 5.19 compares the performance of this SC-FDMA (which can accommodate three users) with the conventional system (which can only accommodate two users). The simulation shows that in order to achieve the same BER while adding another user to the system, the E_b/N_0 should be increased by 2 dB for the case of users 2 and 3. However, there is no need to increase the E_b/N_0 for the case of user 1. This is a clear improvement compared with scenario 1 where all the users have to increase their E_b/N_0 by 2 dB in order to achieve the same BER.

5.4.3 Third Simulation Scenario

The simulations presented in the previous scenario showed that it is possible to improve the BER performance of user 1 by approximately 2 dB comparatively with user 2 and 3. The main reason for this improvement is because the set of subcarriers allocated to user 1 contains data that is coming from only one source signals. Instead of improving the performance of user 1 only, the scenario presented in this section proposes to improve the performance of two users and this is realized by the subcarrier mapping configuration shown in figure 5.20.

The idea is still the same as what was proposed in the second scenario. That is, recovering the transmitted signals by using MRC for the subcarriers that contain only one source symbol and MRC+ZF for the subcarriers that contain two source symbols. However, the main difference in this scenario is that user 1's source symbols are no longer transmitted alone on all the subcarriers. In fact, half of user 1's source symbols is transmitted alone while the other half is transmitted with user 3's source symbols. Doing this will certainly decrease the BER performance of user 1 comparatively with the previous scenario. However, this will allow user 2 to transmit half of its source symbols on a set of subcarriers that contain only one user source symbols. Therefore,

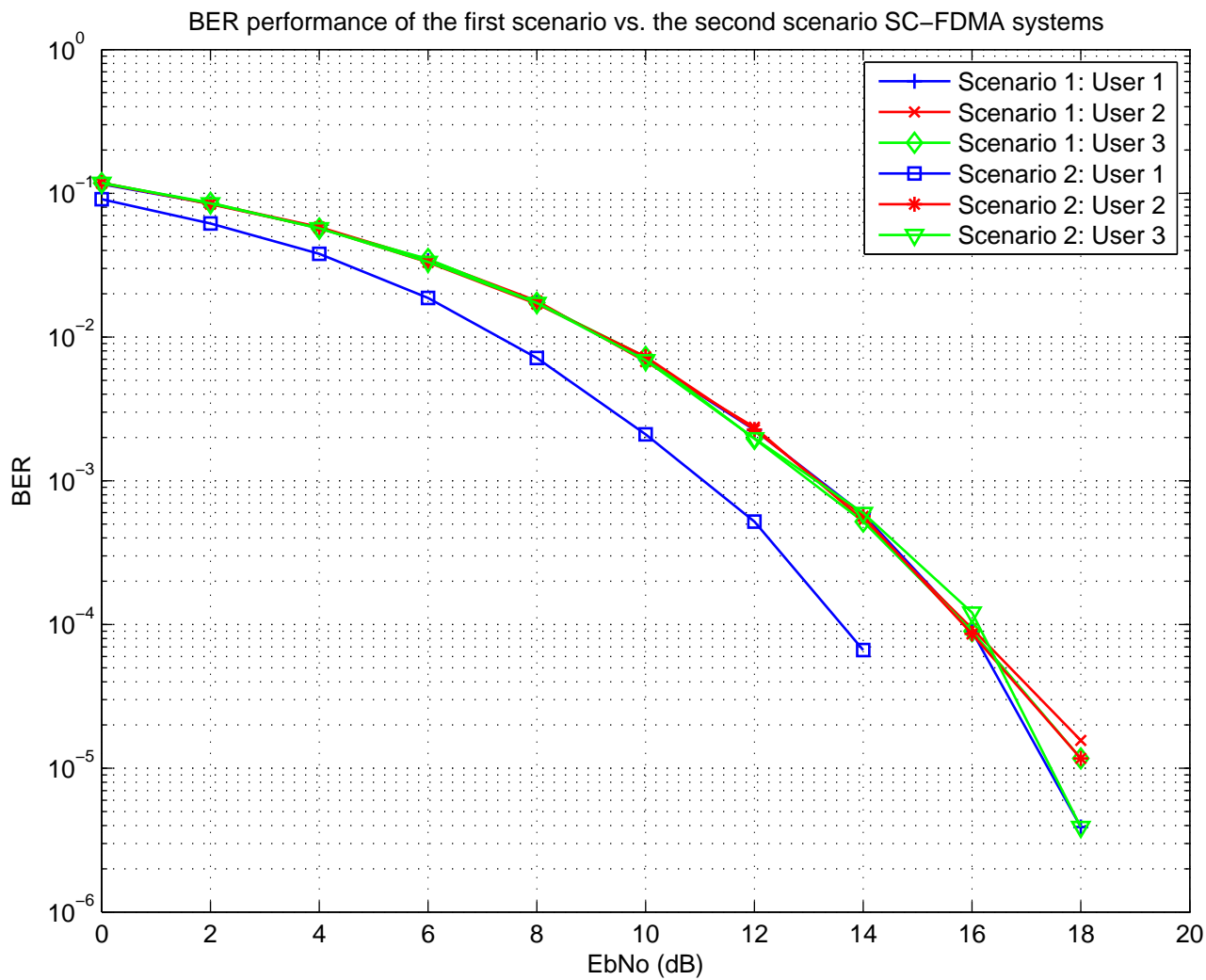


Figure 5.18: BER vs. E_b/N_0 of the first scenario SC-FDMA system and the second scenario.

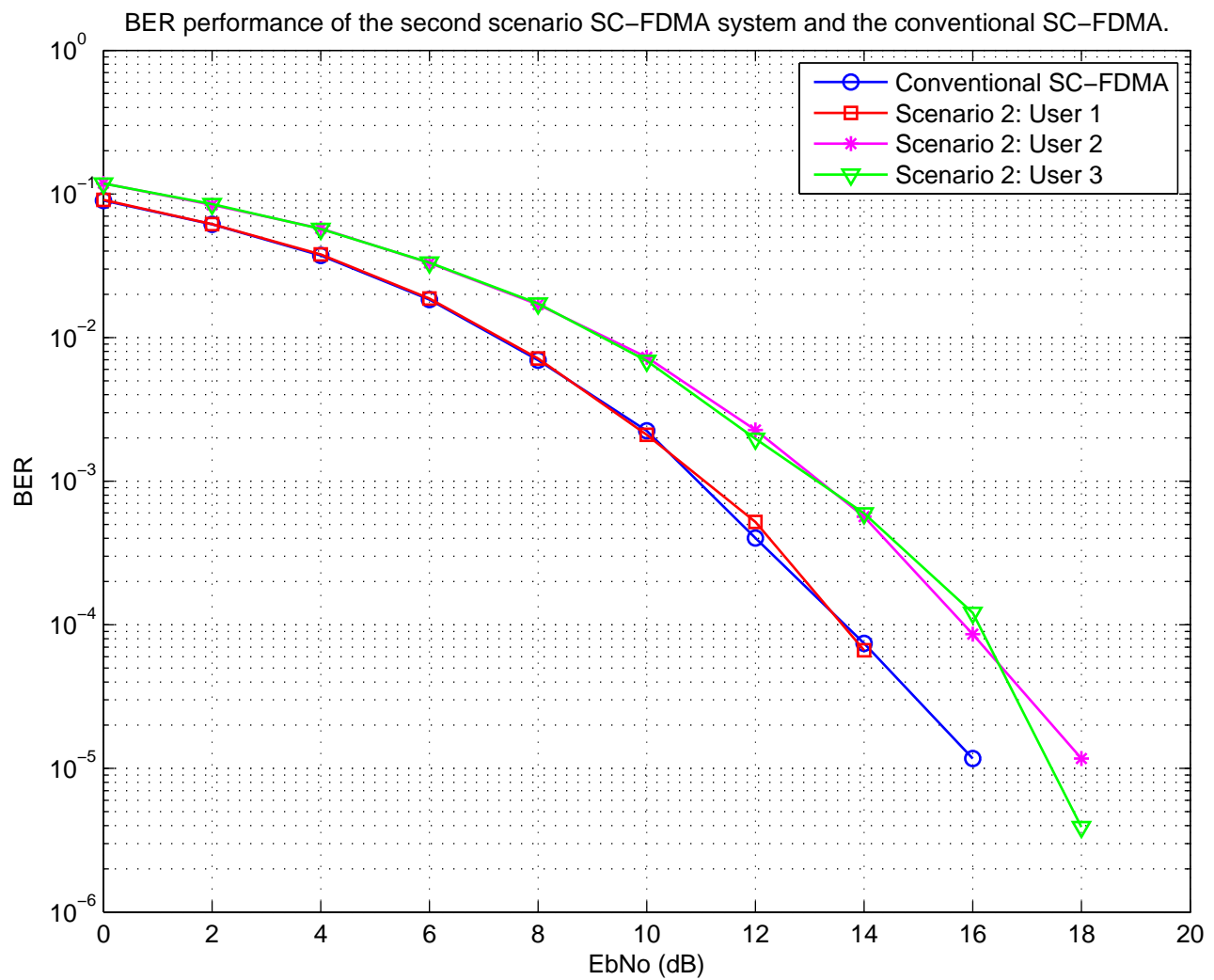


Figure 5.19: BER vs. E_b/N_0 of the second scenario SC-FDMA system and the conventional system.



Figure 5.20: An example of the third scenario subcarrier mapping for $N = 8$ total subcarrier and $M = 4$ subcarrier per user.

this will decrease the performance of user 1 but improve the performance of user 2 and the overall system performance should be improved comparatively with the previous scenario. Figure 5.21 shows a simulation of the proposed scenario as well as the system presented in the previous scenario. As it was expected, the BER curves show that user 2's performance is improved while user 1's performance decrease slightly. Comparing the second and third scenarios at a BER of 10^{-3} , it possible to see the user 1 loses 1 dB while user 2 gains 1 dB in terms of E_b/N_0 . However, the BER curve of user 3 does not change because the same technique of MRC+ZF was applied to all its subcarriers to recover the transmitted symbols.

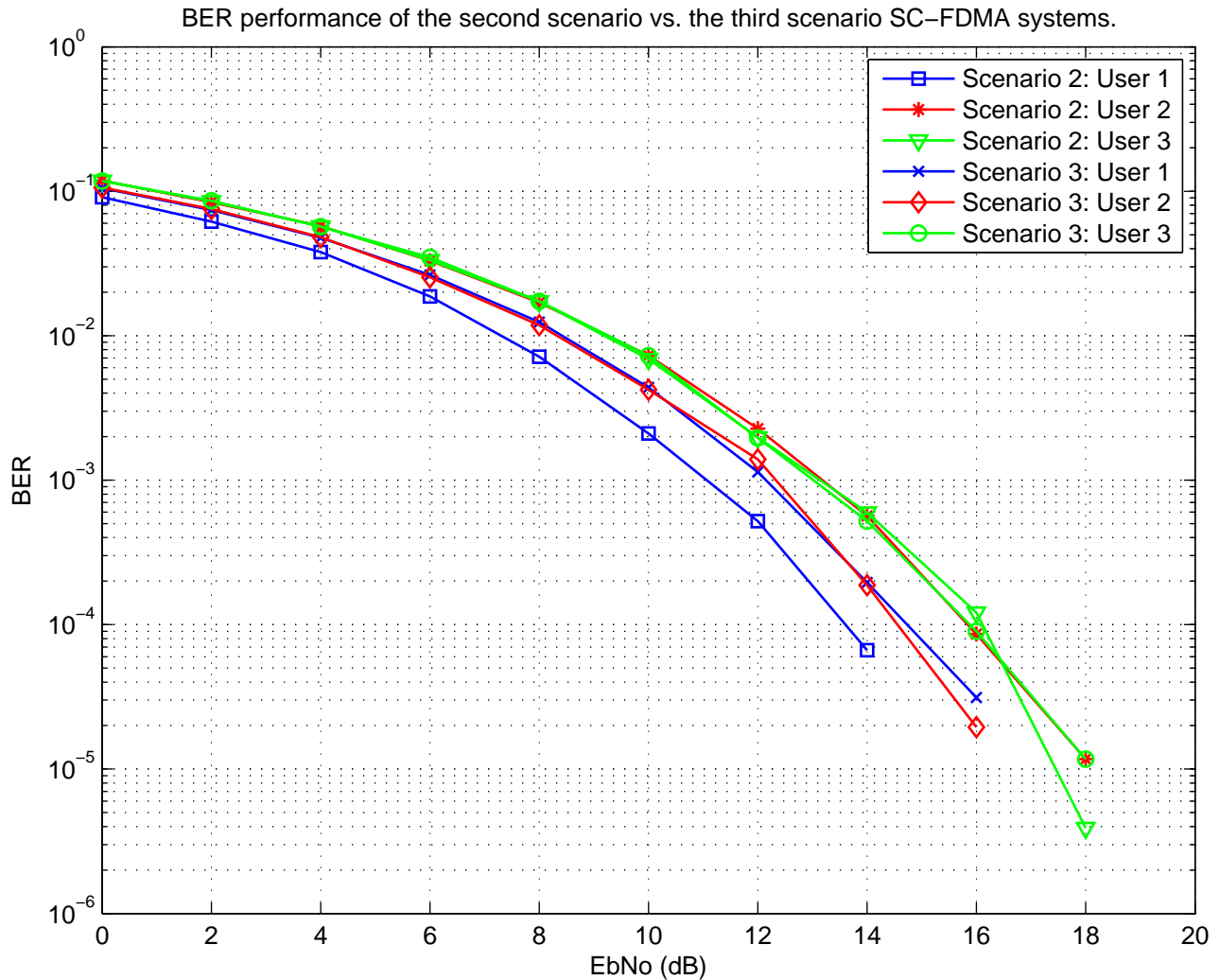


Figure 5.21: BER vs. E_b/N_0 of the second scenario SC-FDMA system and the third scenario.

Figure 5.22 compares this system with the conventional SC-FDMA system that can accommodate only two users at a time. This simulation shows that it is possible to add a third user to the system by increasing the E_b/N_0 of users 1 and 2 by 1 dB and user 3 by 2 dB in order to achieve the same BER of 10^{-3} as the conventional system.

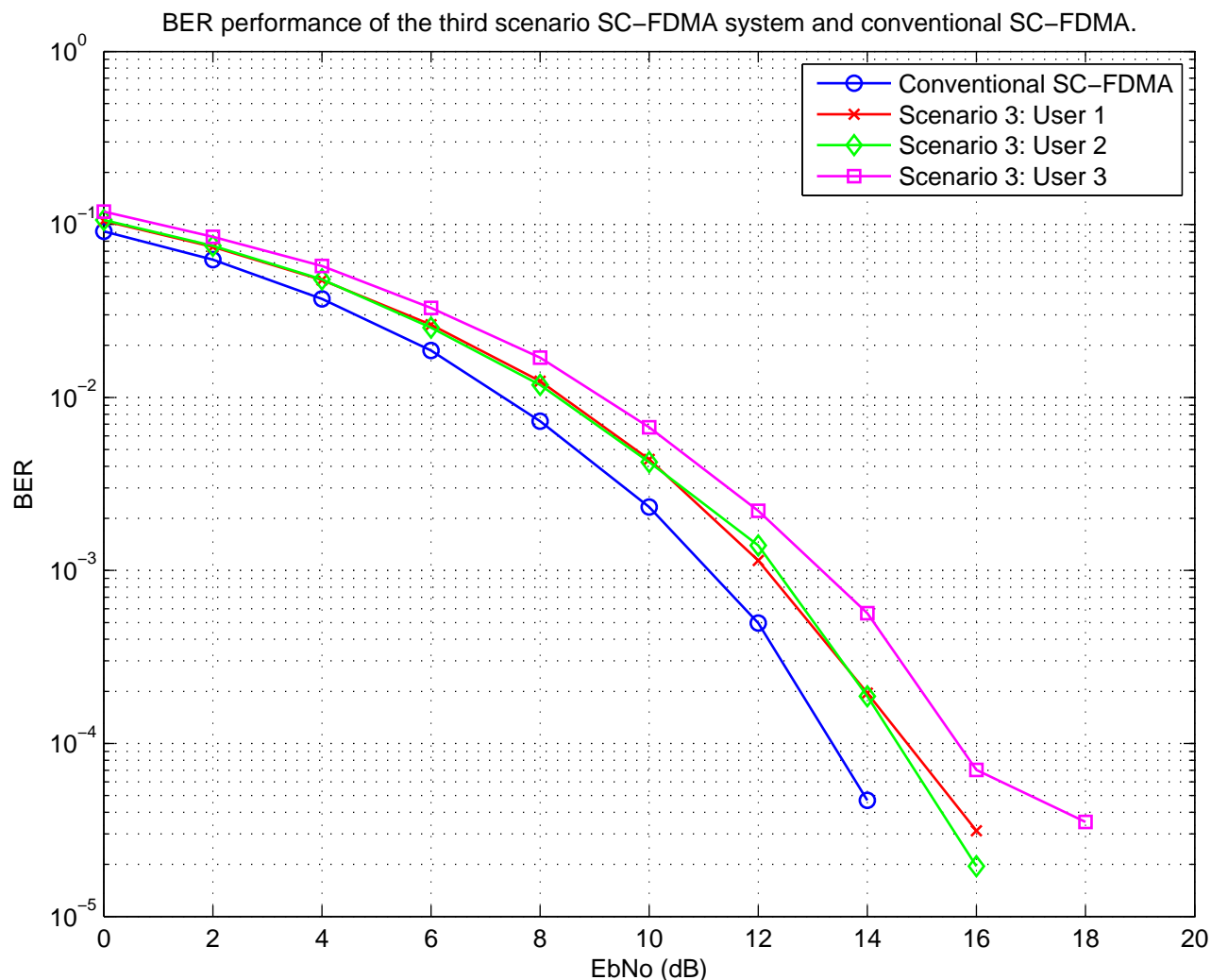


Figure 5.22: BER vs. E_b/N_0 of the third scenario SC-FDMA system and the conventional system.

5.4.4 Fourth Simulation Scenario

The main focus of the third scenario is to improve the BER performance of users 1 and 2 comparatively with the first scenario. In fact the proposed method decreases the required E_b/N_0 for users 1 and 2 by approximately 1 dB but it did not improve the performance of user 3. In this scenario, the objective is to improve the BER performance of user 3. As it can be shown in figure 5.23, the subcarrier mapping scheme is still the same as in the

previous scenario. However, the approach that is used to estimate the transmitted signals is very different. The idea behind this estimation technique is to consider the received SC-FDMA symbol as two superposed layers of subcarriers. As shown in figure 5.23, the first layer A consists of the set of subcarriers containing user 3's modulation symbols while layer B consists of the interleaved subcarriers containing modulation symbols from users 1 and 2. The received SC-FDMA symbol can be considered as the summation of A and B. One way of obtaining a better estimate for user 3 is to separate layers A and B at the receiver and to look at each layer as an independent SC-FDMA symbol which has to be estimated.



Figure 5.23: An example of the fourth scenario subcarrier mapping for $N = 8$ total subcarrier and $M = 4$ subcarrier per user.

Given that the receiver receives $A+B$, it is not possible for the system to recover A and B perfectly. However, it is possible to estimate A and B . In order to do this, the technique proposed in this scenario takes $A+B$ and calculates an estimate of B (denoted \tilde{B}). After that, it calculates an estimate of A (denoted \tilde{A}) by subtracting the estimate of B from $A + B$ (i.e. $\tilde{A} = (A + B) - \tilde{B}$). Once \tilde{A} is calculated, it is possible to recover user 3's transmitted symbols with fewer errors than in the previous scenario.

In order to do this, the proposed technique takes the received SC-FDMA symbol $A + B$ and only estimates users 1 and 2 using the same technique as in the previous scenario. That is, by applying MRC for the subcarriers that contains only one user and MRC+ZF for the subcarriers that contain two users. Once user 1 and 2 source signals are estimated and the transmitted bits are recovered, the receiver remodulate these bits as if they were to be sent again. After that, it convolves the obtained signal with the channel in order to simulate a retransmission. Doing this manipulation allows the system to calculate \tilde{B} . Thus, it is possible to calculate \tilde{A} by subtracting \tilde{B} from the SC-FDMA symbol $A + B$ that was initially received. As shown in figure 5.24, the calculated \tilde{A} is simply the layer of subcarriers containing data from user 3 only. Therefore, the receiver

can consider it as a conventional SC-FDMA system and calculate user 3's transmitted symbols using MRC.



Figure 5.24: An example of the calculated \tilde{A} in the fourth scenario for $N = 8$ total subcarrier and $M = 4$ subcarrier per user.

Figure 5.25 shows a system simulation of the proposed technique. Comparing the BER curve for user 3 with the curve of the previous scenario shows that there is clear improvement in terms of BER performance. In fact, at a typical BER of 10^{-3} the proposed technique requires an E_b/N_0 of approximately 12 dB while the system of the previous scenario requires 13 dB in order to achieve the same BER. Thus, user 3 gained 1 dB in terms of E_b/N_0 with respect to the previous scenario. Comparatively with the previous scenario, there is no change in terms of performance for users 1 and 2 given that both scenarios use the same technique of MRC+ZF to estimate these users' transmitted signals.

Figure 5.26 compares the performance of the system presented in this scenario with the conventional SC-FDMA that can accommodate only two users at a time. This simulation shows that it is possible to add a third user to the system and achieve the same BER of 10^{-3} as the conventional system if the E_b/N_0 is increased by approximately 1 dB.

5.4.5 Fifth Simulation Scenario

In the four previous scenarios, the main objective was to add a third user to the SC-FDMA system with the lowest possible increase in terms of E_b/N_0 . The scenario presented in this section extend this idea to see if it is possible to add a fourth user to the system and what is the impact in terms of BER performance. One possible way of mapping the subcarriers in order to accommodate four users is shown in figure 5.27. This figure shows an example of the proposed mapping scheme for a system with 8 total subcarriers, however the same principle can be applied to any number N of subcarriers.

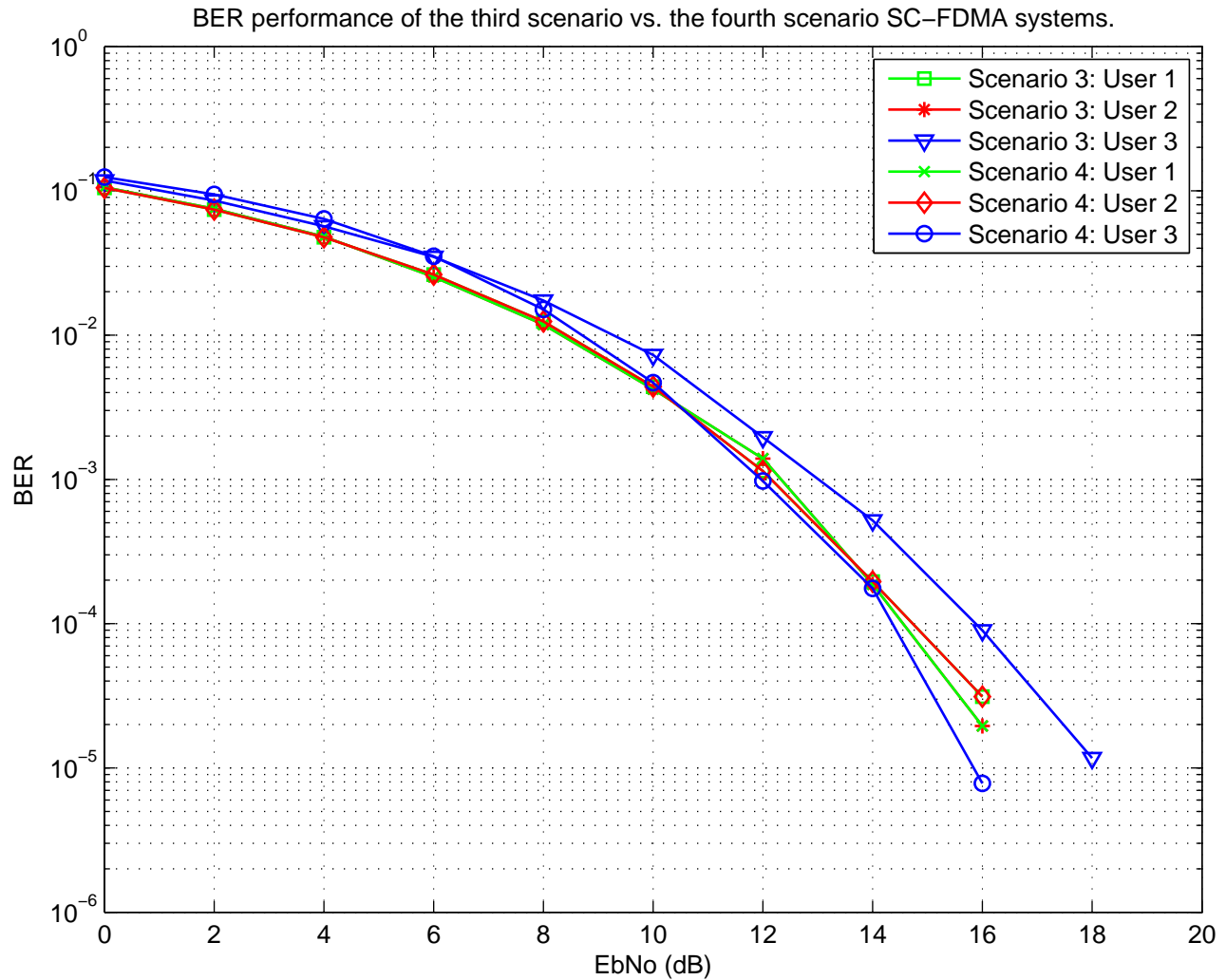


Figure 5.25: BER vs. E_b/N_0 of the third scenario SC-FDMA system and the fourth scenario.

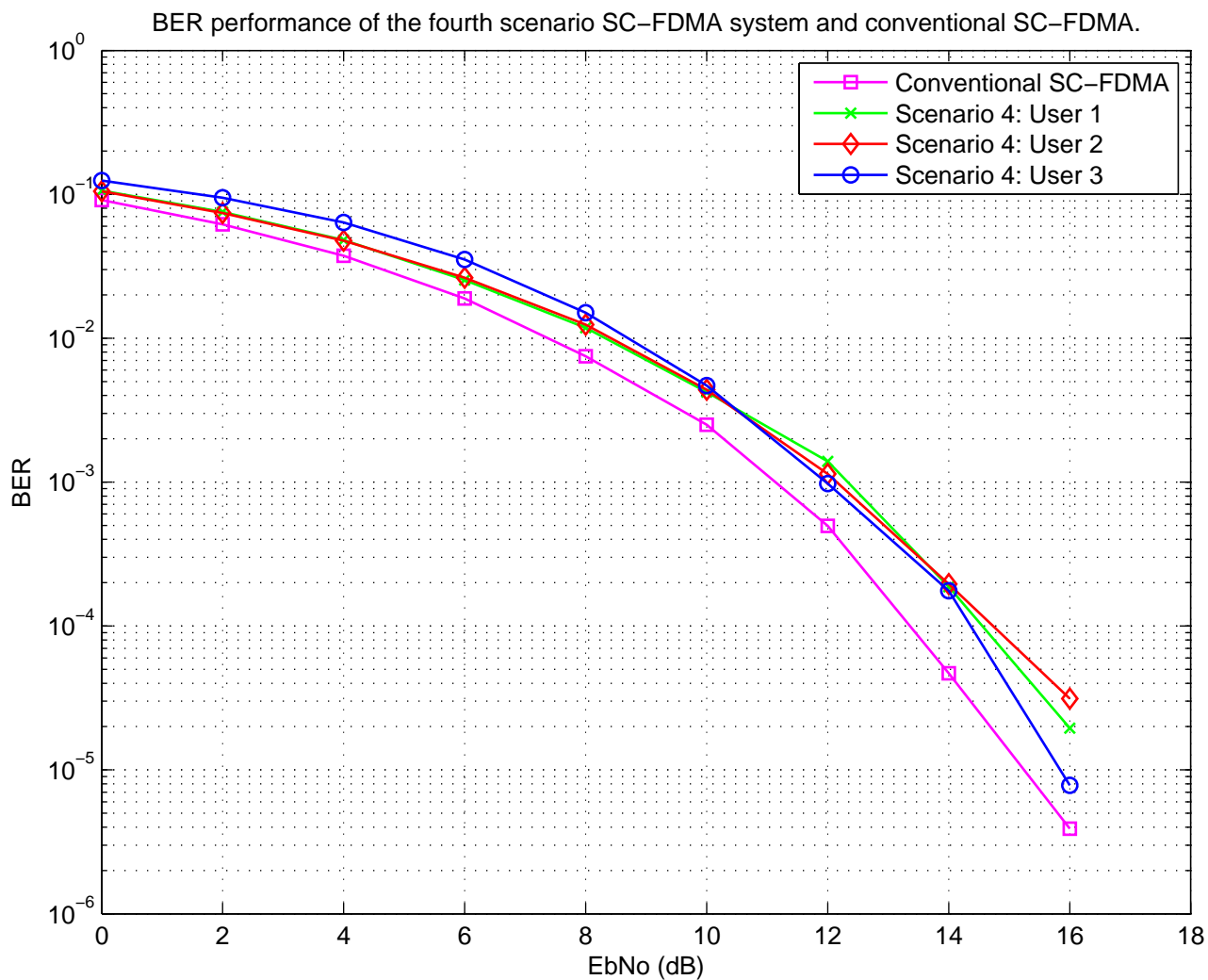


Figure 5.26: BER vs. E_b/N_0 of the fourth scenario SC-FDMA system and the conventional system.

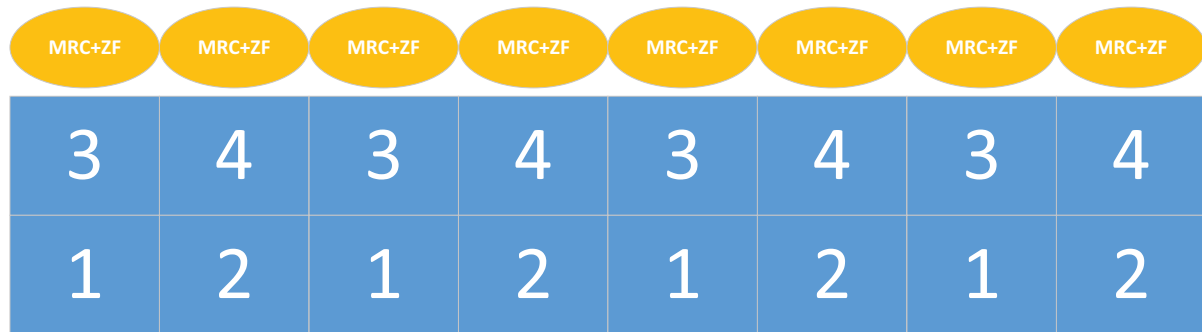


Figure 5.27: An example of the fifth scenario subcarrier mapping for $N = 8$ total subcarrier and $M = 4$ subcarrier per user.

As it can be seen in this figure, all the SC-FDMA subcarriers contain modulation symbols from two users. Therefore, it is possible to recover the transmitted signals using the method of MRC+ZF presented in section 4.5.2 of the previous chapter. Figure 5.28 shows a simulation of an SC-FDMA system that uses this technique. As it can be seen from the BER vs. E_b/N_0 curves, all the four users have the same performance and this is because the same technique of signal recovery was used for all of them. Furthermore, these curves show that comparatively with the conventional SC-FDMA system, the E_b/N_0 should be increased by approximately 2 dB in order to achieve the same BER. Therefore, this simulation shows that it is possible to accommodate four users at the same time and on the same number of subcarriers as conventional SC-FDMA by applying the technique of MRC+ZF and increasing the E_b/N_0 by 2 dB in order to keep the overall system performance unchanged.

Figure 5.29 shows a simulation of a conventional SC-FDMA system with 4 users. As it can be clearly seen, the BER performance is very bad and this transmission system is practically not useful. In fact, the BER stays almost the same and does not decrease even with a very high E_b/N_0 . Furthermore, an increase in the number of receive antennas seems to not improve the system performance. As shown in figure 5.30, even with 10 antennas used at the receiver, there is a very small decrease in BER but the system still performs very badly because the estimated source signals contain too much errors.

Comparing figure 5.28 with figures 5.29 and 5.30 shows very clearly that the proposed method of signal recovery using MRC+ZF as discussed in the previous chapter makes a real difference in terms of performance and allows SC-FDMA systems to considerably increase their capacity simply by increasing the value of E_b/N_0 as shown previously and without any loss in term of BER performance. Without using this technique, the

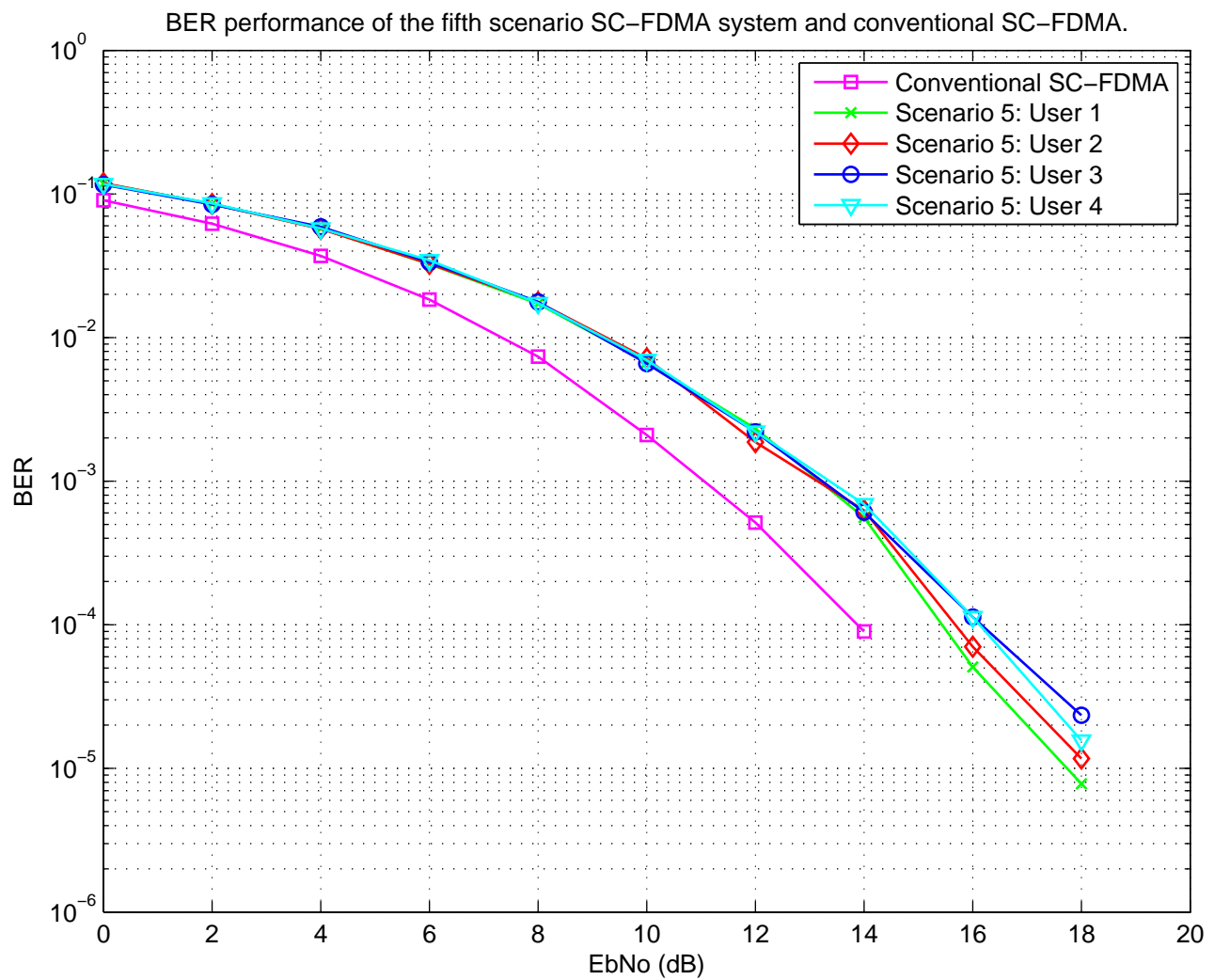


Figure 5.28: BER vs. E_b/N_0 of the fifth scenario SC-FDMA system and the conventional system.

conventional SC-FDMA system does not have the ability to accommodate more than two users.

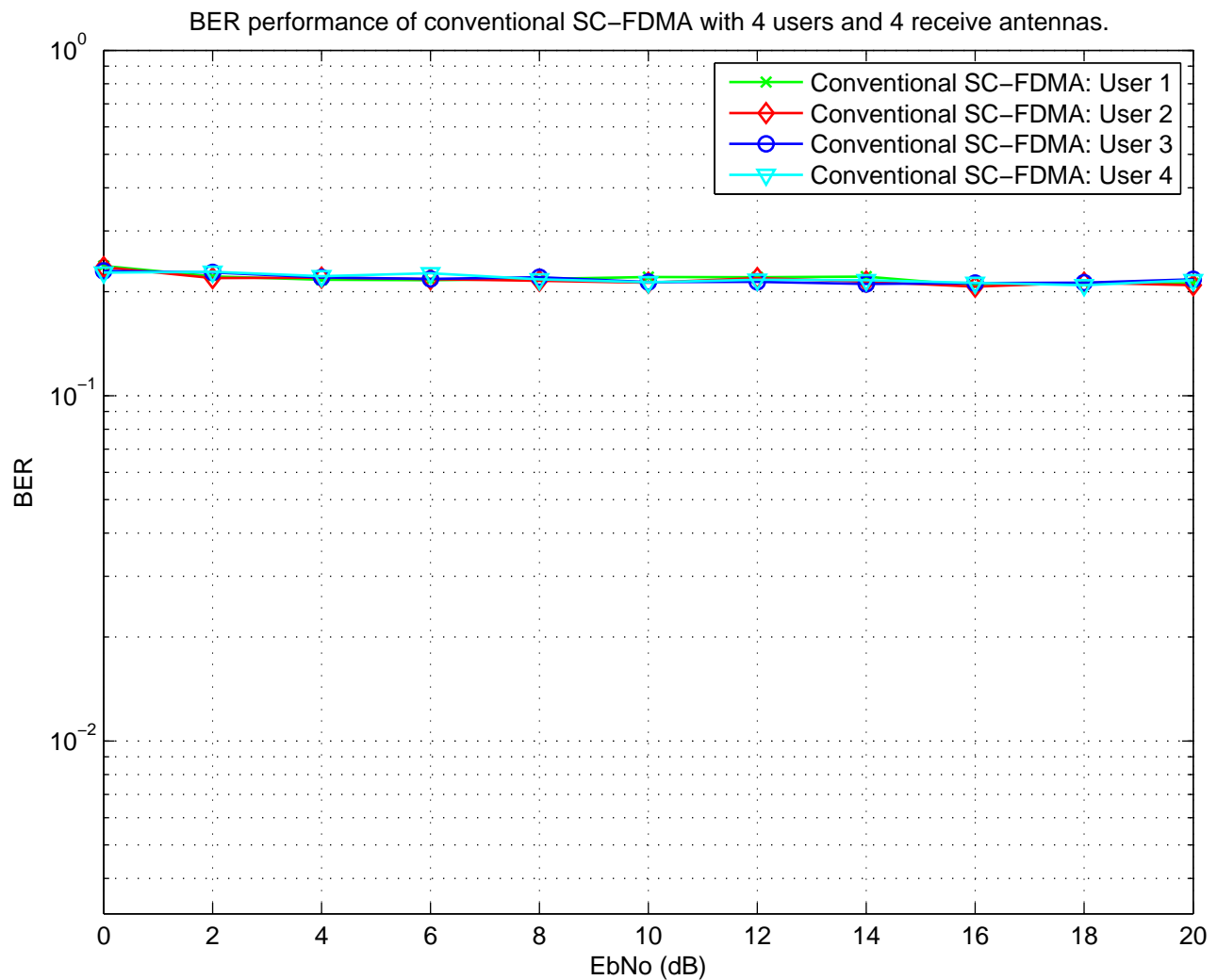


Figure 5.29: BER vs. E_b/N_0 of conventional SC-FDMA with 4 users and 4 receive antennas (with subcarrier sharing and no multiuser detection).

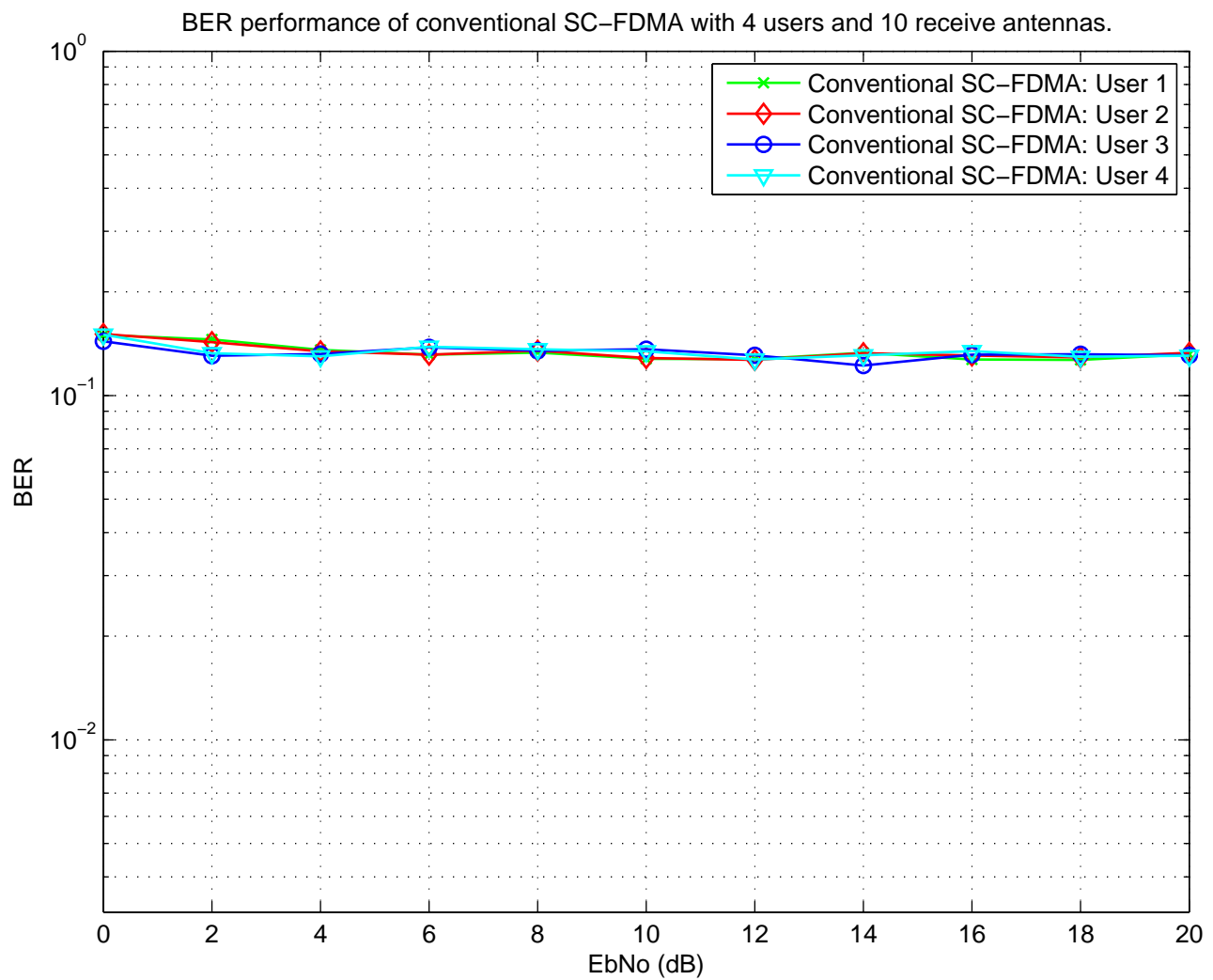


Figure 5.30: BER vs. E_b/N_0 of conventional SC-FDMA with 4 users and 10 receive antennas (with subcarrier sharing and no multiuser detection).

5.5 Link Level Simulation of Spectrally Efficient SC-FDMA with three Transmit Symbols on the same Subcarrier

The main objective of the several scenarios and techniques presented in this chapter as well as in the previous one is to find a way to increase the channel capacity of an SC-FDMA system without increasing the bandwidth or going to a higher modulation order. The scenarios presented in the previous section showed that it is possible to achieve this objective by assigning the same set of SC-FDMA subcarriers to two users at the same time and use a multiuser detection technique to separate and recover the transmitted signals as described in section 4.5.2 of the previous chapter. The simulation results showed that this technique allows the system to transmit up to two users on the same subcarriers with a relatively small increase in terms of system complexity and transmission power E_b/N_0 .

This section studies the possibility of improving the SC-FDMA system further and making it more efficient. In fact, the objective is to see if it is possible to place three users instead of two on the same set of subcarriers and still recover the transmitted signals with a relatively low complexity and an acceptable E_b/N_0 . In order to do this, the simulated scenario will use the technique presented in the previous chapter in section 4.5.2.

5.5.1 Sixth Simulation Scenario

In the five previous scenarios, the main objective was to add a third and fourth user to the SC-FDMA system with the lowest possible increase in terms of E_b/N_0 . The scenario presented in this section extends this idea to see if it is possible to accommodate six users at the same time and what is the impact on the system in terms of BER performance. This is realized by mapping three users to the same set of subcarriers instead of only two. One possible way of accommodating six users is shown in the example of figure 5.31.

As it can be seen in this figure, every SC-FDMA subcarrier now contains three modulation symbols from three different users. Therefore, it is possible to recover the transmitted signals using the technique presented in section 4.5.2. This system was simulated and the results are shown in figure 5.32. As it can be seen from these curves, the six users have the same BER performance and this is what is expected given that the same signal recovery method was used for all of them. Comparing these curves with the conventional

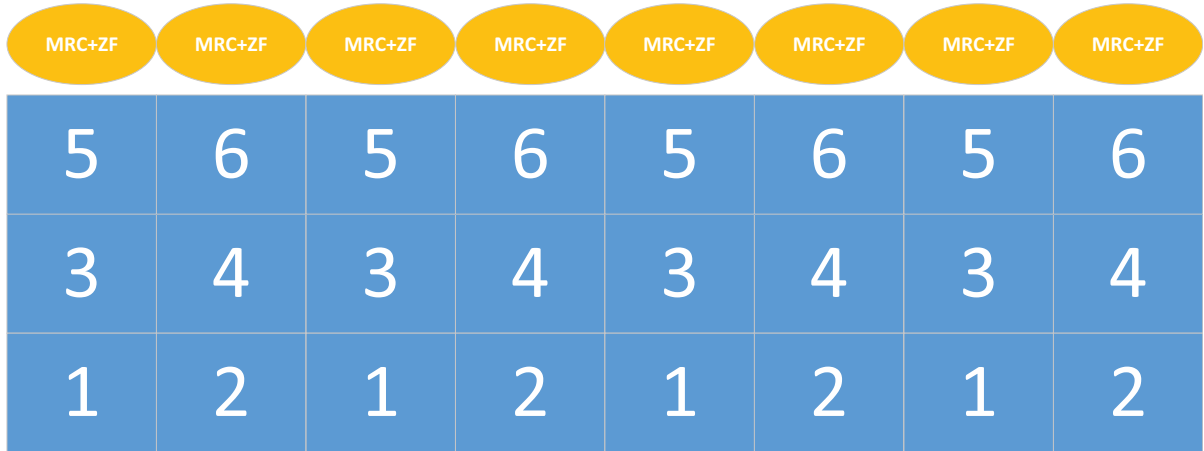


Figure 5.31: An example of the sixth scenario subcarrier mapping for $N = 8$ total subcarrier and $M = 4$ subcarrier per user.

SC-FDMA (which can accommodate only two users), it is possible to see that this system requires an increase of approximately 6 dB in terms of E_b/N_0 in order to achieve the same BER performance. Therefore, this simulation shows that with the proposed technique, it is possible to accommodate six independent users at the same time while using the same number of subcarriers as the conventional SC-FDMA and still achieve the same BER performance if the E_b/N_0 is increased by 6 dB.

5.6 Summary

In this chapter, different computer simulations of SC-FDMA systems were presented. The main objective was to study the system performance for different scenarios and see what is the effect of adding more users to the system in every case. These simulations were realized using the multiuser detection techniques described in the previous chapter.

The first three sections started by giving a general overview of the SC-FDMA system that is simulated by describing the channel model, the transmission model as well as different parameters and assumptions that were used to simulate the SC-FDMA systems. In section 5.3, a link level simulation of a conventional SC-FDMA system (with different users occupying different sets of subcarriers) was presented. The simulations showed that interleaved subcarrier mapping offers a better performance in terms of BER than localized subcarrier mapping and this is due to the fact that IFDMA provides better frequency diversity to the system since the source signals are spread over the entire

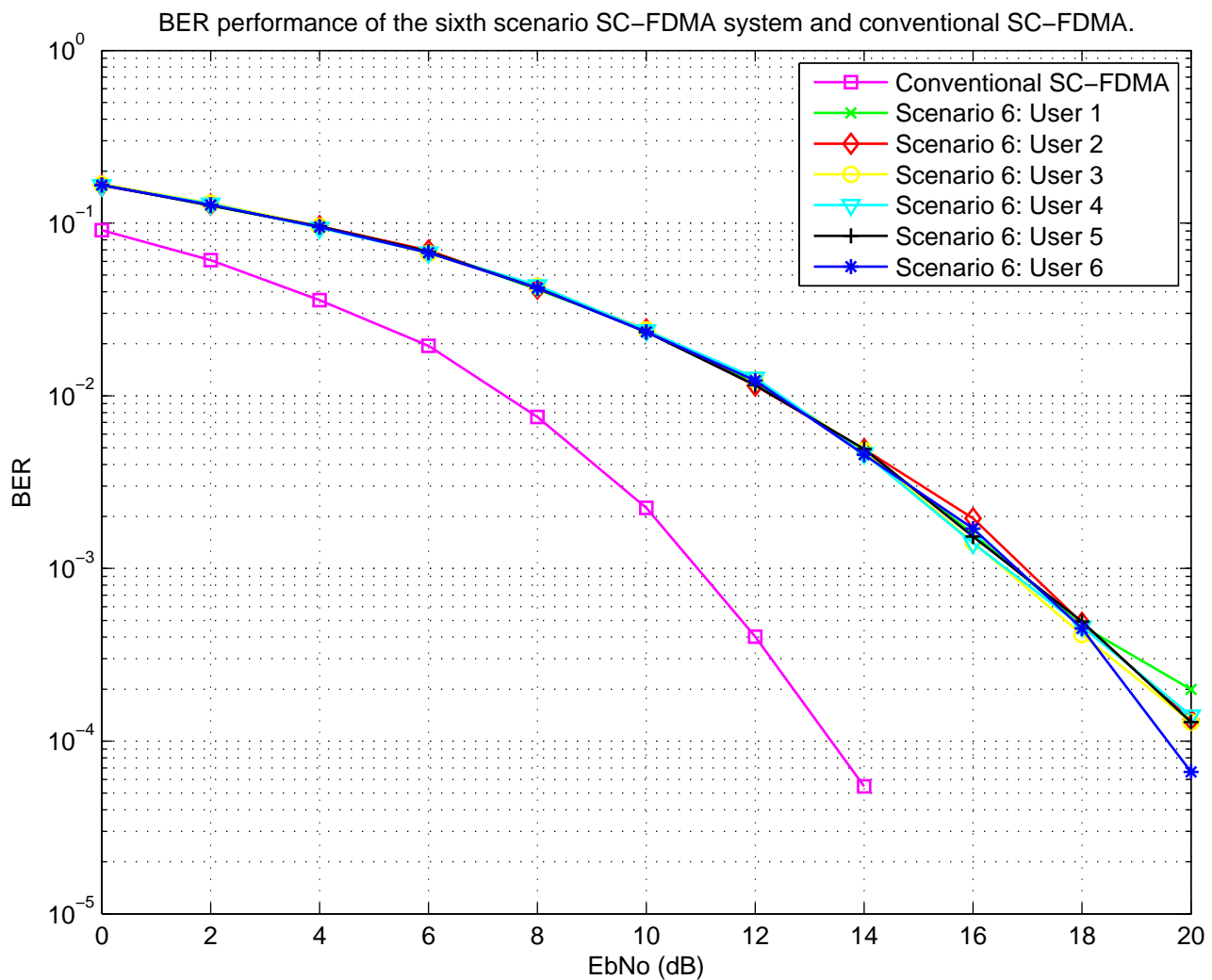


Figure 5.32: BER vs. E_b/N_0 of the sixth scenario SC-FDMA system and the conventional system.

bandwidth. It was also shown in this section that the performance of an SC-FDMA system using MRC at the receiver can be improved considerably if the number of antennas at the receiver is increased.

Section 5.4 studied the case of increasing the channel capacity of SC-FDMA systems by transmitting source signals from two different users on the same set of subcarriers using the multiuser detection method described in section 4.5.2 of the previous chapter. The first four scenarios studied the effect of adding a third user to a conventional SC-FDMA system operating at its full capacity with two users. The simulation showed that with the proposed technique, it is possible to add a third user to the system and still achieve the same BER performance as the conventional system if the E_b/N_0 is increased by approximately 1 dB. Adding a third user correspond to multiplying the transmission rate by 1.5. The fifth simulation scenario proposed to add a fourth user to the system using the same method and it was shown that this technique requires an increase of 2 dB in terms of E_b/N_0 to achieve the same BER. Therefore, it is possible to double the transmission rate of an SC-FDMA system only by increasing E_b/N_0 without going to a higher modulation order or using more bandwidth.

Section 5.5 extended this concept to see if it is possible to transmit source signals from three independent users on the same subcarriers and proposed to add four users to the conventional system, making it a total of six users per SC-FDMA symbols. This scenario showed that it is possible to triple the transmission rate of an SC-FDMA system by assigning the same set of subcarriers to three different users at the same time and using a multiuser detection technique to separate and recover the transmitted signals as described in section 4.5.2. In order to keep the same BER as conventional SC-FDMA, the E_b/N_0 should be increased by 6 dB. All in all, the different simulations presented in this chapter showed that it is possible to double and even triple the spectral efficiency of an SC-FDMA system and still provide the same performance without the need for additional bandwidth or a higher modulation order. This is realized by increasing the value of E_b/N_0 and using the multiuser detection techniques presented in the previous chapter.

Chapter 6

Conclusion and Future Work

This dissertation presented the work developed during the application and analysis of new algorithms that can be implemented in a SC-FDMA system in order to improve its spectral efficiency. While the first part of this thesis presented the current technologies and the mathematical background to perform the aforementioned work, the second part provided the mathematical descriptions as well as several simulations of the proposed techniques. The main conclusions and contributions derived from this analysis were discussed and presented after each stage of the study. This final chapter presents a brief summary of the previous chapters in order to mention the more significant insights. In addition, it provides some future lines and applications regarding this work.

6.1 Synthesis of the Dissertation

Chapter 1 provided an overview of the wireless technology development in the successive cellular generations as well as the main cellular standards organizations. It also discussed some of the main characteristics of 3GPP Long Term Evolution (LTE) and briefly presented the main differences between Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA) schemes. While OFDMA data symbols are transmitted in parallel, SC-FDMA sub-carriers are transmitted sequentially and this allows SC-FDMA systems to have a lower peak-to-average power ratio (PAPR). This is the main reason why SC-FDMA was adopted by 3GPP for the uplink transmission.

Chapter 2 was devoted to introduce the main motivation of this work, which is to propose new ways of improving the spectral efficiency of SC-FDMA transmission without

requiring more resources in terms of bandwidth and with the minimum possible increase in system complexity. It was discussed that current SC-FDMA systems can accept new users in the transmission without decreasing the transmission rate of the other users either by using more bandwidth or transmitting at a higher modulation order, which are two solutions that are not always possible in practice. The technique proposed in this dissertation should enable the system to accommodate more users without requiring more bandwidth or going to a higher modulation order, thus improving the spectral efficiency of the system. These techniques are based on simple algorithms that are very easy to implement in practice and do not bring a considerable increase to the overall system complexity.

Chapter 3 presented a general overview of SC-FDMA transmission as well as the related techniques. First, it started by describing single-carrier and multi-carrier systems. Single-carrier systems transmit data sequentially on a single frequency band using a single frequency carrier. While this transmission technique is very simple, it has many weaknesses such as a high sensitivity to inter-symbol interference caused by multipath propagation. These problems are mitigated by using multi-carrier transmission techniques such as Orthogonal Frequency Division Multiplexing (OFDM) where the data is transmitted in parallel on multiple carriers. While OFDM systems offer a very good performance in terms of spectral efficiency, they have the disadvantage of operating at a relatively high peak-to-average power ratio (PAPR), which imposes the need for powerful amplifiers. Single-carrier Modulation with Frequency domain Equalization (SC-FDE) is a new single-carrier transmission technique that is very practical for mitigating the effects of frequency selectivity due to the fact that the transmitted information is processed on a per block basis, as opposed to conventional single-carrier systems. SC-FDE delivers similar performance to OFDM with essentially the same overall complexity. However, SC-FDE systems also have the advantage of operating at a lower PAPR than OFDM. Single Carrier Frequency Division Multiple Access (SC-FDMA) and Orthogonal Frequency Division Multiple Access (OFDMA) are two multiple access schemes based on SC-FDE and OFDM respectively. Due to its high PAPR, OFDMA was prescribed by 3GPP only for the downlink transmission given that it is not very critical to have a high power consumption at the base stations. In return, SC-FDMA was chosen for the uplink transmission and this is mainly because of its low PAPR which allows the power amplifiers at the mobile terminals to be much simpler and power efficient than they would be with OFDMA systems. Two SC-FDMA subcarrier mapping schemes were discussed in this chapter. In the localized subcarrier mapping mode (LFDMA), the data symbols occupy

a set of consecutive subcarriers. In the distributed subcarrier mapping mode (DFDMA), the transmitted data symbols occupy a set of subcarriers that are spread over the entire channel bandwidth and this allows the system to have better frequency diversity. For the two mapping schemes, frequency diversity can be improved using channel dependent scheduling (CDS). However, the performance improvement using CDS is significantly important in the case of LFDMA. The peak power characteristics of SC-FDMA signals were also studied for the different mapping schemes and a comparison between SC-FDMA and OFDMA modulation techniques was presented at the end of the chapter.

Chapter 4 provided the mathematical description of a multiuser detection technique that can considerably improve the spectrum efficiency of a SC-FDMA transmission by allowing multiple users to transmit their signals on the same set of subcarriers instead of transmitting each source signal on a separate set of subcarriers as it is the case for conventional SC-FDMA. The proposed system is based on several techniques related to multiple input multiple output (MIMO) transmission, diversity combining as well as frequency domain equalization. It was shown in this chapter that MIMO transmission can significantly increase the data throughput as well as the transmission reliability of a communication system without the need for additional bandwidth or increased transmission power. In fact, by spreading the transmit power over the antennas, MIMO systems can achieve a spatial diversity gain that improves the communication reliability and/or a spatial multiplexing gain that improves the spectral efficiency. Single input multiple output (SIMO) transmission is a special case of MIMO where there is only one antenna at the transmitter. The second technique used in the proposed system is called diversity combining. Diversity combining techniques use multiple antennas at the receiver in order to create a set of independent paths for the transmitted signal. The outputs of these independent channels are combined at the receiver in accordance with a certain criterion that will improve the quality of the received signal. Depending on the criterion used for combining these signals, there are three main diversity combining techniques, namely, selection combining, equal-gain combining and maximal-ratio combining (MRC). Among the three techniques, MRC was chosen for the system proposed in this chapter given that it is the optimum solution in terms of power efficiency. Frequency domain equalization is another technique used in the proposed multiuser detection technique. The chapter presented two frequency domain equalizers, which are zero-forcing (ZF) and minimum mean-square error (MMSE). Usually, MMSE equalizers achieve a significantly lower bit error rate (BER) than ZF equalizers at low to moderate SNRs. However, MMSE equalizers introduce more complexity to the system and in many practical situations, a ZF

equalization is sufficient to provide a good performance. Therefore, ZF frequency domain equalization was chosen for the proposed system.

The second part of chapter 4 presented a spectrally efficient SC-FDMA system with multi-receive antennas and multiuser detection. As mentioned earlier, the proposed technique is based on the use of multiple antennas at the receiver as well as maximal ratio combining and zero-forcing equalization. A mathematical description of a conventional SC-FDMA system (i.e. with different source signals occupying different sets of subcarriers) using MRC at the receiver was first presented. This system was then modified in order to transmit multiple source signals on the same set of subcarriers. It was shown that this modified version of the conventional SC-FDMA can increase considerably increase the spectral efficiency of the system by transmitting several SC-FDMA symbols on the same subcarrier and using a decorrelator at the receiver to recover the transmitted signals.

Chapter 5 presented several simulations of the multi-user detection techniques discussed in chapter 4 in order to evaluate and compare the performance of the proposed systems with the conventional SC-FDMA. This chapter started by giving a general overview of the SC-FDMA model that was used for simulation including the channel model, the transmission model as well as the main simulation parameters and assumptions. The next section of this chapter provided a link level simulation of a conventional SC-FDMA system using MRC at the receiver. The SC-FDMA system performance was evaluated by calculating the bit error rates (BER) for different energy per bit to noise power spectral density ratios (E_b/N_0). It was shown that the SC-FDMA performance can be greatly affected by the presence of frequency selectivity in the transmission channel. It was also shown that in the case of LFDMA subcarrier mapping, the BER performance of the system varies significantly depending on the location of the subband where the signal is being transmitted and this is mainly due to the fact that the localized mapping scheme does not provide frequency diversity to the system. On the other hand, IFDMA subcarrier mapping does not suffer from this problem given that in this interleaved mapping mode, every source signal is spread over the entire bandwidth, which leads to an inherent frequency diversity. Simulations also showed that the performance of SC-FDMA with MRC can be considerably improved if the number of antennas at the receiver is increased.

The second part of the chapter studied a practical case where an SC-FDMA system is operating at its full capacity with two users and a third user wants to join the transmission. Several scenarios were presented in order to see how to add the third users without affecting the transmission performance of the two others. While it was not possible to

accommodate three users at the same time using the conventional SC-FDMA system, one of the scenarios showed that it is possible to add a third user to the system and still achieve the same BER performance as the conventional system if the E_b/N_0 is increased by approximately 1 dB. This is realized by using the proposed technique of multiuser detection based on ZF and MRC. Using this same technique, it was also shown that the system can accept a fourth user, thus doubling the transmission rate, and still achieve the same performance if the E_b/N_0 is increased by 2 dB.

The last part of the chapter extended the same principle to the case where the SC-FDMA system is transmitting three source signals on the same set of subcarriers, thus accommodating six users at the same time instead of only two. Using the proposed technique in chapter 4, simulation results showed that it is possible to triple the transmission rate of a SC-FDMA system and still provide the same performance as conventional systems if the E_b/N_0 is increased by 6 dB.

Although the simulations presented in this chapter were for a SC-FDMA system with 16QAM modulation, 64 total subcarriers and initially two users, it is important to note that the proposed technique applies to any SC-FDMA configuration and provide the same performance independently of the number of users or available subcarriers in the system. In other words, it is possible to double or triple the spectral efficiency of any SC-FDMA system and still keep the same performance in terms of BER if the values of E_b/N_0 are increased by 2 dB and 6 dB respectively. The same technique can be applied to SC-FDMA systems transmitting more than three source signals on the same subcarriers. However, simulations showed that each increase in channel capacity would require the system to use more power at the transmitter to keep the same BER performance. Therefore, one has to make a trade-off between channel capacity and transmission power.

6.2 Contributions

The main contributions of this thesis is the development of new multiuser detection algorithms that can be easily implemented in SC-FDMA systems in order to improve the spectral efficiency of the LTE uplink transmission without the need for more bandwidth or increased system complexity. Special attentions were paid to the cases where two and three source signals are being transmitted on the same set of subcarriers, which leads respectively to doubling and tripling the channel capacity. The proposed algorithms were validated through simulations and compared with the current SC-FDMA technology in

order to evaluate their performance and see if there are any improvements. This comparison showed that using the proposed multiuser detection algorithms can considerably increase the channel capacity of SC-FDMA transmission while maintaining the same performance as a conventional SC-FDMA in terms of BER. This is realized by slightly increasing the transmission power and using a maximal-ratio combiner followed by a zero-forcing equalizer at the receiver. Most of the simulations were realized with a fixed number of antennas at the receiver. However, it was shown that increasing the number of receive antennas improves considerably the system performance and this because the receiver uses a MRC to combine all the received signals and generate one output signal that is optimum in terms of power efficiency.

The proposed technique can be implemented in any SC-FDMA system with a relatively very low complexity while allowing more than one user to share a common set of subcarriers. While having the same benefits as conventional SC-FDMA, the proposed system achieves a higher throughput and requires a relatively low computational complexity. The resulting power/spectral efficiency can provide considerable wireless improvements in future wireless communication systems. Also, due to its ability of multiuser detection, this technique can be efficiently used in the cell edges, where the same frequency resource is reused in the neighbouring cells to increase the total throughput.

6.3 Future Work

- The possibility of applying the proposed algorithms to SC-FDMA systems with channel state dependent scheduling (CDS). Including CDS to the system should provide more frequency diversity to the system and improve its BER performance.
- By using minimum mean-square error (MMSE) frequency domain equalization instead of zero-forcing (ZF), it is possible to further improve the performance of the proposed algorithms because MMSE equalizers achieve a significantly lower BER than ZF equalizers at low to moderate SNRs.
- The SC-FDMA system performance can be improved significantly by applying Turbo Multiuser Detection techniques at the receiver. [24].
- Adding some realistic and sophisticated features to the SC-FDMA simulator such as channel coding and soft decision decoding will provide a more realistic model of the proposed SC-FDMA system. In fact using some error control coding techniques

such as space-time coding in the system will further improve the BER performance of the proposed multi-user detection algorithms.

- The presented results assume that the receiver has a perfect knowledge of the frequency response of the channel. It may be very interesting to start with the assumption that the channel coefficients are unknown to the receiver and use some channel estimation techniques based on pilot signals insertion such as Least Square (LS) or without pilots insertion such as the one based on subspace decomposition which is a blind estimation technique proposed by professor Claude D'Amours [25]. Including the effects of channel estimation errors will provide a more realistic evaluation of the systems performance in terms of BER and spectral efficiency.
- Last but not the least, it is possible to extend this study with the inclusion of advanced MIMO techniques such as multi-user MIMO (MU-MIMO). In fact, instead of having every SC-FDMA user communicating from a single antenna transmitter to a single multi-antenna receiver, it is possible to use MU-MIMO to apply an extended version of space-division multiple access (SDMA) to allow each SC-FDMA user to communicate from a multi-antenna transmitter to multiple receivers.

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