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Performance Evaluation of Uplink Multiple Access Techniques in LTE Mobile Communication System

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Abstract

The User Equipments (UE) nowadays are able to provide various internet applications and services that raise the demand for high speed data transfer and Quality of Service (QoS). Accordingly, next generation mobile communication systems driven by these demands are expected to provide higher data rates and better link quality compared to the existing systems. Orthogonal Frequency Division Multiple Access (OFDMA) and Single Carrier Frequency Division Multiple Access (SC-FDMA) are strong multiple access candidates for the uplink of the International Mobile Telecommunications-Advanced (IMT-Advanced). These multiple access techniques in combination with other promising technologies such as multi-hops transmission and Multiple-Input-Multiple-Output (MIMO) will be utilized to reach the targeted IMT-Advanced system performance.

In this thesis, OFDMA and SC-FDMA are adopted and studied in the uplink of Long Term Evolution (LTE). Two transmission scenarios are considered, namely the single hop transmission and the relay assisted transmission (two hops). In addition, a hybrid multiple access technique that combines the advantages of OFDMA and SC-FDMA in term of low Peak-to-Average Power Ratio (PAPR) and better link performance (in terms of Symbol Error Rate (SER)) has been proposed in relay assisted transmission scenario.

Simulation results show that the proposed hybrid technique achieves better end-to-end link performance in comparison to the pure SC-FDMA technique and maintains the same PAPR value in access link. In addition, a lower PAPR is achieved compared to OFDMA case, which is an important merit in the uplink transmission due to the UE's power resources constraint (limited battery power).

Keywords: IMT-Advanced, LTE, LTE-Advanced, OFDMA, SC-FDMA, Multi-hop transmission, PAPR.

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Dedication

To our families and friends for their encouragement and continued support,

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List of Acronyms

3GPP	Third Generation Partnership Project
3GPP2	The 3rd Generation Partnership Project 2
ACK	Acknowledgment (in ARQ protocols)
ARQ	Automatic Repeat request
BS	Base Station
EDGE	Enhanced Data rates for GSM Evolution
eNB	Evolved Universal Terrestrial Radio Access Network Node B
EPC	Evolved Packet Core
E-UTRAN	Evolved Universal Terrestrial Radio Access Network
FDD	Frequency Division Duplexing
FDMA	Frequency Division Multiple Access
HARQ	Hybrid ARQ
HSDPA	High-Speed Downlink Packet Access
HSPA	High-Speed Packet Access
HSUPA	High-Speed Uplink Packet Access
ITU	International Telecommunication Union
IMT-A	International Mobile Telecommunications Advanced
LTE	Long Term Evolution
MIMO	Multiple-Input Multiple-Output
NACK	Negative Acknowledgment (in ARQ protocols)
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak-to-Average Power Ratio
QAM	Quadrature Amplitude Modulation
QoS	Quality-of-Service
QPSK	Quadrature Phase-Shift Keying
RN	Relay Node
SC-FDMA	Single Carrier FDMA
TDD	Time Division Duplexing
TDMA	Time Division Multiple Access
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Telecommunications System
UTRAN	Universal Terrestrial Radio Access Network

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CHAPTER 1

Introduction

1.1 Introduction

The demand for high-speed mobile broadband access is growing exponentially in the last decade and expected to continue growing even more in the future, driven by unlimited possibilities in internet services and applications, and advances in handheld and portable equipments. To meet with current and future demands for reliable high data rates over the mobile networks, the International Telecommunication Union (ITU) started working since October 2005 to set a definition and standards for the future Fourth-Generation (4G) mobile system also known as IMT-Advanced. One of the key features in IMT-Advanced is to provide enhanced peak data rates up to 100 Mbps (in outdoors) and 1 Gbps (indoors) [1, 2].

In response to the ITU call for proposals on IMT-Advanced, six proposals were submitted in October 2009, as candidates for IMT-Advanced by different organizations. These proposals are based either on the Third Generation Partnership Project (3GPP) standards (mainly LTE and beyond (LTE-Advanced)) or the Institute of Electrical and Electronics Engineers (IEEE) standards (mainly IEEE802.16e and IEEE802.16m technology standards) [3].

One of the key requirements in next generation mobile communication systems is to design robust air interface techniques that are capable to provide high data rate in which an especial attention is given to the uplink transmission merits such as higher spectral efficiency, higher throughput, and long battery life (power efficiency). Towards this goal, both IMT-Advanced candidate standards proposed efficient modulation and access techniques based on OFDMA and SC-FDMA. The 802.16e (mobile WiMax) adopts the OFDMA technique in downlink and uplink directions. While LTE uses the OFDMA in the downlink direction and a modified version of OFDMA known as SC-FDMA, due to its favorable low PAPR characteristics, in the uplink direction. In addition, the use of the multi-hop cellular architecture is expected to be a cost-effective solution to provide the UE with favorable channel conditions and higher throughput. The Relay Node (RN) is placed between the UE and the Base Station (BS) either to extend the cell coverage area or to increase the cell capacity [4].

1.2 Thesis scope and contribution

The aim of this thesis work is to investigate different uplink radio access techniques for upcoming IMT-Advanced standards (mainly those proposed by LTE Rel8 and mobile WiMax (IEEE802.16e) standards) under single-hop and two-hop scenarios. Accordingly the scope of this thesis work will cover the following points:

- Study the performance of SC-FDMA and OFDMA access techniques in term of Symbol Error Rate (SER) in different scenarios, namely the single hop and two hop transmission scenarios.
- Two subcarriers mapping schemes, the localized and the interleaved schemes are studied and their performance is compared in the OFDMA and SC-FDMA cases in terms of SER.
- A hybrid multiple access technique is proposed to enhance the performance in relay assisted scenario which is based on using different combination of the SC-FDMA/OFDMA in the access link and relay link.

1.3 Thesis report outline

This thesis report has been organized into six chapters; *chapter one* provides a general introduction to the thesis work scope and outlines the contents of the thesis report. The contents of the remaining five chapters can be highlighted as follows:

Chapter two is organized into two sections: in the first section, an overview of the LTE evolution towards LTE-Advanced is provided. In the second section an introduction to the relaying technology in the LTE-Advanced is provided.

Chapter three is also organized into two sections: in the first section, an introduction to the mobile channel characteristics and radio propagation is given. In the second section, the Orthogonal Frequency Division Multiplexing (OFDM) and Single Carrier modulation with

Frequency Domain Equalization (SC-FDE) techniques are introduced, in term of their basic operation and pros and cons.

In Chapter four, the basic concepts of the proposed multiple access techniques (i.e. OFDMA and SC-FDMA) are discussed. In addition, the adoption of these techniques in view of LTE standard, in terms of frame structure and format, is introduced. Further, the basic concepts of the subcarriers mapping schemes are discussed: the localized and interleaved subcarriers mapping schemes. At the end of the chapter, the low PAPR value as main advantage of the SC-FDMA is discussed.

In Chapter five, a description of the conducted simulation study is provided. In the first section the layout of the applied simulation in terms of the designed scenarios with used parameters and assumptions are discussed. In the last section of this chapter, the simulation results are presented and analyzed.

Finally in Chapter six, the main thesis findings and simulation results are presented.

CHAPTER 2

An Overview of LTE and LTE-Advanced Systems

2.1 Introduction

The advances towards high speed mobile wireless access can be divided into two main migration paths. The first path represents the evolution of the current Third Generation (3G) mobile cellular systems towards the IMT-Advanced. It includes systems specified by 3GPP such as Wideband Code Division Multiple Access (WCDMA), High-Speed Downlink Packet Access (HSDPA), High-Speed Uplink Packet Access (HSUPA), High-Speed Packet Access Plus (HSPA+) and LTE/LTE-Advanced, and other cellular systems specified by the 3GPP2 such as CDMA20001x and Ultra Mobile Broadband (UMB). The second evolution path depends on modifying some existing fixed wireless system to incorporate mobility standards which is represented by the IEEE roadmap towards IEEE802.16e and its amended version IEEE802.16m. The evolution paths are presented in Figure 2-1[5, 6].

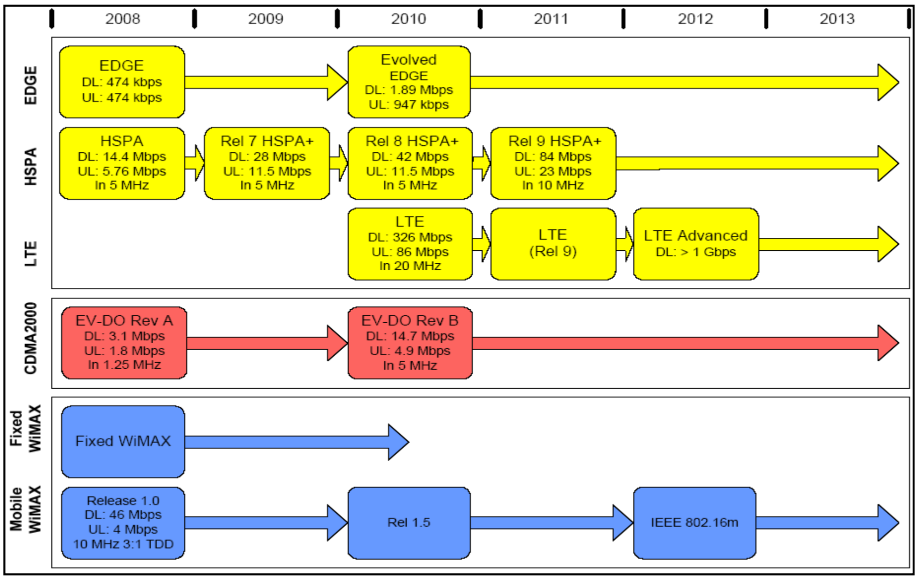

Figure 2-1 3GPP, 3GPP2 and IEEE Roadmaps Toward 4G [6].

2.2 The Trends in LTE-Advanced Standardization Process

The LTE Rel8 standard is key step in 3GPP roadmap towards IMT-Advanced but further enhancements are still required to fulfill the system level performance targeted by IMT-advanced. That is why the 3GPP started working on an extension for LTE standard known as LTE-Advanced [5]. In the following subsections, the LTE Rel8 standard is briefly overviewed along with the main emerging technologies and enhancements towards LTE-Advanced.

2.2.1 Networks Architecture of LTE Releases 8

The basic architecture of LTE system is demonstrated in Figure 2-2. All the network interfaces are based on internet protocols (IP). The LTE system as depicted in Figure 2-2 consists of radio access network and the core network which represent the IP connectivity layer of LTE system [5, 7].

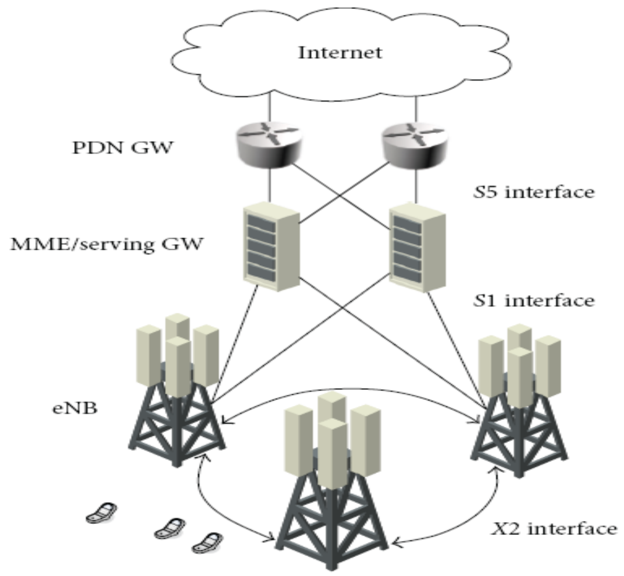

Figure 2-2 LTE Release 8 Network Architecture [1].

2.2.1.1 Core Network Part:

All operations of the core network in LTE are completely based on packet switching domain, i.e., all the network interfaces are based on IP protocols, and so it is called Evolved Packet Core (EPC) [1, 7]. The main idea of EPC is to keep the number of operating nodes and interfaces as minimum as possible (flat structure). The EPC divides the network entities, according to their functionality, into control-plane entities such as the Mobility Management Entity (MME) and data/barer-plane entities such as the Serving Gateway (SGW). The main entities in the EPC can be described briefly as follows [1, 7]:

i. *The Mobility Management Entity (MME):* The MME is a signaling only entity; it represents the control plane function of the EPC. The main control functions performed by the MME are the subscribers' equipments paging, location function, and the bearer/session establishment. Those functions include tasks such as UE location update, roaming management, controlling the UE authentication, authorization procedures, the connections establishment, and security negation [1, 7].

ii. *The Serving Gateway (S-GW):* S-GW is a switching and routing node that routes and forwards the user data packets to and from the BS or Evolved- Universal Terrestrial Radio Access Network NodeB (eNB). For example, during the connection mode (i.e. UE is connected), the S-GW establishes a tunnel to relay data traffic between UE (via specific BS) and the P-GW (Packet Data Network Gateway), which is the interface to the internet [1, 8].

iii. *Packet Data Network Gateway (PDN GW):* is the interface point or edge router between the EPC and the external packet data network. A UE may have simultaneous connectivity with more than one PDN GW [1, 8].

iv. *The Policy and Charging Rules Function (PCRF):* the PCRF performs the Policy and Charging Control (PCC) functions. It controls the tariff making and QoS configuration of each user. The defined tariff and QoS policies for each UE are provided to the P-GW and the S-GW, in order to be implemented [1, 8].

2.2.1.2 Radio Access Network

The radio access network of LTE is called Evolved Universal Terrestrial Radio Access Network (E-UTRAN). This evolved RAN for LTE consists of a single node, i.e., BS or eNB, which deal with the UEs. The BS/e-NB is a radio base station that controls all the radio interface related functions, the eNB acts as a gateway between UE and the EPC. The eNB function is to handle all the communication towards the UE using the related radio protocols and forward radio connection to core network (EPC) using the corresponding IP based connectivity. To achieve its function as interface between the radio and core parts of the network, the eNB hosts two bunches of protocols, the Evolved Universal Terrestrial Radio Access (E-UTRA) user plane protocols and the control plane protocols. The first bunch, i.e., the user plane contains the Physical (PHY), Radio Link Control (RLC), Medium Access Control (MAC), and Packet Data Control Protocol (PDCP) layers protocols that necessary to transfer the data traffic to and from the UE. The other bunch of protocols i.e. the control plane is associated with the Radio Resource Control (RRC) and it handles functions such as the radio resource management, admission control and resource scheduling [8, 9].

2.2.2 Key Technologies in LTE Radio Access Network

2.2.2.1 Efficient Modulation and Multiple Access Techniques

The basic modulation scheme in LTE depends on the multicarrier modulation, namely OFDM which is used due to its numerous advantages such as its robustness against the Inter Symbol Interference (ISI). In LTE physical layer, both of the Frequency Division Duplexing (FDD) mode and Time Division Duplexing (TDD) mode are used with different frame structures. OFDMA scheme is the adopted multiple access scheme in the downlink direction. However in the uplink direction, SC-FDMA is preferred due to its low PAPR. More details about the multiple access techniques in LTE are presented in Chapter 4 [1, 5].

2.2.2.2 Dynamic Resource Allocation and Link Adaptation

The radio resources in the LTE are allocated as time-frequency domain grid. The smallest resource that can be allocated to a specific user is called the resource block which consists of 12 subcarriers and one time slot. The role of the scheduler includes the radio frequency resource allocation (Resource Blocks) and the adaptation of the used modulation and coding techniques according to the radio-link quality for each user. In LTE standard the defined modulations are QPSK, 16QAM and 64QAM, which are adaptively selected based on traffic types, available bandwidths and radio channel quality [1, 10].

2.2.2.3 Multi-Antenna Techniques

In order to reach the higher performance goals targeted by the LTE system, multi-antenna transmission techniques are used to achieve better system performance such as increasing the capacity and providing higher data rate per user [11]. Three schemes or ways for utilizing the multi-antenna techniques can be defined as follows [5]:

- *Spatial Diversity*: the goal of this technique is to achieve transmit or receive diversity by suppressing the instantaneous fading effects that is caused by the transmission through multipath channel. The idea behind the spatial diversity is to create a number of independent paths. It transmits and receives with low fading correlation in order to achieve higher gain at the receiver side [5].
- *Beam-forming*: when this technique is used, the base station can direct the transmission or more specifically the radiation beam toward specific user in order to improve the received signal power [5].
- *Spatial multiplexing (SM) or multiple-input and multiple-output (MIMO)*: in this technique a high data rate is achieved by transmitting different data streams over independent parallel channels. This is achieved by utilizing multiple transmit and receive antennas, without increasing the channel bandwidth or the total transmitted power [5].

LTE adopted various multi-antenna techniques such as transmit diversity, single user (SU)-MIMO, multiuser (MU)-MIMO, and dedicated beam-forming [5, 12].

2.2.2.4 Hybrid Automatic Repeat Request (Hybrid ARQ)

In LTE system a combination from the Forward Error Correction (FEC) techniques and the Automatic Repeat Request (ARQ) is used, which is known as hybrid ARQ [1, 13]. ARQ is an error control scheme that encloses procedures to detect the errors occurrence in the received frames and consequently sends a feedback to the transmitter [1]. The FEC technique encloses a redundancy data or error correcting code in the sent information in order to enable the receiver side from detecting and correcting the occurred errors.

2.2.3 Key Technologies Trends towards LTE- Advanced

To meet IMT-Advanced system performance requirements, the 3GPP is working in new standard known as LTE-Advanced. Some of the target performance enhancements in LTE-Advanced are described in Table 2-1.

Table 2-1 system performance requirements for IMT-Advanced [14].

		LTE Rel8	LTE-Advanced	IMT-advanced
Peak Data Rate	**UL**	**75 Mbps**	**1 Gbps**	**1 Gbps (Low mobility)**
	DL	**300 Mbps**	**500 Mbps**	**1 Gbps (Low mobility)**
Peak Spectrum Efficiency [bps/Hz]	**UL**	**3.75**	**15**	**6.75**
	DL	**15**	**30**	**15**

The key technology components that are expected to be part of LTE-Advanced standard are introduced in the following subsections.

2.2.3.1 Enhanced Multi-antenna transmission

As described in previous subsection, the support for multi-antenna transmission is considered as an important part of LTE Release 8 standard. In order to support higher data rate and better spectral efficiency in the LTE-Advanced, the use of a combination of MIMO transmission, beam-forming or Multiuser (MU) MIMO is considered. The LTE-Advanced is expected to support up to eight transmission streams in the downlink direction and up to four transmission streams in the uplink direction [5, 13, 15].

2.2.3.2 Carrier Aggregation

The LTE support flexible bandwidth usage ranging from around 1.4 MHz up to 20 MHz, while for LTE-Advanced wider transmission bandwidth up to 100 MHz is used to achieve the targeted data rate. To maintain backward operation compatibility with LTE Release 8 and to facilitate the use of contiguous and non-contiguous frequency components, the carrier aggregation concept is introduced by LTE-Advanced, in which multiple of LTE release 8 carriers are used as illustrated in Figure 2-3 [15].

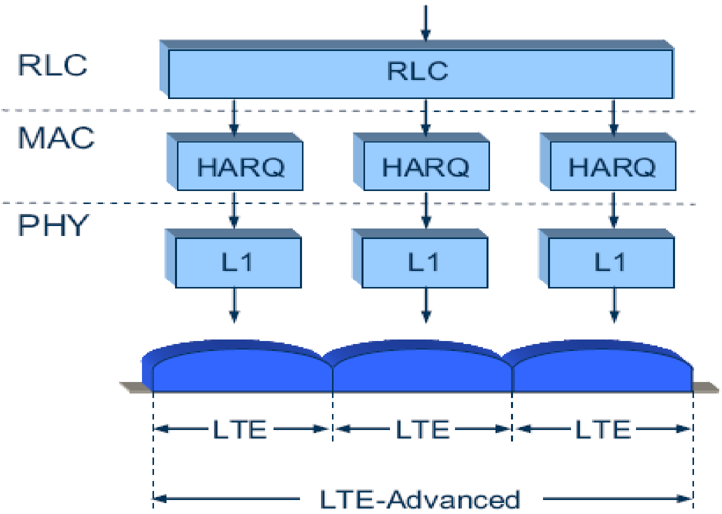

Figure 2-3 Carrier aggregation concept in LTE-Advanced [15].

2.2.3.3 Coordinated Multi-Point (CoMP) Transmission and Reception:

The basic idea behind the coordinated multi-point transmission and reception is to implement robust coordination between different cell sites in terms of dynamic resource scheduling, joint transmission, and reception from and to specific UE [5, 15].

2.2.3.4 Multi-Hops Concept

Another way to provide very high data rate targeted by LTE-Advanced is based on enhancing the cell coverage area by introducing relay node or number of relay nodes. The multi-hop or relaying technologies will be introduced in the next subsections.

2.3 Relaying Technology in LTE/LTE-Advanced

Generally two types of relay nodes have been defined by LTE-Advanced and IEEE802.16j standards which are briefly introduced hereunder [16-19]:

- Relay node type 1 (non-transparency): act as BS for the connected UEs by transmitting reference signal and control information [16, 17].
- Relay node type 2 (transparency): the UE will not be aware of the existence of the RN. The received control message will come from the BS and the relay just forward it. In other words, no logical connection is established between the RN and UE [17].

To forward the end-user traffic the RN will be assigned radio resources in the access link (i.e., link between the UE and RN) and relay link (between RN and BS). According to how the radio resources are assigned two relay node types can be defined. The first type called the in-band relay node, in which the radio resources are shared between the access and the relay links. The second type is called the out-band relay node, in which dedicated radio resources are assigned to the relay link [18]. The relay nodes are also classified according to the type of applied forwarding strategy into three basic categories: amplify and forward strategy, demodulate and forward strategy, and decode-and forward strategy. These strategies are briefly introduced in the following subsections [16].

2.3.1 Amplify and Forward Relay Strategy

When the amplify-and-forward relaying strategy is adopted, the relay node will act as a layer 1 repeater. The received signal from the BS or UE is amplified and then forwarded to the destination (either the UE or the BS) [19]. The advantages of this relay type are the simplicity and low delay time. On the other hand it also amplifies the noise [17].

2.3.2 Decode and Forward Relay Strategy

In this strategy, full decoding and correction operation is performed by the RN o the received signal from the BS or UE based on the adopted channel coding technique. After that the RN encodes the detected information and forwards it to the destination (either BS or UE). This relaying strategy reduces the errors caused by wireless channel impairments but it requires more processing time (high delay) compared to the case of amplify and forward strategy [17].

2.3.3 Demodulate and Forward (Detect and Forward) Relay Strategy

The relay node in this case demodulates the received signal from the UE or BS by performing hard decision (no channel decoding operation is performed). In the second phase the relay forwards the modulated information either to BS or UE. The advantage of this strategy is the less delay time compared to the decode and forward strategy, however the errors caused by propagation over the wireless channel cannot be avoided [17].

CHAPTER 3

Wireless Channel Characteristics and Multicarrier Modulation Techniques

3.1 Introduction

As mentioned in the previous chapter, one of trends in the future wireless communication systems is to utilize wideband spectrum (bandwidth) to achieve the required data rates defined by ITU IMT-A framework (e.g., the adoption of 100 MHz bandwidth in the LTE-Advanced standard) [1, 20]. Current 3G communications systems such as the WCDMA suffer from the frequency selectivity of the channel due to multipath effect. The use of multi-carriers modulation techniques such as OFDM is a promising solution for the ISI problem [7].

The aim of this chapter is to discuss the utilization of the multi-carrier modulation techniques in the LTE system. In the first section of this chapter some important concepts about the wireless channel characteristics are introduced that are necessary for our discussion. In the second section the basic operation concepts of the OFDM and SC-FDE modulation techniques are discussed.

3.2 Wireless Channel Characteristics

The signal transmitted over the wireless channel encounters number of impairments that are originated from different sources. These impairments are summarized into three groups [20]:

- The first source of impairments is related to the radio propagation physics, such as large scale fading, multipath effect, Doppler effect, and slow and fast fading.
- The second source is related to the noise induced by equipments at the transmitter and receiver sides (e.g., nonlinear distortion caused by amplifier, frequency offset, and timing error).
- The third source comes from external inference sources (e.g., co-channel interference, impulse noise, and white noise).

3.2.1 Path-Loss and Shadowing

The received signal power varies according to the distance between the transmitter and the receiver; which is also known as the path-loss effect. The signal power at the receiver end is inversely proportional to the distance between the transmissions endpoints. This relation is described by the following equation:

$$P_r = (k * P_t)\frac{\lambda_c}{4\pi d^2} \quad (3\text{-}1)$$

where P_r is the received power, P_t is the transmitter power, d is the separation distance and λ_c is the wavelength, and k is a proportionality constant.

Due to differences in the positioned obstacles along the path between the transmitter and the receiver, the signal received at the same distance from the transmitter in different directions may not have the same power. This phenomenon is known as the shadowing effect. The path-loss and the shadowing effects represent large scale fading that describes the variation around the mean value of the received signal power for large distances. Many empirical path-loss models exist, such as Okumura and Hata models. These models consider different factors in addition to distance and signal frequency (e.g., the transmitter and receiver antenna heights and the local topography for the transmission area) [20, 22, 23].

3.2.2 Multipath Fading

In wireless communications, number of copies from the transmitted signal appears at the receiving side. One of them may arrive from Line of Sight (LOS) path and the rest are due to reflection and diffraction from nearby obstacles. These various signal copies are added at the receiver causing effects such as delay spread, loss of signal strength, and widening of the frequency spectrum [20, 24]. The maximum delay spread of the wireless channel (T_m) is expressed as the time difference between the arrival of the first signal copy and the last copy of the transmitted signal which cause the ISI effect. To overcome the ISI, time-domain equalization techniques are utilized in the case of single carrier transmission or frequency-domain equalization techniques in the case of multi-carrier transmission such as OFDM [23, 20].

3.2.3 Doppler Shift

Doppler shift describes the change in the received signal frequency due to the motion of the receiver relative to the transmitter. This change is described in terms of Doppler frequency (f_d) defined as:

$$f_d = \frac{v}{\lambda_c} * cos\theta \qquad (3\text{-}2)$$

where v (m/s) is the velocity and θ is the angle of received wave at the receiver [20].

The received signal at the destination has components that vary in frequencies from the basic signal frequency by ($-f_d$Hz) and ($+f_d$ Hz).

3.2.4 Flat Fading and Frequency-Selective Fading

The time dispersion in the transmitted signal, due to multipath effect, causes either flat of frequency-selective fading effect. The flat fading and frequency-selective fading are occurred depending on the relation between the transmitted signal bandwidth and the width of the frequency response of the channel. When the transmitted signal bandwidth is narrow as compared to the flat fading channel bandwidth (coherence bandwidth) the frequency components of the transmitted signal are attenuated equally. In contrast in the frequency selective fading channel, the frequency components of the transmitted signal are attenuated unequally. The channel coherence bandwidth is a statistical measure of the range of frequencies over which the channel is considered to be flat [20, 21].

3.2.5 Standard Models for Wireless Channel

Studying and modeling the propagation effects is a continued research topic in radio and mobile communication fields. Defining good models for the wireless channel characteristics set a base for the performance comparisons between different standards. For these purposes, different propagation and channel models are designed based on theoretical and experimental studies to study and compare specific systems. For example, a set of standard propagation and channel models is provided by ITU-R for evaluating and comparing the performance of IMT-2000 systems [7].

3.3 Orthogonal Frequency Division Multiplexing (OFDM)

In OFDM modulation technique, the available spectrum band is divided into orthogonal narrowband channels referred to as subcarriers. The main concept behind OFDM is to utilize many subcarriers with narrow bandwidth as compared to the channel frequency response. By this way the channel exercises a flat fading effect on the transmitted information on each subcarrier [24]. In addition, OFDM has better spectral efficiency than Frequency Division Multiplexing (FDM) due to the subcarriers spectral overlapping property as shown in Figure 3-1.

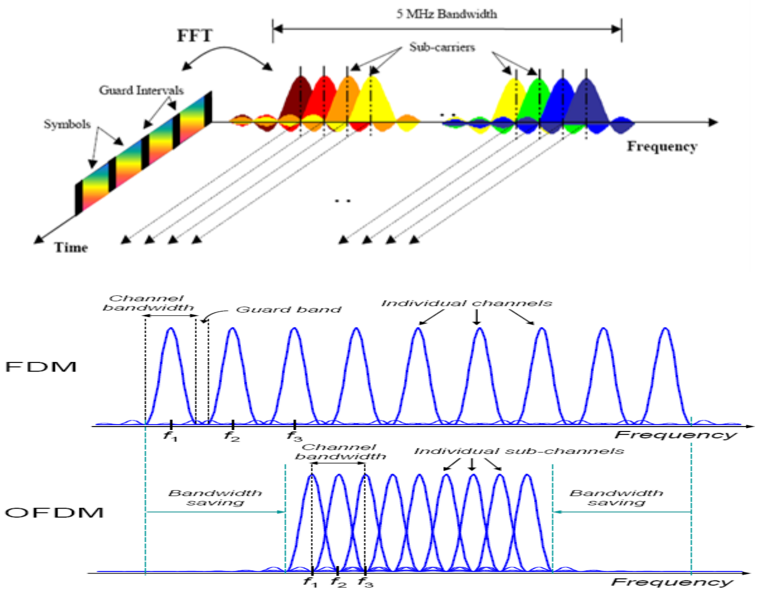

Figure 3-1 OFDM subcarriers overlapping [10].

In the traditional implementation of OFDM transceiver system, bank of frequency oscillators are used at the transmitter and receiver sides. However, less complicated and more practical implementation can be achieved by the aid of Discrete Fourier Transform (DFT) and IDFT as illustrated in Figure 3-2. The DFT/IDFT operation is realized usually by using Fast Fourier Transform (FFT) and Inverse FFT (IFFT) algorithms in to achieve more efficient processing speed [20, 7].

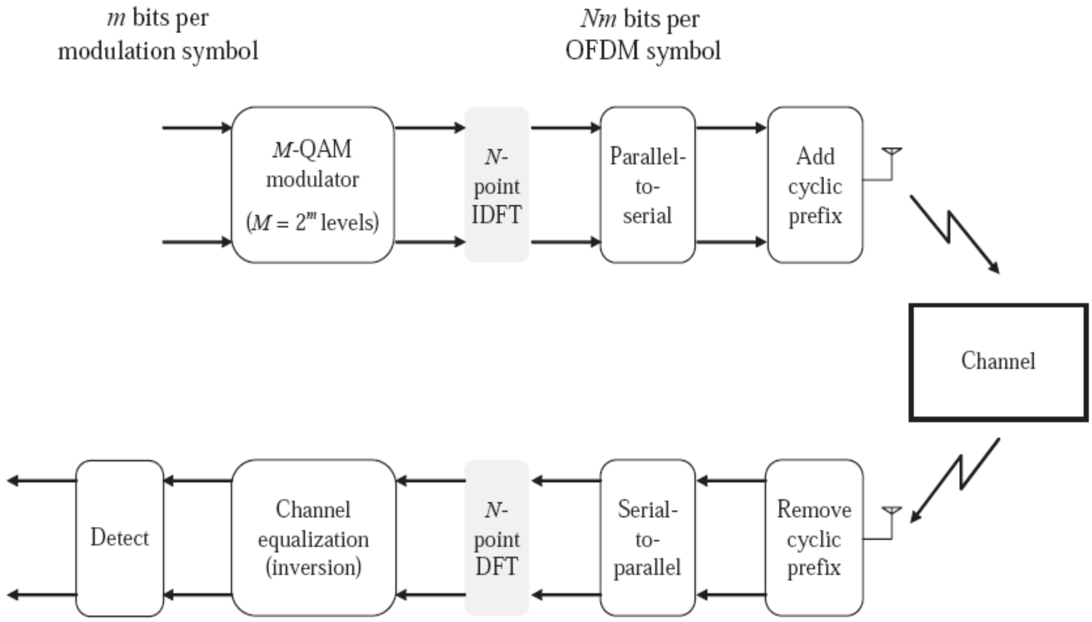

Figure 3-2 Basic OFDM transceiver [20].

3.3.1 OFDM Transmitter

The IFFT module can be considered as the heart of the OFDM transmitter. IDFT block is used to transform the modulated data sequence of length *N {X (k)}* into time domain signal *{Z (n)}* with the following equation:

$$Z(n) = IDFT\{X(k)\} = \frac{1}{N}\sum_{k=0}^{N-1} X(k) * e^{\frac{j2\pi kn}{N}}, \qquad (3\text{-}2)$$

Where N is the IDFT length, $n = 0,1, \ldots, N-1$

In order to compensate for the symbol dispersion that is caused by the channel delay spread (T_m), a guard period between OFDM symbols is added. This is known as cyclic prefix (CP). The aim of this process is to reduce the ISI effect. This CP insertion operation is shown in Figure 3-3.

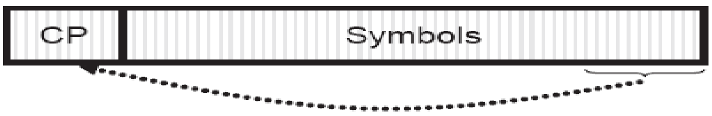

Figure 3-3 Cyclic prefix insertion [20].

The reason behind inserting the CP at the begging of the $Z(n)$ sequence can be explained by considering the signal processing operations and the DFT/IDFT modules on the transmitted signal. A linear convolution operation takes place between the channel impulse response and the transmitted signal while the DFT-based FDE operation performed at the receiver side is a circular convolution operation in time domain. In order to match the two operations a CP is inserted at the transmitter to make the channel filtering look like a circular convolution. After CP insertion, pulse shaping is applied to reduce side lobes in the frequency domain and limit out-of-band interference [20].

3.3.2 OFDM Receiver

The receiver inverses the operations performed at the transmitter. The CP is removed from the received symbol, and then the resulted OFDM symbol in time domain is converted back to frequency domain using DFT operation as described by the following equation:

$$X(k) = DFT\{r(n)\} = \sum_{n=0}^{N-1} r(n) * e^{-\frac{j2\pi kn}{N}} \qquad (3\text{-}3)$$

Where N is the DFT length, $k = 0,1, \dots, N-1$.

The DFT module performs circular convolution operation in time domain which is equivalent to multiplication in frequency domain. The next stage is to perform channel equalization process in the frequency domain. Number of equalization techniques can be implemented such as Minimum Mean Square Error (MMSE) equalizer and the Zero-Forcing Equalizer (ZFE). The final stage is to demodulate and detect the transmitted binary information using suitable detection techniques such as hard decision detection or soft decision detection techniques [20].

3.3.3 Important Parameters in OFDM based Wireless System

To design wireless system based on OFDM transmission technique, number of parameters need to be defined which are described in the following subsections [10].

3.3.3.1 Subcarriers spacing (Δf)

The long OFDM symbol duration has better resistance to the channel multi-path effect; this can be achieved by either increasing the CP length or using narrow bandwidth

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(small subcarrier spacing value). But the use of narrow bandwidth increases the sensitivity towards Doppler effect. The frequency variations due to Doppler spread cause an inter channels inference at receiver side (losing the subcarriers orthogonality) [10].

3.3.3.2 Number of sub-carriers (N_C)

The number of the used subcarriers in OFDM system depends on the allocated bandwidth and the defined subcarrier spacing (Δf). The allocated bandwidth (B) can be expressed as ($B = NC \times \Delta f$). It is important to mention that not the whole allocated bandwidth can be used; some constraint should be considered such as the need for bandwidth guard at the upper and lower frequency spectrum. Typically 10% of the used bandwidth is deducted as guard bands; in case of LTE for example out of 5 MHz only 4.5 MHz is usable so when 15 kHz sub-carrier spacing is used approximately 300 sub-carriers can be exploited [10].

3.3.3.3 The Cyclic Prefix Length

The suitable CP length is important to mitigate the multipath effect. The increase of the CP length reduces the ISI affect at the expense of higher transmitted power loss. In LTE standard two cyclic prefix lengths are defined: normal cyclic prefix (around 5.7 μs) and extended cyclic prefix (around 16.67 μs) which corresponds to seven and six OFDM symbols per slot respectively. Extended cyclic prefix may used specific propagation scenarios with very long delay spread, for example in large cells [10].

3.4 Single Carrier Frequency Domain Equalization (SC-FDE)

The SC-FDE has better immunity towards the channel frequency selectivity as compared to OFDM. The basic SC-FDE transceiver is similar to its OFDM counterparts. The SC-FDE is differentiated from OFDM by performing both the IDFT and DFT operations at the receiver side as illustrated in Figure 3-4. Another difference is related to the modulation and demodulation operations; while OFDM perform these operations in the frequency domain, the SC-FDE perform them in the time domain. The two techniques perform the equalization operation in frequency domain on the receiver side after the DFT operation [20].

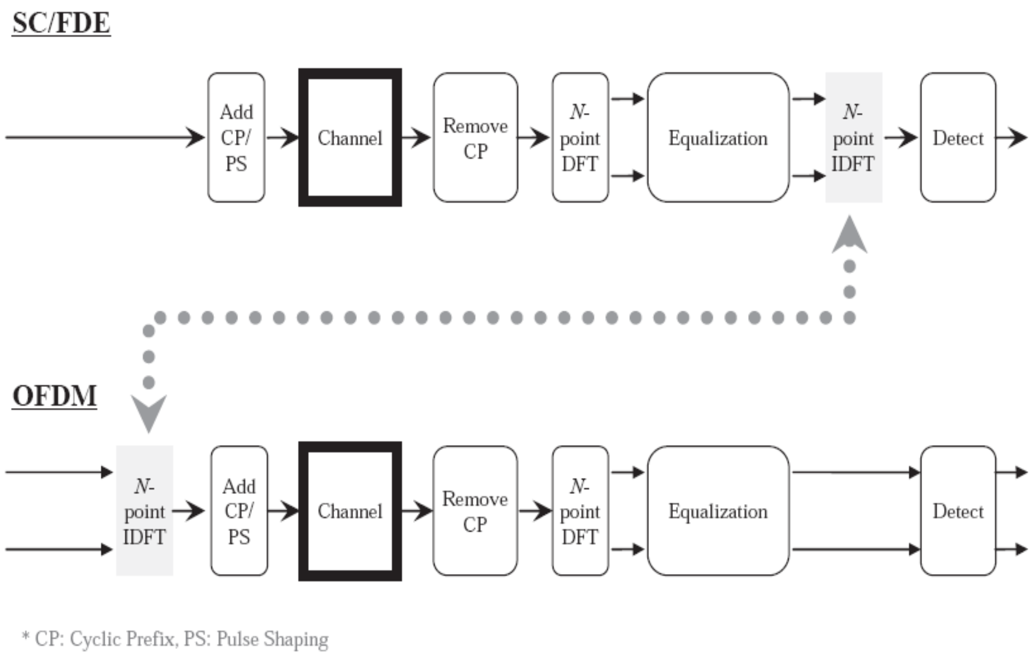

Figure 3-4 OFDM and SC-FDE transceiver comparison [20].

CHAPTER 4

Multiple Access Techniques in LTE

4.1 Introduction

Multiple access techniques are schemes that organize the transmission resources among multi-users to avoid the interference between the active user's communications. The traditional multiple access strategies are based on dividing the available resources among multi-users through the use of frequency, time, or code division multiplexing techniques. In Time Division Multiple Access (TDMA), each user is given a unique time slot, either on demand or in a fixed rotation. In Frequency Division Multiple Access (FDMA), each user is given a unique carrier frequency and bandwidth. In Code Division Multiple Access (CDMA) each user will have a unique code for transmission which allows each user to share the entire bandwidth and time slots with other users [26].

The two candidate standards for the forthcoming IMT-Advanced (i.e., mobile WiMAX and LTE-Advanced) use OFDMA as the multiple access technique in the downlink direction, but they use different frame structures, resource grouping and allocation. However, in the uplink direction the two systems adopt different techniques: mobile WiMAX uses OFDMA where as 3GPP standardization group has decided to use SC-FDMA in LTE [5]. The SC-FDMA technique utilizes a modified version of OFDM scheme to overcome the high PAPR problem. This technique also known as DFT-spread orthogonal frequency division multiple access[20]. The low PAPR property makes SC-FDMA more attractive for uplink transmission especially in the case of low-cost devices with limited power resources.

In this chapter, the basic principles of OFDMA and SC-FDMA are demonstrated as well as their implementation in LTE Rel8.

4.2 Orthogonal Frequency Division Multiple Access (OFDMA)

OFDMA is an OFDM-based multiple access scheme that is adopted in the downlink direction in both LTE and WiMax standards. As illustrated in Figure 4-1, the OFDMA can be seen as a hybrid technique of the FDMA and TDMA techniques. In this technique each user is provided with a unique fraction from the system bandwidth (OFDM subcarriers) per each specific time slot [20, 26]. Many of OFDMA advantages are inherited from OFDM technique (e.g., better spectral efficiency compared to FDMA technique). OFDMA also has the ability to perform the resource scheduling based on the channel time and frequency responses which allow assigning of different subcarriers to each user based on channel condition. This is known as multiuser diversity [27].

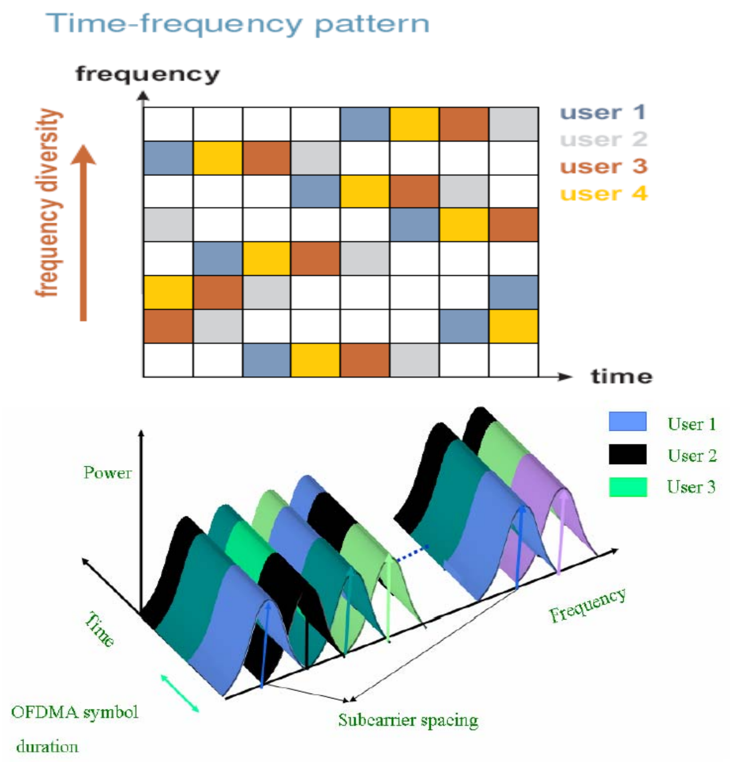

Figure 4-1 OFDMA basic operation [27].

4.3 Single Carrier Frequency Division Multiple Access (SC-FDMA)

SC-FDMA can be regarded as DFT-spread orthogonal frequency division multiple access, where time domain data symbols are transformed to frequency domain by DFT before going through OFDMA modulation as illustrated in Figure 4-2. The orthogonality of the users stems from the fact that each user occupies different subcarriers in frequency domain, similar to the case of OFDMA. The only different between OFDMA and SC-FDMA is introducing an additional DFT module at the transmitter side and IDFT at the receiver side. While equalization is performed in frequency domain in both cases, OFDMA performs modulation and demodulation operations in the frequency domain and SC-FDMA performs these operations in the time domain.

Since SC-FDMA effectively spreads each modulated symbol across the entire channel bandwidth that makes it less sensitive to the channel frequency-selective fading effect as compared to OFDMA. However the use of narrower bandwidth adds advantages to OFDMA over SC-FDMA by allowing possible adaptation of the modulation techniques and power resource per individual subcarrier [7, 20]. The most important advantage and difference between the OFDMA and the SC-FDMA is the low PAPR of SC-FDMA [7].

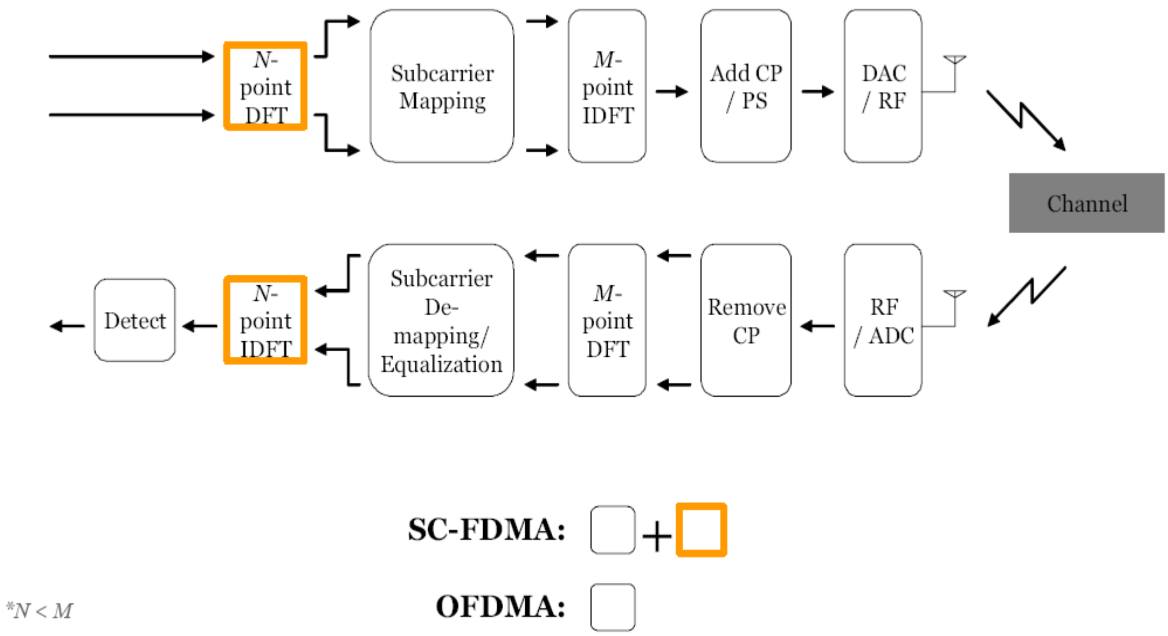

Figure 4-2 OFDMA and SC-FDMA transceiver comparison [25].

4.4 OFDMA and SC-FDMA implementation in LTE

4.4.1 Generic Frame Structure

Two generic frame structures are defined for the radio access network in LTE: frame structure of type 1 for Frequency Division Duplexing (FDD) mode, and frame structure of type 2 for Time Division Duplexing (TDD) mode [28]. As illustrated in the upper part of Figure 4-3, the operation of the FDD mode is depend on two carrier frequencies, one for uplink direction (f_{UL}) and one for downlink transmission (f_{DL}) which allow simultaneous transmission of the uplink and downlink frames. While the TDD operation, as illustrated the lower part of Figure 4.3, is depend on using one carrier frequency for both the uplink and downlink directions. The transmission time separation (guard period) required for TDD operation is achieved by splitting one or two of the ten sub-frames in each radio frame into three special fields namely the downlink part (DwPTS), guard period, and an uplink part (UpPTS) as demonstrated in Figure 4-3 [15].

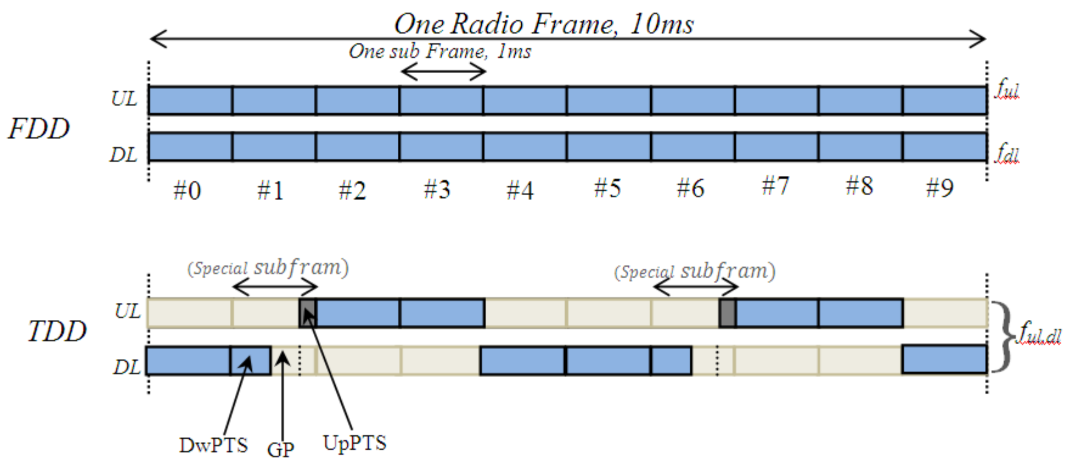

Figure 4-3 LTE frame structure in FDD and TDD modes [15].

Frame structure of type 1, which is applicable for FDD mode, is composed of 20 slots (each slot has duration of 0.5 ms) with total duration of 10 ms. A pair of two adjacent slots form one sub-frame with duration of 1 ms as illustrate in Figure 4-4 [28].

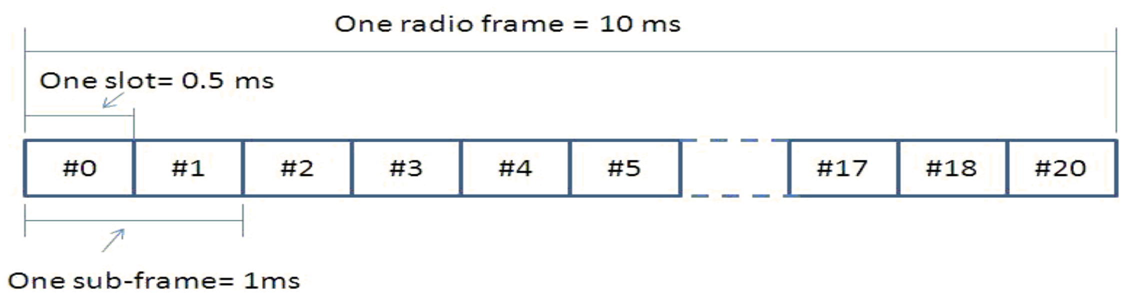

Figure 4-4 LTE frame structure Type1 [28].

Frame structure of type 2, which is applicable for TDD mode, is composed of two half fames of equal length of 5 ms duration slots. Each of the two halves contains five sub-frames of 1 ms duration. A pair of adjacent slots forms one sub-frame with duration of 1 ms as illustrated in Figure 4.5 [28].

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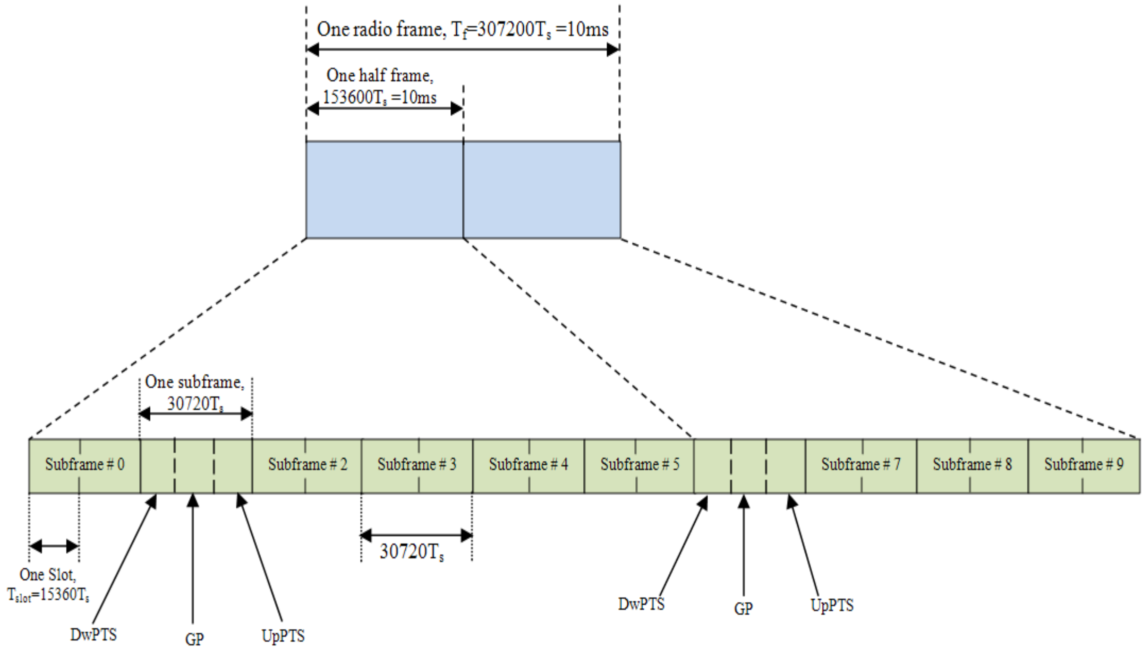

Figure 4-5 LTE frame structure Type 2 [28].

4.4.2 Physical Resource Block Parameters

The radio resources in LTE are organized into time-frequency grid, which is composed of N_{sc} consecutive subcarriers in frequency domain and time-slots in time domain as illustrated in Figure 4-6. The smallest radio resource unit is known as the resource element. It represents the assignment of one subcarrier per one time-slot. In LTE, these resource elements are concatenated in form of resource blocks as illustrated in Figure 4-6.

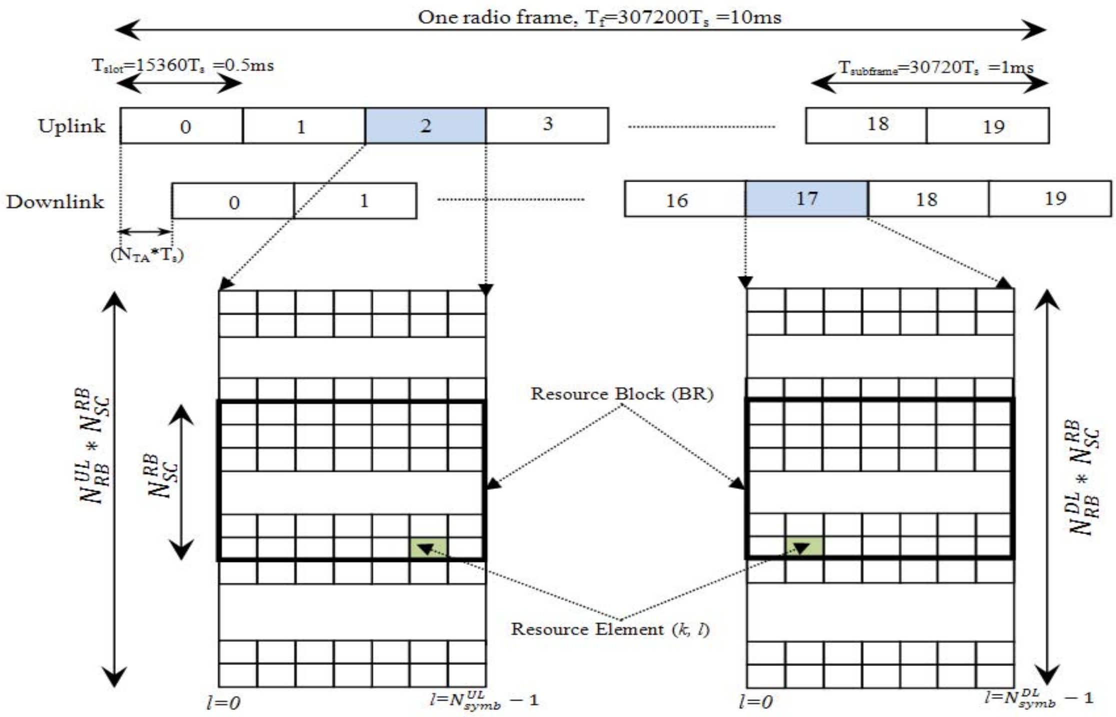

Figure 4-6 Frame structure and physical resource block in LTE uplink & downlink [7].

The Resource Block (RB) in LTE represents the smallest radio resources that can be allocated to any UE per one time slot. One RB is 0.5 ms duration (one slot) and bandwidth of 180 kHz (12 subcarriers or 24 subcarriers depending on the used frequency spacing of 15 kHz or 7.5 kHz, respectively) [7, 20].

The number of RBs in the resource grid vary according to the used bandwidth from 6 RBs for 1.4 MHz to 100 RBs for 20 MHz as illustrated in Table 4-1 [20].

Table 4-1 Resources Blok Number per Channel Bandwidth [20].

Channel Bandwidth [MHz]	1.4	3	5	10	15	20
Number of resource Blocks	6	15	25	50	75	100
Number of occupied subcarriers	72	180	300	600	900	1200
IDFT/DFT (RX) size	128	256	512	1024	1536	2048
Sample rate [MHz]	1.92	3.84	7.68	15.36	23.04	30.72
Sample per slot	960	1920	3840	7680	11520	15360

4.5 Subcarriers Mapping Schemes

In the case of multi-users transmission, the sub-carriers assignment among different users can be performed using two main techniques [10]:

1- Consecutive (or localized) subcarriers mapping.

2- Distributed subcarriers mapping.

4.5.1 Localized Subcarriers Mapping Scheme

In the localized subcarriers mapping scheme number of sub-carriers is allocated in one contiguous block to each user as shown in Figure 4-7. The major drawback of this method is its sensitivity to the channel frequency-selective fading [10].

4.5.2 Distributed/Interleaved Subcarriers Mapping Scheme

In this scheme, the allocated subcarriers to each user are distributed across the whole OFDM bandwidth as shown in Figure 4-7. In literature, the term interleaved is used to describe distributing the subcarriers among the whole bandwidth while distributed mapping refers to partial distribution (not the whole bandwidth is covered). This scheme is less sensitive to the channel frequency diversity due to the distribution of the subcarriers over the whole channel bandwidth. However, this scheme requires robust frequency synchronization [10].

4.5.3 Comparison between the Localized Scheme and the Interleaved Scheme

The good frequency diversity property of the distributed scheme leads to better SER performance but at the expense of complex channel estimation and equalization processes. In contrast, the localized mapping scheme does not have good frequency diversity property but the channel estimation and equalization processes are less complex. One way to exploit the benefits of the two schemes is to introduce a mid way scheme which is called Block-wise consecutive frequency mapping. In this scheme, multiple blocks with equidistant frequency spacing are allocated to users, where each block consists of a few number of consecutive subcarriers as shown in Figure 4-7 [10].

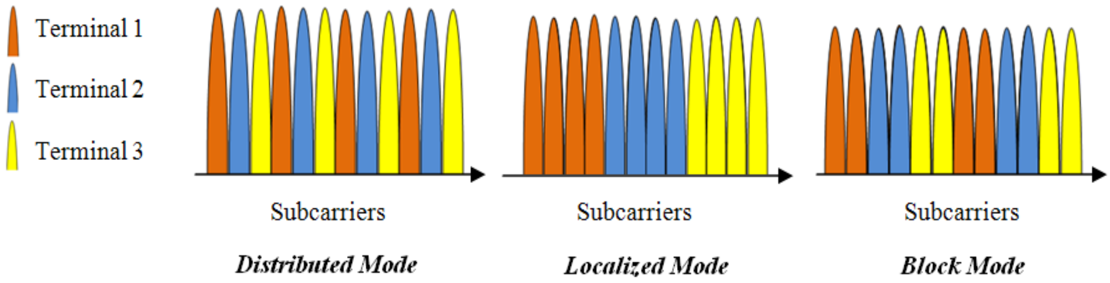

Figure 4-7 Basic subcarriers mapping schemes [25].

4.6 Peak to Average Power Ratio (PAPR)

The main advantage of SC-FDMA over OFDMA is the low PAPR. This comes from the fact that SC-FDMA technique emulates the single carrier transmission structure [7]. This subsection briefly discusses the PAPR concept for OFDMA and SC-FDMA techniques.

The role of the power amplifier in UE is to boost the outgoing signal to a level higher than the level of impairments introduced by the wireless channel. The power amplifier operation heavily consumes the battery power of UE. Thus, a power efficient operation of the UE's amplifier is considered as a key requirement to prolong the UE's battery operation life [29].

PAPR is defined as the ratio of the instantaneous signal power to the average signal power which can be expressed mathematically by [7, 20]

$$PAPR = \frac{|S(t)|^2}{E[|S(t)|^2]} \tag{4.1}$$

The PAPR is an indication for the amplifier efficiency. This can be understood by introducing the basic operation of ideal linear power amplifier. In such amplifier, the linear amplification can be achieved up to the saturation point [20]. Maintaining the operation in the linear region of the power amplifier is essential to achieve efficient operation. The high PAPR is an indication that a power back off is needed to remain in the linear operation region of the amplifier [7, 20]. The Operation in the nonlinear region of the amplifier causes spectral widening of the transmit signal which is resulted in unwanted Out-Of-Band (OOB) noise, which increases the SER at the receiver side [23]. The relationship between PAPR [dB] and transmit power efficiency can be described by:

$$\Gamma = \Gamma_{max} * P^{\frac{-PAPR}{20}} \quad (4\text{-}2)$$

where Γ is the power efficiency of the power amplifier while Γ_{max} is the maximum possible power efficiency.

When a higher order of digital modulation technique is used the PAPR will increase accordingly, especially in the case of Quadrature Amplitude Modulation (QAM). This increase in PAPR is due to the use of more constellations that lead to higher variations in the resulted modulated signal envelope [7, 20].

4.6.1 PAPR Properties of OFDMA (OFDM based Signal)

The main difference between an OFDM signal and single carrier signal is that OFDM consists of a number of independently modulated symbols by different carriers (*Nc*). Those carriers with different amplitudes and frequencies are summed together to form one OFDM signal as defined by the following equation:

$$S(t) = \sum_{n=0}^{N-1} S(n) * e^{j2\pi n\Delta f t} \quad (4\text{-}3)$$

where Δf is frequency spacing between any two adjacent subcarriers, $0 \le t \le Ts$ (*Ts* is the OFDM symbol duration)

The OFDM signal represented in equation (4-3) has large variation in its envelope values that is why OFDM modulation technique and its OFDMA version suffer from high PAPR. For an OFDM signal that consists of *Nc* sub-carriers, the PAPR can be estimated by equation (4-4), in which the PAPR will be less or equal to *Nc* [10, 23].

$$PAPR_{max} = N_C \quad (4\text{-}4)$$

4.6.2 PAPR Properties of SC-FDMA

In SC-FDMA the modulated symbols block are converted to frequency domain, then subcarriers mapping operation is taken place based on one of the two main schemes: the localized or the interleaved mapping schemes. Depending on the subcarriers mapping scheme, the resulting SC-FDMA modulated symbols in time domain are different. In the case of interleaved subcarriers mapping the resulting SC-FDMA modulated symbols in time domain are repetition of the original modulated input symbols with differences in the phase a and scaling factor of $\left(\frac{1}{Q}\right)$, where Q is the ratio between data block size and IDFT module size. In localized mapping, the resulting SC-FDMA symbols have the same copies of the modulated input sample scaled by $\left(\frac{1}{Q}\right)$ in the related consecutive positions (block size positions). In remaining positions, the values of the samples are sum of all complex values in the block size with different complex scaling factor [25]. In [20] and [25] numerical analysis of the Complementary Cumulative Distribution Function (CCDF) of the PAPR values for SC-FDMA and OFDMA is carried out using Monte Carlo simulations. This study shows that SC-FDMA has lower PAPR than OFDMA.

CHAPTER 5

Simulation Models and Results

5.1 System Model layout

In this thesis, the performance of proposed multiple access techniques for LTE system is studied in term of the Symbol Error Rate (SER). Two main single user transmission scenarios are modeled and simulated in Matlab focusing on the uplink direction. In the following subsections, a description of the designed simulation models is provided.

5.1.1 Direct Transmission Model (One Hop Link)

This model consists of a single user transmission scenario, in which the UE is directly connected to the BS as shown in Figure 5-1. Two multiple access techniques are compared in this scenario: the OFDMA and SC-FDMA. The OFDMA and SC-FDMA transceivers are modeled and simulated considering both the interleaved and localized subcarriers mapping schemes. The wireless channel is modeled based on the ITU recommendations as will be illustrated later in this chapter.

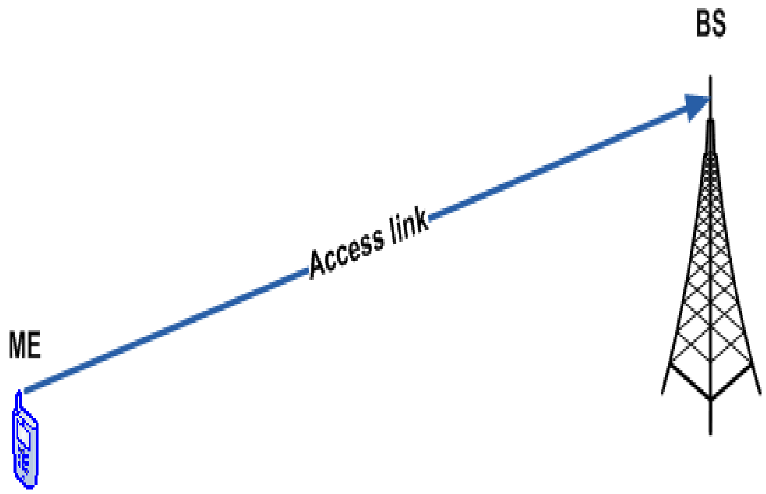

Figure 5-1 One Hop Model.

5.1.2 Relay Assisted Transmission Model (Two Hops Link)

In this scenario a RN is introduced between the UE and the BS, which breaks the direct link between the UE and the BS into two high quality wireless links (two hops) as depicted in Figure 5-2.

The RN operates in half duplex mode, in first time slot the RN receives the transmission from UE and in second slot the received data is transmitted/forwarded to the BS. The RN operates according to detect and forward strategy. Both the localized and interleaved subcarriers mapping schemes are studied for SC-FDMA and OFDMA techniques in the two hops scenario.

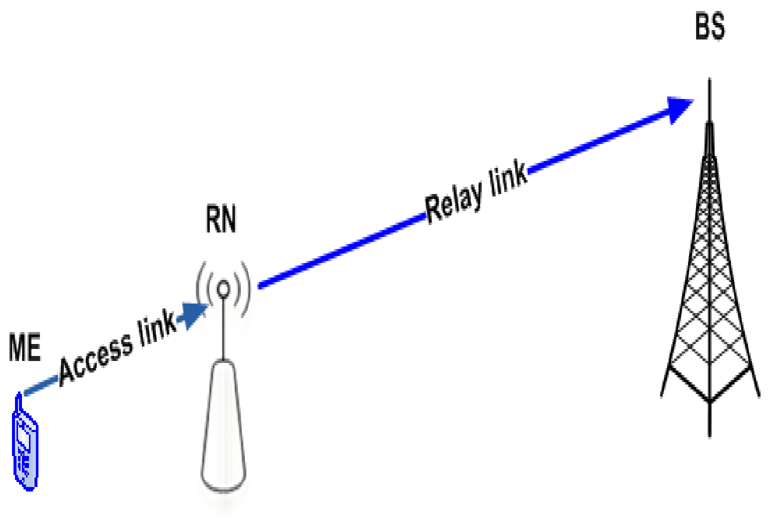

Figure 5-2 Two Hops Model.

5.2 Simulation parameters and Assumptions

5.2.1 Channel Models

Two multipath channel models are used in the study of the mentioned scenarios (i.e., one hop and two hops): the ITU Pedestrian-A (Ped-A) and ITU Vehicular-A (Veh-A). The Ped-A channel has relatively short channel delay spread compared to the Veh-A. Consequently, the Veh-A has much more severe frequency selectivity. Table 5-1 describes the power delay profiles of the two channels. The channel frequency domain responses of Ped-A and Veh-A channels are shown in Figure 5-3 and Figure 5-4 respectively.

Table 5-1 channels delay profiles [20].

Channel Models		Path 1	Path 2	Path 3	Path 4	Path 5	Path 6
ITU Ped-A (UE speed is 3 km/h)	Delay [ns]	0	110	190	410	-	-
	Power [dB]	0	-9.7	-19.2	-22.8	-	-
ITU Veh-A (UE speed is 120 km/h)	Delay [ns]	0	310	710	1090	1730	2510
	Power [dB]	0	-1.0	-9.0	-10.0	-15.0	-20.0

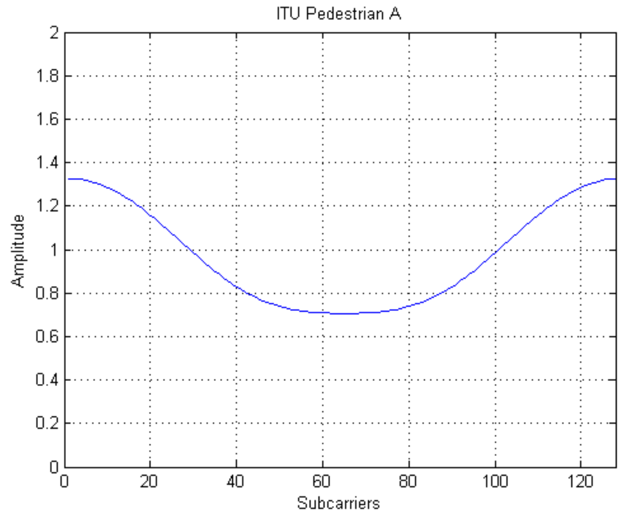

Figure 5-3 Frequency domain channel response of ITU Pedestrian A.

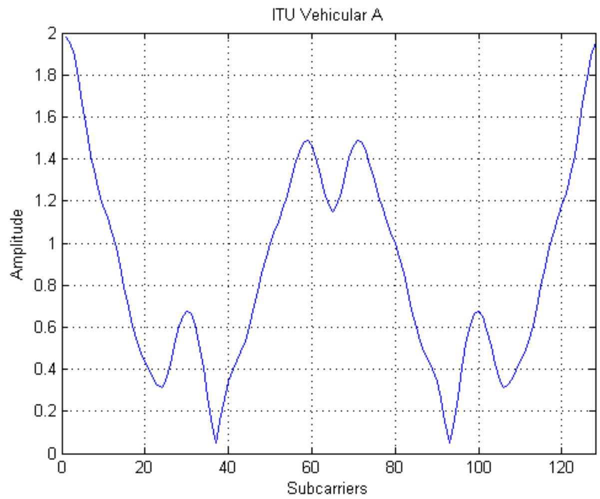

Figure 5-4 Frequency domain channel response of ITU Vehicular A.

5.2.2 Equalization

Two different types of channel equalization are used, Minimum Mean Square Equalization (MMSE) and Zero Forcing Equalization (ZFE).

The rest of the parameters and assumptions that were used throughout this work are summarized in Table 5-2.

Table 5-2 Simulation parameters and assumptions.

Parameter	**Value**
System bandwidth	1.4 MHz
Sampling rate	5 mega sample/second
Modulation	QPSK
Pulse shaping	None
Cyclic prefix	20 samples
Transmitter IFFT size	128
SC-FDMA input block size	16 symbols
SC-FDMA input FFT size	16
Channel estimation	Perfect
Equalization	ZFE/MMSE
Channel coding	None
Number of iterations	10,000

5.3 Results and Analysis

Following the above descriptions the systems are simulated in Matlab using the ideal wireless channel case (i.e. AWGN) and both of the multipath channel models described previously (i.e. ITU Ped-A and ITU Veh-A). The simulation results for each of the three channel models are shown, respectively, in the following subsections.

5.3.1 AWGN Channel Model Results

This subsection discusses the results obtained using AWGN channel model in the previously mentioned simulation scenarios (i.e., one hop and two hops scenarios).

Figure 5-5 shows the link level performance comparison between the direct transmission (one hop case) and the relay assisted transmission (two hops case). The results are obtained for the following settings: OFDMA and SC-FDMA using localized subcarriers mapping scheme, Zero Forcing Equalization, and sub-band 0. The sub-band indicates the assigned part from the physical resource (128 subcarriers) to a specific user.

The results in Figure 5-5 indicate that SER performance of relay-assisted transmission scenario (two hops) is better than one hop system (e.g., when SER value is equal 10^{-2} a performance gain of around 2 dB gain is achieved). Also Figure 5-5 shows that the performance of OFDMA is better compared to the performance of SC-FDMA (e.g., when SER value is equal 10^{-2} a performance gain of around 7 dB is achieved).

The results in Figure 5-6 are obtained by using the same settings as in Figure 5-5 with the exception that, the subcarrier mapping scheme is changed to the interleaved scheme. From Figure 5-6, it can also be seen that, the performance of two hops is better than that of one hop and the OFDMA is better than that of SC-FDMA.

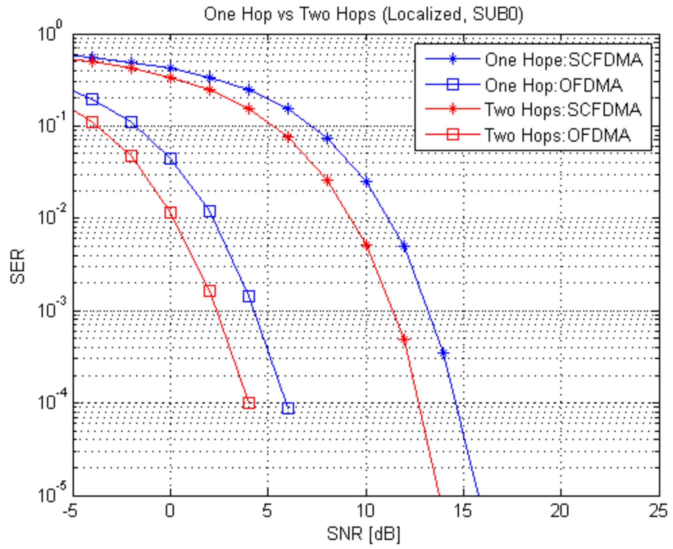

Figure 5-5 One hop vs. two hops (Localized, SUB0).

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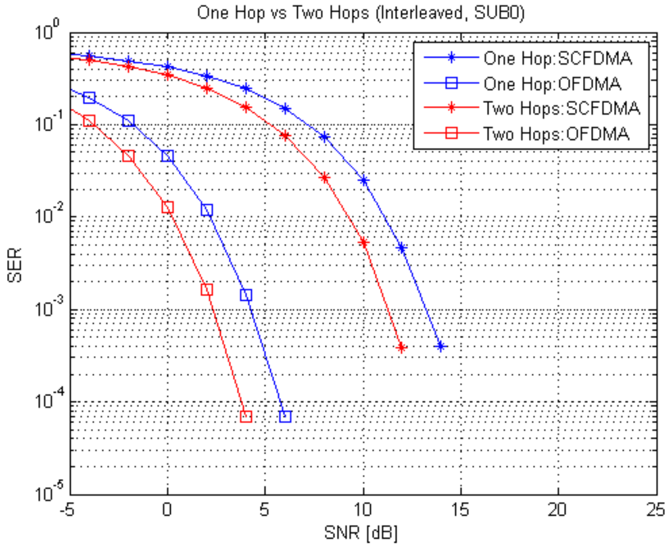

Figure 5-6 One hop vs. two hops (Interleaved, SUB0).

Figure 5-7 and Figure 5-8 represent repeated versions of Figure 5-5 and Figure 5-6, respectively, for sub-band 3. Also in Figure 5-7 and Figure 5-8 the performance of one hop OFDMA is better than that of one hop SC-FDMA, the two hops OFDMA outperforms the one hop OFDMA, and the two hops SC-FDMA outperforms the one hop OFDMA.

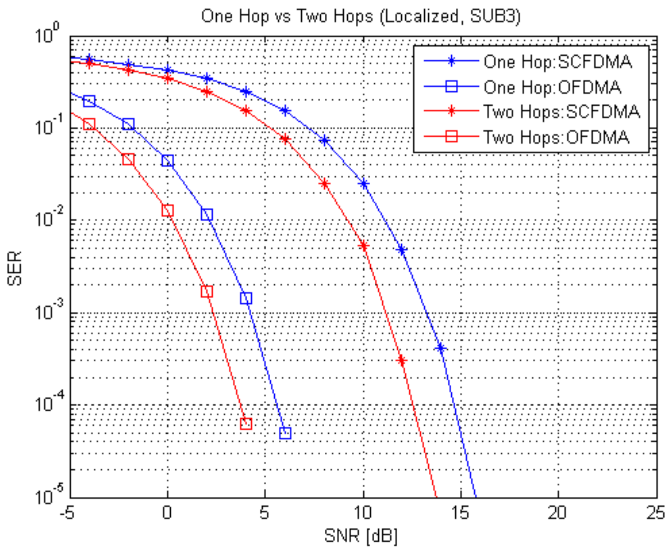

Figure 5-7 One hop vs. two hops (Localized, SUB 3).

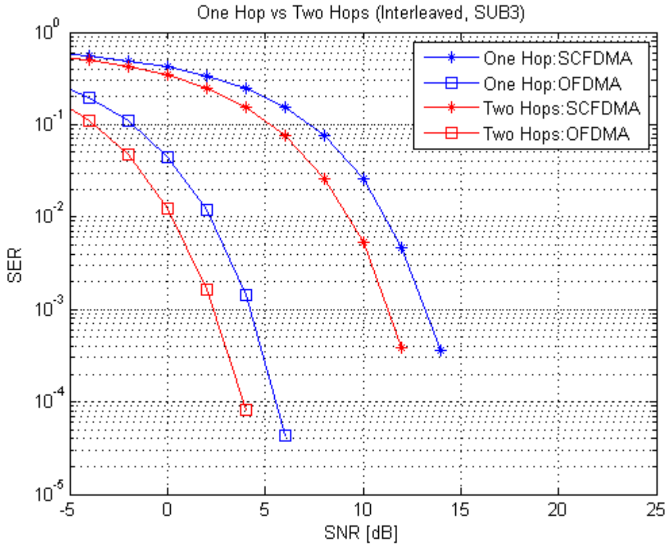

Figure 5-8 One hop vs. two hops (Interleaved, SUB 3).

The following results discuss the case of two hops link only. Three combinations for the links are taken into account. Table 5-3 summarizes these three situations.

Table 5-3 Two hops link combinations

Multiple Access technique	Access link	Relay link
SC-FDMA	SC-FDMA	SC-FDMA
OFDMA	OFDMA	OFDMA
Hybrid SC-FDMA/OFDMA	SC-FDMA	OFDMA

Figure 5-9 shows the performance of the three multiple access techniques combinations described in Table 5-3. It also compares the performance of localized subcarriers mapping scheme and interleaved subcarriers mapping scheme for sub-band 0. For each subcarrier mapping scheme the performance of the OFDMA link is better than the performance of SC-FDMA link and the hybrid link is in between (e.g., when SER value is equal 10^{-2}, the OFDMA achieves performance gain of 7 dB as compared to the SC-FDMA while the hybrid technique achieves less performance gain as compared to OFDMA by around 2.5 dB). Both of the interleaved and the localized schemes achieve the same results; this is due to the flat characteristics of the AWGN channel model.

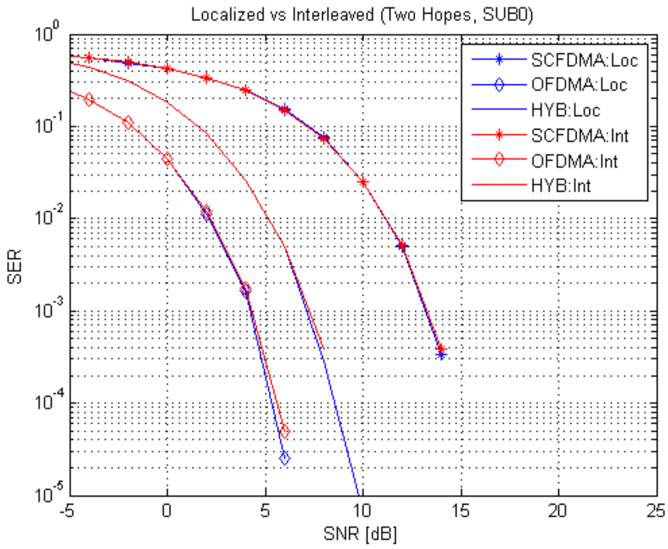

Figure 5-9 Localized vs. Interleaved subcarriers mapping (Two Hops, SUB 0).

Figure 5-10 shows the performance of three multiple access techniques combinations described in Table 5-3. It also compares the performance of localized subcarriers mapping scheme and interleaved subcarriers mapping scheme for sub-band 3. Similar to the obtained results in the sub-band 0 case, for both the localized and interleaved schemes the performance of the OFDMA link is better than the performance of SC-FDMA link and the hybrid link is in between. Both of the interleaved and the localized subcarriers mapping schemes achieve the same results; this is due to the characteristics of the AWGN channel model.

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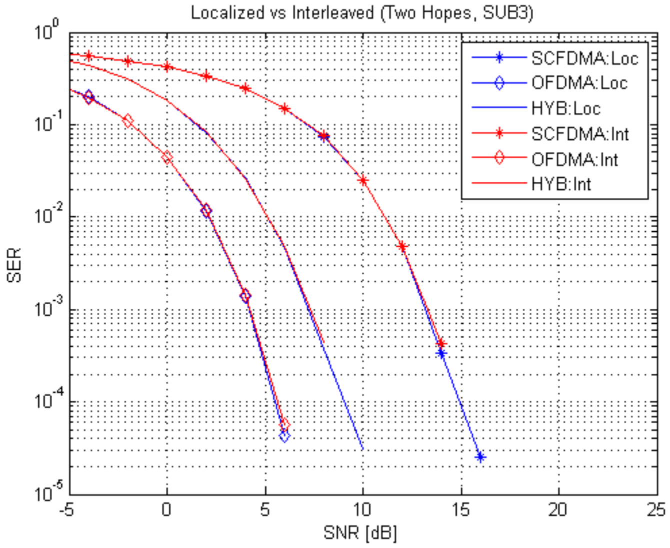

Figure 5-10 Localized vs. Interleaved subcarriers mapping (Two Hops, SUB0).

Figure 5-11 and Figure 5-12 present a comparison of MMSE and ZFE for sub-band 0 and sub-band 3, respectively. This comparison is carried out only for the proposed hybrid multiple access technique (refer to Table 5-3), considering both of the localized subcarriers mapping and interleaved subcarriers mapping schemes. The results are the same in both cases (i.e. sub-band 0 and sub-band 3).

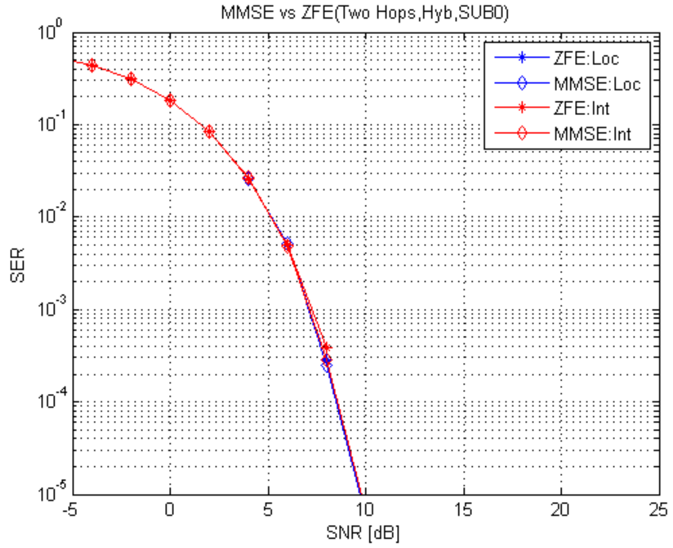

Figure 5-11 MMSE vs. ZFE equalization technique (Two Hops, Hybrid, SUB 0).

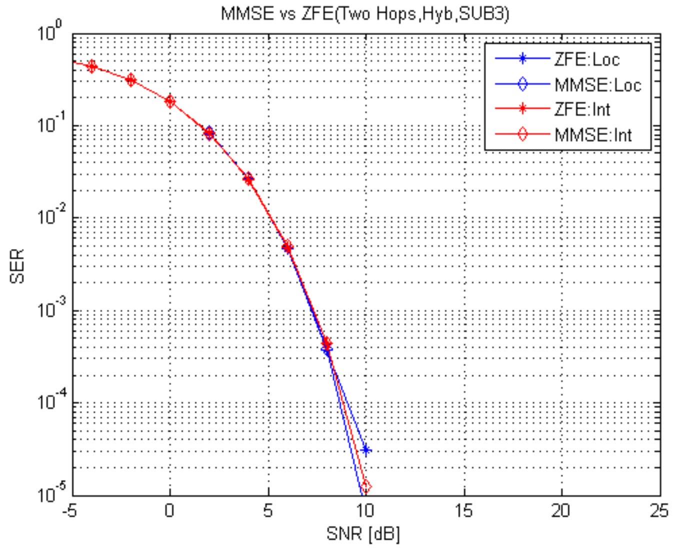

Figure 5-12 MMSE vs. ZFE equalization technique (Two Hops, Hybrid, SUB 3).

5.3.2 ITU Pedestrian-A Channel Model Results

This subsection discusses the obtained results using the ITU Ped-A channel model. Figure 5-13 shows a link level performance comparison between the direct transmission (one hop case) and the relay assisted transmission (two hops case). The results are obtained for the following settings, OFDMA and SC-FDMA using localized subcarriers mapping scheme, Zero Forcing Equalization, and sub-band 0. The sub-band indicates the assigned part from the physical resource (128 subcarriers) to a specific user. The location of the chunk (sub-band) in relation to the used channel characteristics can be figured out from the channel frequency response represented in Figure 5-3.

The results in Figure 5-13 indicate that SER performance of the relay assisted transmission scenario (two hops) is better than one hop system (e.g., when SER is equal to 10^{-2}, a performance gain of around 2 dB gain is achieved). Also Figure 5-13 shows that the performance of OFDMA is better as compared to the performance of SC-FDMA (e.g., when SER is equal to 10^{-2}, a performance gain of around 7 dB gain is achieved).

The results in Figure 5-14 are obtained by using the same settings as in Figure 5-13 with the exception that, the subcarrier mapping scheme is changed to the interleaved scheme. From Figure 5-14, it can also be seen that the performance of two hops is better than that of one hop, and the performance of OFDMA is better than that of SC-FDMA.

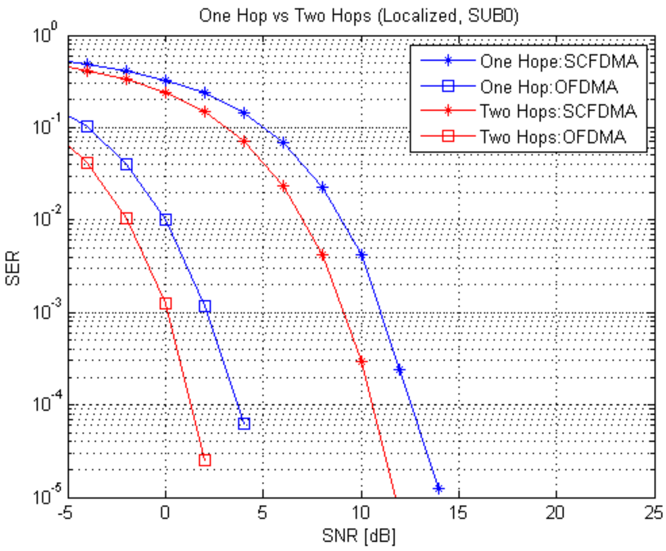

Figure 5-13 One hop vs. two hops (Localized, SUB0).

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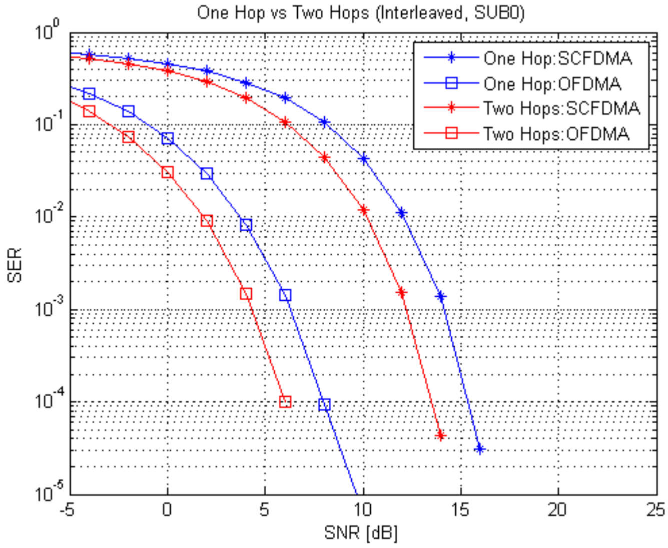

Figure 5-14 One hop vs. two hops (Interleaved, SUB0).

Figure 5-15 and Figure 5-16 represent repeated versions from Figure 5-13 and Figure 5-14, respectively, for sub-band 3. Also in Figure 5-15 and Figure 5-16 the performance of one hop OFDMA is better than that of one hop SC-FDMA, the two hops OFDMA outperforms the one hop OFDMA, and the two hops SC-FDMA outperforms the one hop OFDMA.

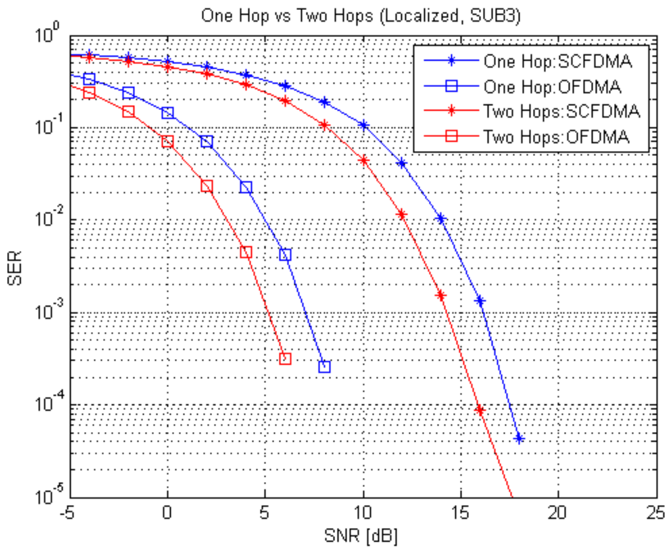

Figure 5-15 One hop vs. two hops (Localized, SUB 3).

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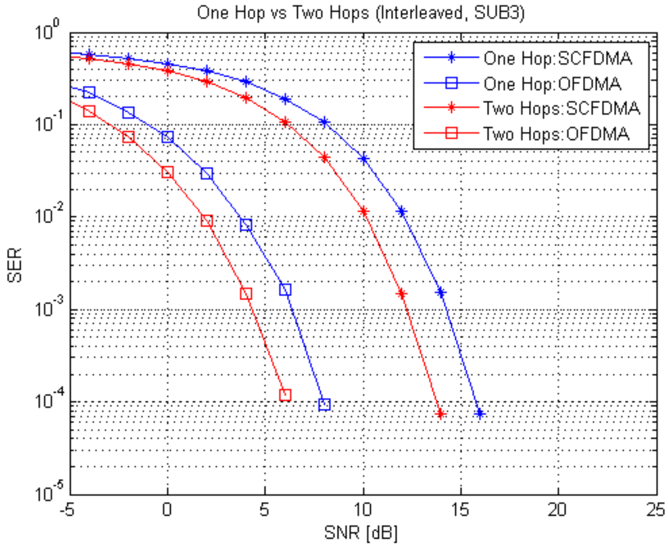

Figure 5-16 One hop vs. two hops (Interleaved, SUB 3).

The following results discuss the case of two hops link only. The three combinations for the multiple access techniques which are illustrated in Table 5.3 are studied and the obtained results are presented in Figure 5-17 and Figure 5-18

Figure 5-17 compares the performance of localized subcarriers mapping and interleaved subcarriers mapping for sub-band 3. For each subcarriers mapping scheme the performance of the OFDMA link is better than the performance of SC-FDMA link and the hybrid link performance is in between (e.g., when SER is equal to 10^{-2}, the OFDMA achieves performance gain of 7 dB as compared to the SC-FDMA while the hybrid technique achieves less performance gain as compared to OFDMA by around 2.5 dB). The interleaved subcarriers mapping scheme achieves better performance compared to localized subcarrier mapping case (e.g., when SER is equal to 10^{-2}, a performance gain of around 2 dB gain is achieved). These results are due to fact that the localized subcarriers scheme has lower gain compared to the average (interleaved) when sub-band 3 is used. This can be noticed by referring to the channel frequency domain response in Figure 5-3. In contrast when sub-band 0 is used the localized subcarriers mapping scheme has higher gain compared to the average (interleaved) and accordingly the performance of the localized subcarrier mapping scheme is better in this case as shown in Figure 5-18.

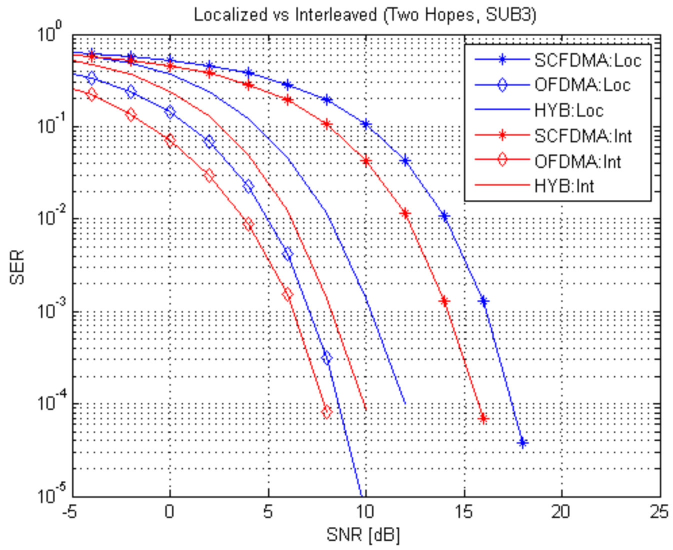

Figure 5-17 Localized vs. Interleaved subcarriers mapping (Two Hops, SUB 3).

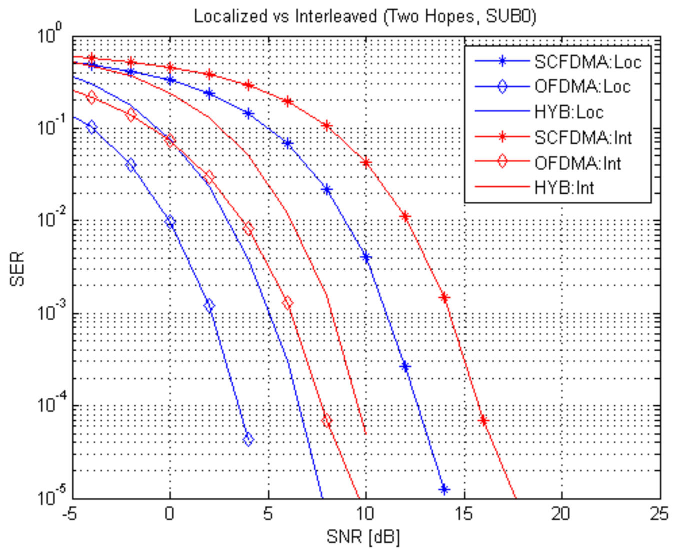

Figure 5-18 Localized vs. Interleaved subcarriers mapping (Two Hops, SUB 0).

Figure 5-19 and Figure 5-20 present a comparison of MMSE and ZFE for sub-band 0 and sub-band 3, respectively. This comparison is carried out only for the proposed hybrid multiple access technique (refer to Table 5-3), considering both of the localized subcarrier mapping and interleaved subcarrier mapping schemes. Both of the ZF and MMSE have the same performance.

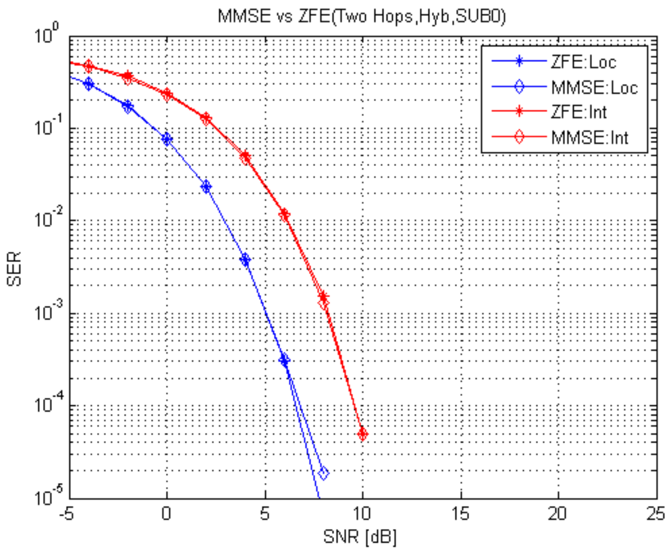

Figure 5-19 MMSE vs. ZFE equalization technique (Two Hops, Hybrid, SUB 0).

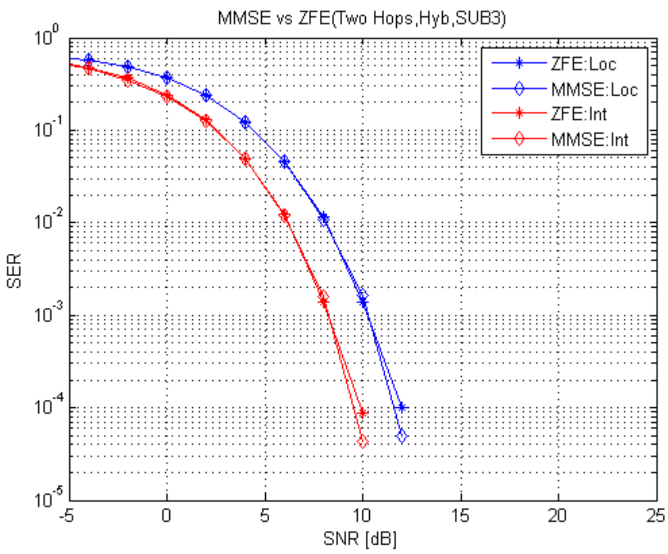

Figure 5-20 MMSE vs. ZFE equalization technique (Two Hops, Hybrid, SUB 3).

5.3.3 ITU Vehicular-A Channel Model Results

This subsection discusses the results obtained when the ITU Vehicular-A (Veh-A) channel model is used for the two models (i.e., one hop and two hops models).

Figure 5-21 shows the performance of one hop in and two hops scenarios, using localized subcarrier mapping scheme, Zero Forcing Equalization, and sub-band 0. It can be seen that, the SER performance of the relay-assisted transmission scenario (two hops) is better than one hop system (e.g., when SER is equal to 10^{-2}, a performance gain of around 2 dB gain is achieved). The location of the chunk (sub-band) can be figured out from the channel frequency response in Figure 5-4. Also Figure 5-21 shows that the performance of OFDMA is better as compared to the SC-FDMA (e.g., when SER value is equal to 10^{-2}, a performance gain of around 7 dB gain is achieved). In Figure 5-22 the interleaved subcarriers mapping scheme has been used. From Figure 5-22, it can also be seen that, the performance of two hops is better than one hop and the performance of OFDMA is better than the performance of SC-FDMA.

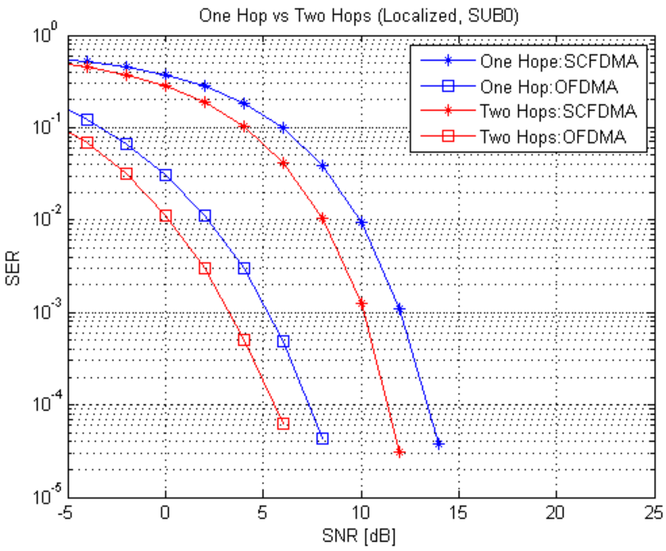

Figure 5-21 One hop vs. two hops (Localized, SUB 0).

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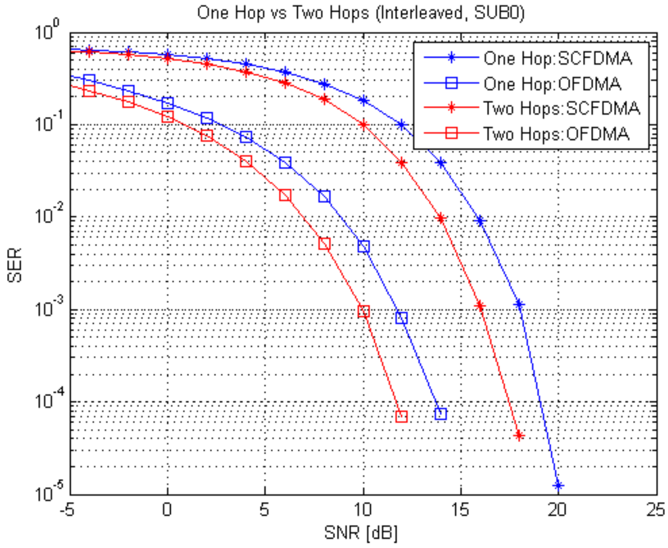

Figure 5-22 One hop vs. two hops (Interleaved, SUB 0).

Figure 5-23 and Figure 5-24 represent repeated versions of Figure 5-21 and Figure 5-22, respectively, for sub-band 3. It can be seen from Figure 5-23 and Figure 5-24 that the performance of one hop OFDMA is better than that of one hop SC-FDMA. The performance of the two hops OFDMA is better than that of one hop OFDMA and the two hops SC-FDMA transmission outperforms the one hop OFDMA.

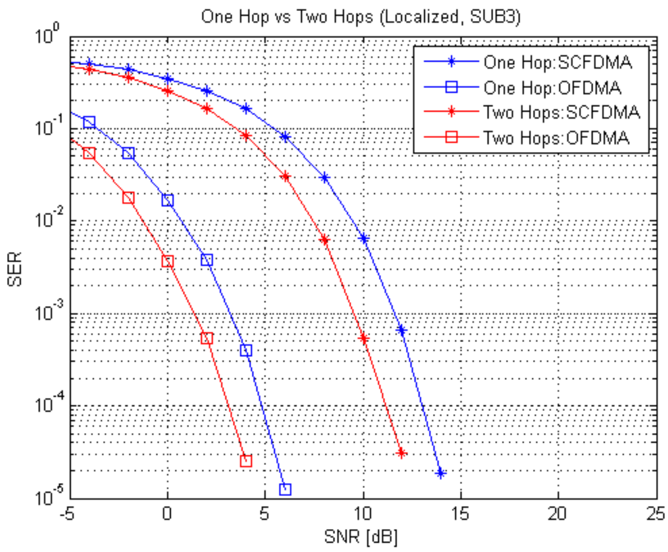

Figure 5-23 One hop vs. two hops (Localized, SUB 3).

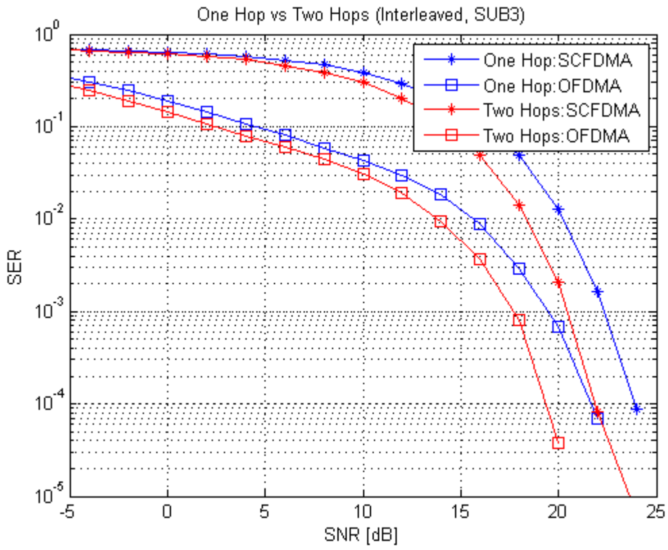

Figure 5-24 One hop vs. two hops (Interleaved, SUB 3).

The three combinations for the multiple access techniques which are illustrated in Table 5.3 are studied and the obtained results are presented in Figure 5-25 and Figure 5-26. Figure 5-25 shows the performance of these combinations, for the localized subcarrier mapping and interleaved subcarrier mapping schemes for sub-band 0. For both mapping schemes the performance of the OFDMA link is better than the performance of SC-FDMA link and the hybrid link is in between (e.g., when SER is equal to 10^{-2}, the OFDMA achieves performance gain of 7 dB as compared to the SC-FDMA while the hybrid technique achieves less performance gain as compared to OFDMA by around 2.5 dB). Figure 5-25 and Figure 5-26 show that the localized subcarriers mapping scheme has better performance as compared to the interleaved subcarriers mapping scheme in both of sub-band 0 and sub-band 3 cases. This is due to fact that the localized subcarriers mapping scheme has higher gain compared to the interleaved subcarriers; this can be figured out from the channel frequency domain response in Figure 5.4.

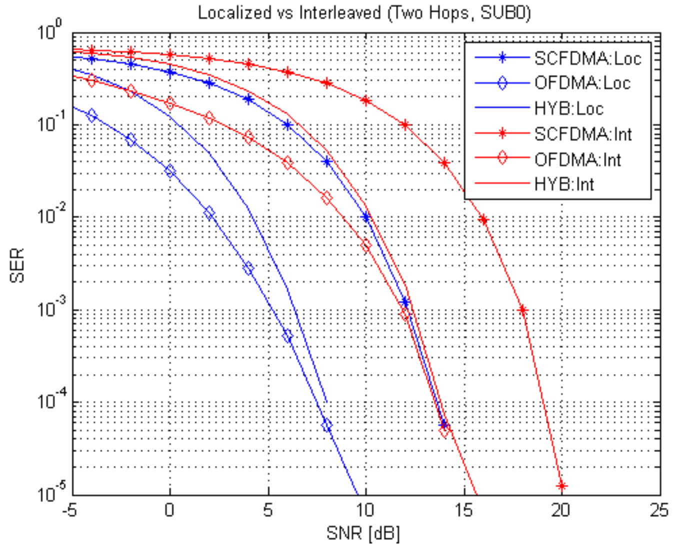

Figure 5-25 Localized vs. Interleaved subcarriers mapping (Two Hops, SUB 0).

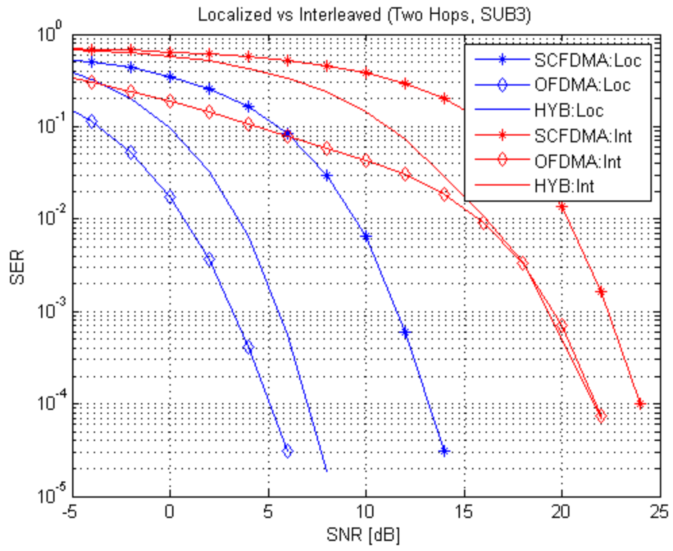

Figure 5-26 Localized vs. Interleaved subcarriers mapping (Two Hops, SUB 3).

Figure 5-27 and Figure 5-28 present a comparison for MMSE and ZFE for sub-band 0 and sub-band 3, respectively. In both cases hybrid link has been considered for localized subcarrier mapping as well as interleaved subcarrier mapping. The results for both sub-bands show that ZFE and MMSE have the same performance in the case of localized subcarrier mapping. For sub-band 0 in Figure 5-27, the ZFE and MMSE in both of interleaved and localized schemes have the same results. For sub-band 3 as shown by Figure 5-28 MMSE outperforms ZFE for low SNR (less than 16 dB) and ZFE outperforms MMSE for higher SNR (higher than 16 dB) in the interleaved case and achieve similar performance in the localized case.

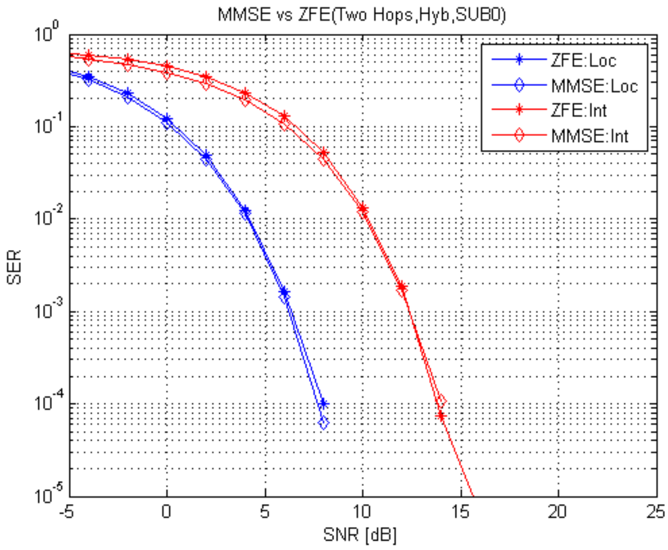

Figure 5-27 MMSE vs. ZFE equalization technique (Two Hops, Hybrid, SUB 0).

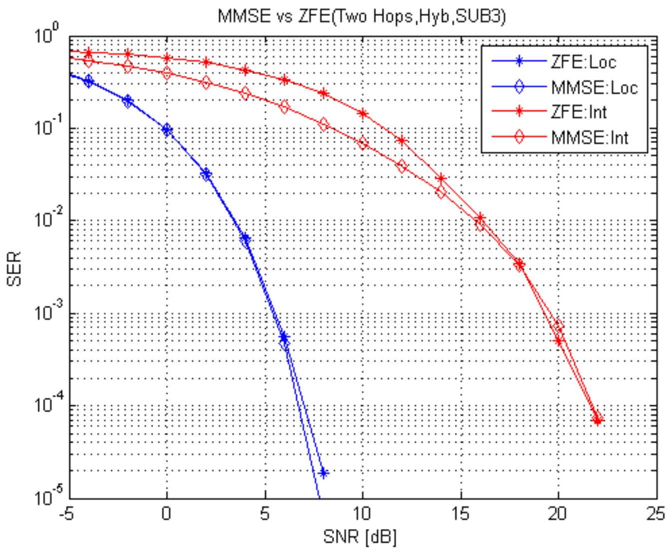

Figure 5-28 MMSE vs. ZFE equalization technique (Two Hops, Hybrid, SUB 3).

5.3.4 Summary of the Simulation Results

All the studied simulation scenarios in the previous subsections are focused on the uplink link level performance in term of SER. The direct transmission (one hop) and the relay assistant transmission (two hops) scenarios are studied. The main outcomes from this simulation study can be summarized in the following:

- Regardless the other defined simulation parameters when ITU Ped-A channel is used in combination with sub-band 0, the localized subcarriers scheme achieve better performance than the interleaved subcarriers mapping scheme.
- Regardless the other defined simulation parameters when ITU Ped-A channel is used in combination of sub-band 3, the interleaved subcarriers mapping scheme outperform the localized subcarriers mapping.
- When ITU Veh-A channel is used for sub-band 0 or sub-band 3, the localized subcarriers mapping scheme achieves better results in both cases compared to the interleaved mapping scheme.
- The obtained results from the relay-assisted transmission (two hops) are better than those obtained from the direct transmission (one hop) for all the studied scenarios.
- The performance of the proposed hybrid scheme is always in between the OFDMA and SC-FDMA techniques for the studied scenarios.
- When the performance of the proposed hybrid technique (SC-FDMA/OFDMA) is studied using ITU Ped-A, both ZFE and MMSE show the same results for the both of the subcarriers mapping schemes.
- When the performance of the hybrid technique (SC-FDMA/OFDMA) is studied under ITU Veh-A channel, both of ZFE and MMSE equalizers show the same performance for the localized subcarrier mapping case (regardless the used sub-band). While in the interleaved mapping scheme MMSE outperforms ZFE for low SNR (less than 16 dB) and ZFE outperforms MMSE for higher SNR in the case of sub-band 3 and they have the same results for sub-band 0.

Chapter 6

Conclusions

In this thesis work the SC-OFDMA and OFDMA multiple access technique have been studied for single and two hops scenarios. The performance is measured in term of the SER, considering the use of different subcarriers mapping schemes (the localized and interleaved). A Hybrid multiple access technique has been proposed in as tradeoff between PAPR and the link performance requirements. This hybrid technique combines the OFDMA and SC-FDMA techniques in the relay- assisted transmission scenario by adopting the SC-FDMA technique in the access link and OFDMA technique in the relay link. The obtained results show that the proposed hybrid technique achieves better end-to-end link performance as compared to the pure SC-FDMA technique and maintains the same PAPR value in access link. In this way, a lower PAPR is achieved compared to OFDMA case, which is an important merit in the uplink transmission due to the UE's power resources constraints (limited battery power).

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