Delft University of Technology

Wireless and Mobile Communication (WMC) Group
Faculty of Electrical Engineering, Mathematics and Computer Science
Delft University of Technology

Downlink Scheduling in 3GPP Long Term Evolution (LTE)

ASSIGNMENT : Master of Science Thesis
SUPERVISOR : Dr. Anthony Lo
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STUDENT : Tshiteya Dikamba
STUDENTNUMBER : 1377612

Abstract

In this report an overview of the Long Term Evolution (LTE) is presented. LTE is the evolution of the Universal Mobile Telecommunications System (UMTS). It allows mobile users to access Internet through their devices (mobile telephones, laptop…). LTE intends to deliver high speed data and multimedia services to next generation. In the coming years LTE mobile broadband technology will be widely used by devices such as notebooks, smartphones, gaming devices and video cameras.

The Long Term Evolution provides a high data rate and can operate in different bandwidths ranging from 1.4MHz up to 20MHz. LTE supports high peak data rates (100 Mb/s in the DL and 50 Mb/s in the UL), low latency (10ms round-trip delay), improves system capacity and coverage and reduces operating costs. Furthermore it supports Multiple Input Multiple Output (MIMO) and allows seamless integration with existing systems.

A scheduler assigns the shared resources (time and frequency) among users terminals. In this master thesis the focus is on the downlink scheduling. The Best CQI scheduling algorithm and the Round Robin scheduling algorithm have been considered in this report. The implementation, the analysis and the comparison of these scheduling algorithms were done through simulations executed on a MATLAB-based downlink link level simulator from the Vienna University. I have examined the impact of the scheduling schemes on the throughput and I have investigated the fairness of each scheduling scheme. Furthermore the throughput results are compared to the system capacity (Shannon Capacity).

The main contribution of this thesis work is to propose a new scheduling algorithm that can be a compromise between the throughput and the fairness. The novel scheduling scheme has been designed and tested to investigate whether it achieves its goal. Two ITU-channel types have been used: The Pedestrian B and the Vehicular A channel. I have studied the impact of the channel delay on the throughput. MIMO systems have been used to increase the throughput.

Acknowledgement

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First of all I am particularly indebted to Dr. Anthony Lo, my daily supervisor. He was been a great support when I had unexpected problems during my project and for the patience and flexibility with which he allowed me to work on my graduation project. Further, I want to express my deep respect to my supervisor, Prof. Ignas Niemegeers.

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1 Introduction

In this chapter, the 3GPP LTE will be introduced and all its relevant features. We will begin with the background information on the subject we present in section1.1. The motivation for our thesis project and its goals are stated in Section 1.2. The last section 1.3 gives the thesis outline.

1.1 Background

In the recent years, the world was introduced to mobile broadband. Multimedia applications through the Internet have gathered more attention. Applications such as live streaming, online gaming, mobile TV require higher data rate. *The Third-generation Partnership Project* (3GPP) started to work on solutions to these challenges and came up with the HSPA. The HSPA is currently used in 3G phones for such applications. Later, the 3GPP has worked on the Long Term Evolution (LTE) and intends to surpass the performance of HSPA. Thus LTE will enhance applications such as online gaming and interactive TV. It is expected that in 2014, 80% of broadband users will be mobile broadband subscribers and they will be served by HSPA and LTE networks [1].

The 3GPP is the standards-developing body that specifies the 3G UTRA and GSM systems. LTE as defined by the 3GPP [2] is the evolution of the Third-generation of mobile communications, UMTS. LTE intends to create a new radio-access technology which will provide high data rates, a low latency and a greater spectral efficiency. The 3GPP has started with the RAN Evolution workshop in November 2004 [3]. A lot of research has been carried out and proposals have been presented on the evolution of the Universal Terrestrial Radio access Network (UTRAN). The specifications related to LTE are formally known as the evolved UMTS terrestrial radio access (E-UTRA) and evolved UMTS terrestrial radio access network (E-UTRAN), but are in general referred as project LTE.

In December 2008, the LTE specification was published as part of Release 8. The initial deployment of LTE was expected in 2009. The first release of LTE namely release-8 supports peak rates of 300Mb/s, a radio-network delay of less than 5ms. *Multiple Input Multiple Output* (MIMO) have gathered a lot of attention recently. It allows the achievement of high peak data rates. Furthermore LTE operates both *Frequency Division Duplexing* (FDD) and Time *Division Duplexing* (TDD) and can be deployed in different bandwidths. With TDD the uplink and downlink operate in same frequency band whereas with TDD the uplink and downlink operate in different frequency bands.

Orthogonal Frequency Division Multiplexing (OFDM) has been adopted as the downlink transmission scheme for the 3GPP LTE. A downlink is a transmission from the base station to the mobile station. OFDM divides the transmitted high bit-stream signal into different sub-streams and sends these over many different sub-channels. A base station (BS) is called an *Evolved NodeB* (eNodeB) in the Long Term Evolution and a mobile station (MS) is called a *User Equipment* (UE) in the Long Term Evolution. For the sake of simplicity we will use BS and MS to refer to eNodeB and UE respectively.

The downlink physical resource is represented as a time-frequency resource grid consisting of multiple *Resource Blocks* (RB). A resource block is divided in multiple *Resource Elements* (RE). A scheduler is a key element in the BS and it assigns the time and frequency resources to different users in the cell. Thus a RB is the smallest element that can be assigned by the scheduler. Our research is focused on the Round Robin scheduling and on the Best CQI scheduling. The Best CQI scheduling assigns the resource blocks to the user with the highest CQI on that RB. To perform this scheduling the MS must feedback the Channel Quality Indication (CQI) to the BS. In Round Robin (RR) scheduling the terminals are assigned the resource blocks in turn (one after another) without taking the CQI into account. Thus the terminals are equally scheduled.

The Round Robin scheduling and Best CQI scheduling [4] have been simulated in a MATLAB-based Downlink Link Level Simulator from the Vienna University. The performance of these scheduling algorithms in terms of throughput is analyzed. Furthermore the throughput results are compared to the channel capacity (Shannon Capacity). We have used the Pedestrian B channel and the Vehicular A channel. We have examined the impact of the channel delay on the throughput. The throughput of a MIMO (2x2) and MIMO (4x4) systems have been taken into consideration in this report.

1.2 Motivation and goal of the thesis

1.2.1 Motivation

The motivation to work on this project comes from the fact that LTE is the future of mobile broadband. It is expected that in the future 80% of all mobile broadband users will be served by LTE [1]. The time and frequency are scared resources. The scheduler is a key element in the BS since it determines to which users the resource blocks should be assigned.

Round Robin scheduling and Best CQI scheduling have been selected because of their characteristics. The Best CQI scheduling optimizes the user throughput by assigning the resource block to the user with the good channel quality and the Round Robin scheduling is fair in the long term since it equally schedules the Mobile Station (MS). In general cell-center users have a good channel quality compare to the cell-edge users. In order to find a trade-off between the throughput and the fairness a new scheduling algorithm has been proposed. The proposed new scheduling algorithm can be considered as a compromise between the Best CQI scheduling and the Round Robin scheduling.

1.2.2 Thesis goal

The purpose of this thesis is to implement and simulate the downlink scheduling in LTE. We have also investigated the impact of the scheduling algorithms on the throughput and on the fairness. To achieve this goal two scheduling algorithms are considered: the Best CQI scheduling and the Round Robin scheduling. We have analyzed and compared the performance of these two scheduling algorithms in terms of throughput. Furthermore MIMO systems will be used for different scheduling algorithms. For the multipath channel, the ITU Pedestrian B and ITU Vehicular A are used. The effect of channel delay on the cell throughput will be examined.

The main contribution of this thesis work is to propose a new scheduling algorithm that can be a compromise between the throughput and the fairness. The novel scheduling scheme has been designed and tested to investigate whether it achieves its goal. To perform simulations a MATLAB-based Link Level simulator from the Vienna University is used.

1.3 Thesis Scope

This thesis is organized in 6 chapters. The rest of the chapters are organized as follows: Chapter 2 gives an overview of LTE. Chapter 3 explains the related work one the downlink scheduling algorithms in LTE. Chapter 4 introduces the proposed new scheduling algorithm. Chapter 5 presents the simulation results. Finally chapter 6 draws the conclusion and gives recommendations for future works.

2 An Overview of LTE

In this chapter an overview of the 3GPP Long Term Evolution is provided. We will begin with LTE requirements. Then Orthogonal Frequency Division Multiplexing (OFDM) will be introduced. In section 2.4 the downlink transmission scheme is explained and in section 2.5 MIMO is reviewed. Finally, section 2.6 provides information on the theoretical channel capacity.

2.1 LTE requirements

To achieve its goals, LTE must satisfy the following requirements [3]:

Data rates

LTE should support a data rate up to 100 Mb/s within a 20 MHz downlink spectrum allocation and 50 Mb/s within a 20 MHz uplink or, equivalently, spectral efficiency values of 5bps/Hz and 2.5 bps/Hz, respectively.

Throughput

The downlink average throughput per MHz is about 3 to 4 times higher than in the release 6. The uplink average user throughput per MHz is about 2 to 3 times higher than in the release 6.

Bandwidth

LTE allows bandwidth ranging from 1.4 MHz up to 20 MHz, where the latter is used to achieve the highest LTE data rate. Furthermore, LTE operates in both paired and unpaired spectrum by supporting both Frequency-Division Duplex (FDD) and Time-Division Duplex (TDD).

Mobility

The mobility is optimized for low terminals speeds ranging from 0 to 15 km/h. The connection should be maintained for very high UEs speeds up to 350 km/h or even up to 500 km/h.

Coverage

The above targets should be met for 5 km cells and some slight degradation in throughput and spectrum efficiency for 30 km cells. 100 km cells and up can't meet the targets requirements.

2.2 Orthogonal Frequency Division Multiplexing

Orthogonal Frequency Division Multiplexing (OFDM) has gathered much attention in recent years and has been adopted as the downlink transmission scheme for the 3GPP LTE. OFDM is a multicarrier transmission scheme because it splits up the transmitted high bit-stream signal into different sub-streams and sends these over many different sub-channels [5]. In other words OFDM simply divides the available bandwidth into multiple narrower sub-carries and transmits the data on these carries in parallel streams. Each sub-carrier is modulated using different levels of modulation, e.g. QPSK, QAM, 64QAM and an OFDM symbol is obtained by adding the modulated subcarrier signals.

2.3 Spectrum Flexibility

In LTE communication is available in different frequency bands, of different sizes. Furthermore the communication can take place both in paired and unpaired bands. Paired frequency bands means that the uplink and downlink transmissions use separate frequency bands, while unpaired frequency bands downlink and uplink share the same frequency band. In LTE downlink transmissions are grouped in (radio) frame of length 10 ms. One radio frame is formed of 10 subframes of 1ms duration. Therefore there are ten subframes in the uplink and ten frames in the downlink. Each subframe is divided into two slots of 0.5 ms duration. Each slot counts 6 or 7 OFDM symbols for normal or extended cyclic prefix used. The LTE frame structure is illustrated in the Figure 2.1

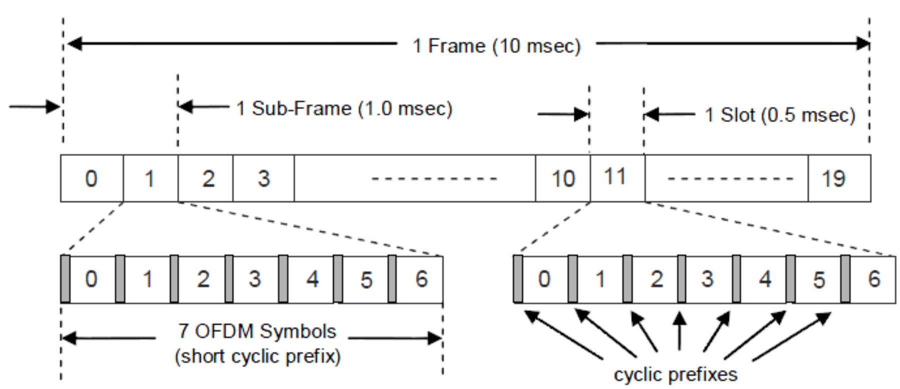

Figure 2.1 *LTE Frame structure* [6]

The spectrum is very flexible and allows LTE to use different bandwidths ranging from 1.4 MHz to 20 MHz. The larger the bandwidth is, the higher the LTE data rates.

2.4 Downlink physical resource

Orthogonal Frequency Division Multiplex (OFDM) is the core of LTE downlink transmission [7]. LTE downlink physical resource can be represented as a time-frequency resource grid as depicted in the Figure 2.2. A *Resource Block* (RB) has a duration of 0.5 msec (one slot) and a bandwidth of 180 kHz (12 subcarriers). It is a straightforward to see that each RB has 12x7 = 84 resource elements in the case of normal cyclic prefix and 12x6 = 72 resource elements in the case of extended cyclic prefix.

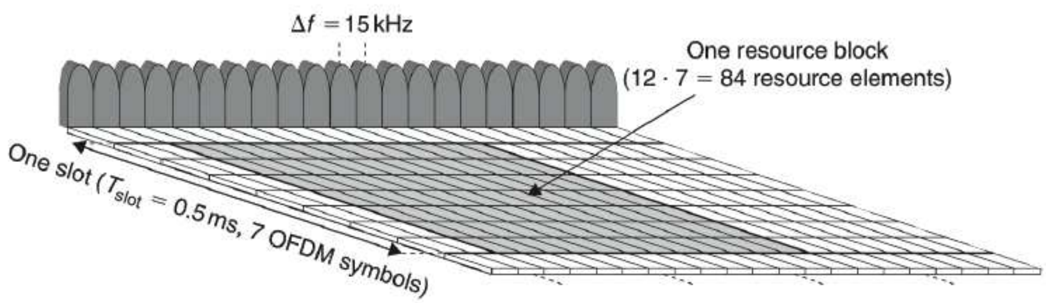

Figure 2.2 *LTE downlink physical resource based on OFDM* [8].

The *resource grid* refers to a number of resource blocks in the available bandwidth. Each entry of the resource block is called a *Resource Element* (RE) which represents one ODFM subcarrier during one OFDM symbol interval [3]. The number of RB in a resource grid varies according to the size of the bandwidth. The OFDM subcarrier spacing is 15 kHz. The table 2.1 shows the LTE bandwidth and resource configuration.

Table 2.1 *Bandwidth and Resource blocks specifications [9].*

Bandwidth (MHz)	1.4	3	5	10	15	20
Number of Resources Blocks	6	15	25	50	75	100
Number of occupied subcarriers	72	180	300	600	900	1200
IFFT/FFT Size	128	256	512	1024	1536	2048
Subcarrier Spacing (KHz)	15	15	15	15	15	15

Downlink reference signals

To perform channel estimation, *reference symbols (reference signals)* are embedded in the *Physical resource block* (PRB) as shown in Figure 2.3. Reference signals are inserted in the first and fifth OFDM symbols of each slot in the case of the short CP and during the first and fourth OFDM symbols in the case of the long CP. Thus there are four reference symbols within one PRB.

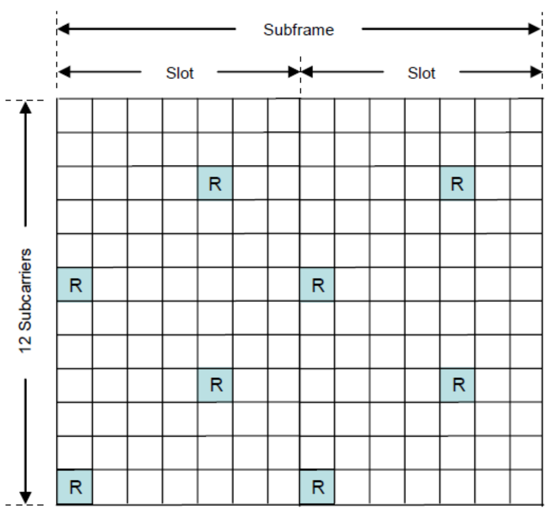

Figure 2.3 *LTE downlink reference signal assuming normal CP* [6]

The *Physical Resource Block* (PRB) is the smallest element assigned by the base station scheduler.

Downlink transport channel processing

At the beginning of the transport channel processing, a *Cyclic Redundancy Check* (CRC) is computed and attached to each transport block (TB) for the detection of errors in the TB by the receiver. After the CRC insertion, the data (TB + CRC) to be sent are turbo coded with a coding rate of 1/3. The task of the hybrid-ARQ is to take care of the retransmission if erroneously received packets are received. Retransmission must represent the same information bits as the initial message but the coded bits used for each retransmission can be different than the original message. Later the information to be transmitted is modulated using one of the following modulation schemes: QPSK, 16QAM, and 64QAM representing two, four, and six bits per modulation symbol, respectively (see Figure 2.4).

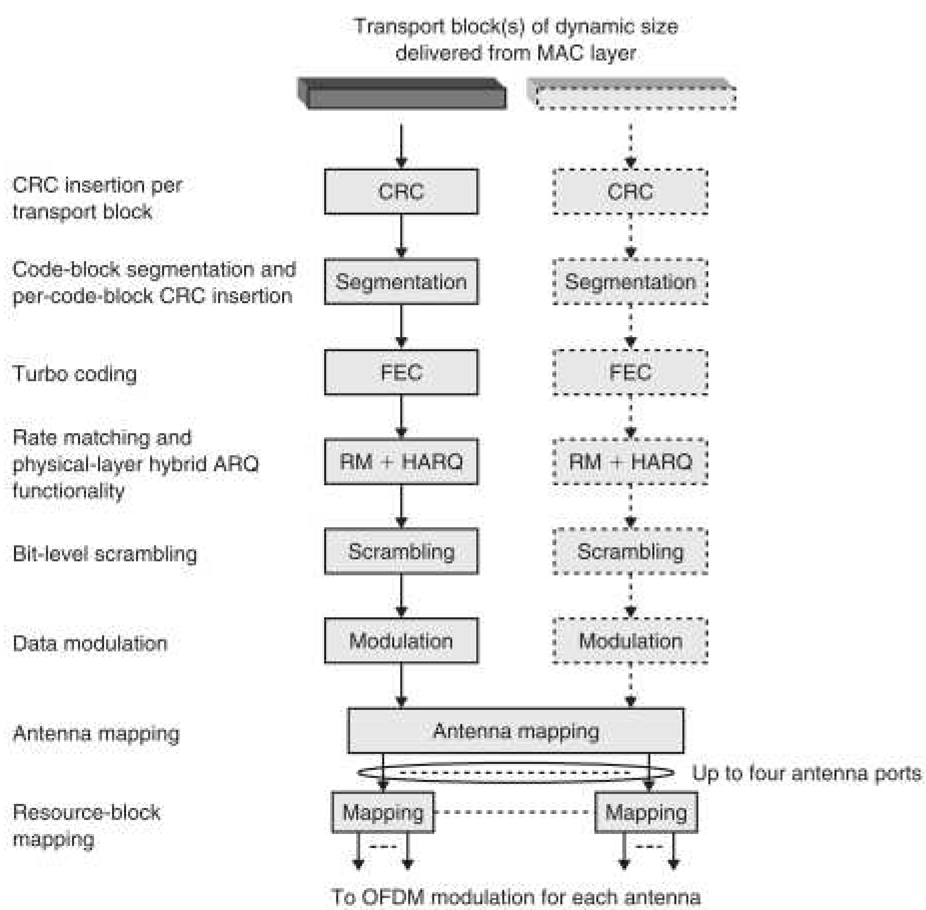

Figure 2.4 *LTE downlink transport-channel processing* [8].

The Antenna mapping block maps the transport block to different antennas. LTE uses up to four transmit antennas. LTE supports different multiple transmit antennas schemes: transmit diversity, beamforming and spatial multiplexing. The goal of the resource block mapping is to map the data to be sent on each antenna to a set of resource blocks assigned by the scheduler. The Figure 2.5 displays the downlink resource block mapping.

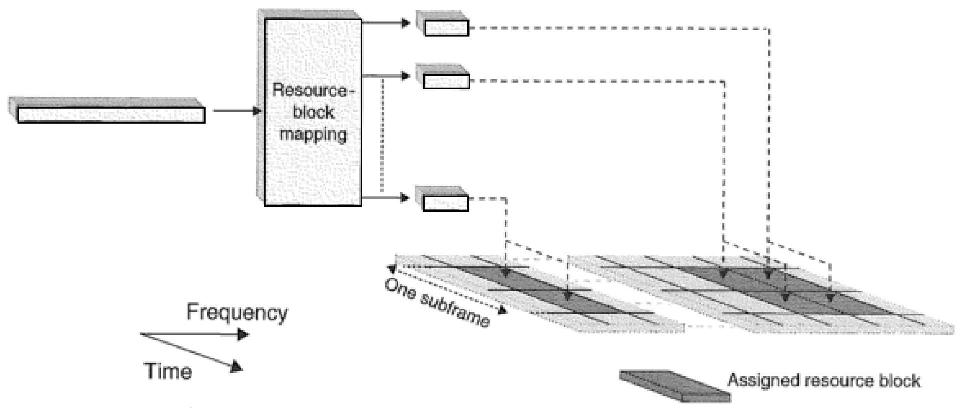

Figure 2.5 *Downlink resource block mapping* [8].

2.5 Multiple Input Multiple Output

Multiple input multiple output (MIMO) techniques support multiple antennas at the transmitter and at the receiver (see Figure 2.6). The aim of MIMO is to achieve different kinds of gains namely: spatial diversity and spatial multiplexing.

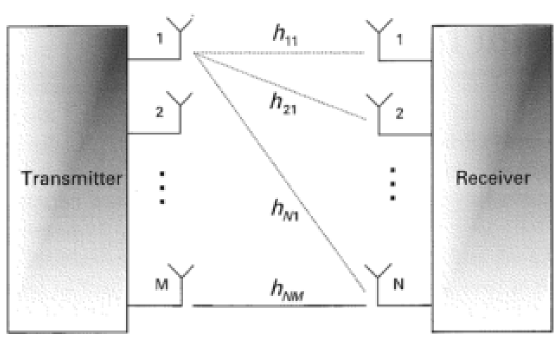

Figure 2.6 *MIMO systems* [10]

Spatial multiplexing allows to increase the capacity by transmitting different streams of data simultaneously in parallel from different antennas. Spatial diversity can be used to increase the robustness of communication in fading channels by transmitting multiple replicas of the transmitted signal from different antennas. Thus MIMO can be used to improve the cell capacity. Furthermore *beam-forming* can be used to shape the antenna beam in the direction of certain UEs.

SISO capacity

In [11], Claude Shannon showed that the maximum error-free bit for an *Additive White Gaussian Noise* (AWGN) channel is given by (2.1).

$$\frac{C}{B} = \log_2\left(1 + \frac{S}{N}\right) \qquad (2.1)$$

Where C is the channel capacity (b/s), B is the channel bandwidth (Hz) and S/N is the signal-to-noise power ratio (watts/watts) at the input to the digital receiver.
The system capacity is defined as the Shannon capacity adjusted by the inherent system losses. The system capacity of an AWGN channel is [12]:

$$C = FB\log_2\left(1 + \frac{S}{N}\right) \qquad (2.2)$$

Here, B is the bandwidth occupied by the data subcarriers, and F the correction factor.
The bandwidth is given by

$$B = \frac{N_{sc} \cdot N_s \cdot N_{rb}}{T_{sub}} \qquad (2.3)$$

Where N_{sc} =12, the number of subcarriers in one RB, N_s is the number of OFDM symbols in one frame (often fourteen when the normal Cyclic Prefix is used), N_{rb} is the number of RBs in the selected bandwidth, and T_{sub} is the duration of one sub-frame equal to 1ms. Since the transmission of an OFDM signal needs the transmission of the CP and the transmission of reference symbols, a correction factor needs to be used in the Shannon capacity formula. This factor represents the inherent system losses and is computed as

$$F = \frac{T_{frame} - T_{cp}}{T_{frame}} \cdot \frac{N_{sc}.N_s/2 - 4}{N_{sc}.N_s/2} \qquad (2.4)$$

Where T_{frame} is the frame duration equal to 10ms and T_{cp} is the total CP time of all OFDM symbols within one radio frame.

MIMO capacity

MIMO can be used to increase the signal-to-noise power ratio. In a system with N_t transmit antennas and Nr receive antennas, the received SNR can increase in proportion to N_t x N_r. From (2.1), for small x, we can use the approximation $\log_2$ (1+x) = x. It implies that at lower SNR the capacity increases proportional to the SNR. In the same way, for higher x we have the approximation $\log_2(1+x) = \log_2(x)$. It means at higher SNR the capacity increases logarithmically with the SNR. Thus in the case of multiple antennas at the transmitter and the receiver, there is a way to have up to $N_l = \min\{N_t, N_r\}$ parallel channels with N_l times lower SNR since the signal power is divided among the channels. In this way the channel capacity becomes

$$C = FB\log_2\left(1+\left(\frac{Nr}{min_{Nt,_{Nr}}}\right)\cdot\frac{S}{N}\right) \tag{2.5}$$

Because we have N_l parallel channels, the overall channel capacity of MIMO system is

$$C = FBN_l\log_2\left(1+\frac{N_r}{N_l}\cdot\frac{S}{N}\right) \tag{2.6}$$

$$C = FBmin_{Nt,_{Nr}}\cdot\log_2\left(1+\frac{Nr}{min_{Nt,_{Nr}}\cdot\frac{S}{N}}\right) \tag{2.7}$$

Codewords and layer mapping

The maximum number of layers or streams is called the MIMO rank. The Figure 2.7 depicts a MIMO chain with codewords and layers.

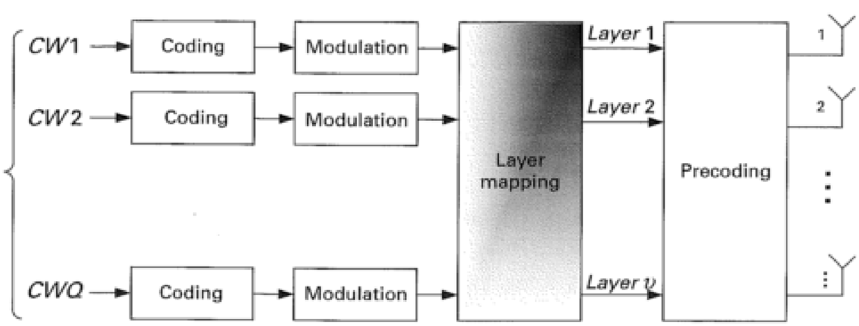

Figure 2.7 *MIMO transmit chain with codewords and layers* [10].

LTE supports a maximum of two codewords (coded and modulated transport block). The mapping of the codeword to layer mapping is done in the following way. The first codeword is mapped to the first layer and the second codeword is mapped to the second layer. A rank one transmission uses one, two or four antenna ports while a rank two transmission uses two or four antennas ports.

MIMO precoding

In general a MIMO channel is represented by a channel matrix containing channel gains and phase information from each transmit antennas to each receive antennas (Figure 2.6). The channel for the M x N MIMO system consists of an N x M matrix given as:

$$H = \begin{pmatrix} h11 & h12 & \cdots & \cdots\cdot & h1m \\ h21 & h22 & \cdots & \cdots\cdot & h2m \\ \cdots & \cdots & \cdots & \cdots\cdot & \cdots \\ \cdots & \cdots & \cdots & \cdots\cdot & \cdots \\ hn1 & hn2 & \cdots & \cdots & hnm \end{pmatrix} \qquad (2.8)$$

Where h_{ij} represents the channel gain from transmission antenna j to the receive antenna i. In order to get information about the channel, *Channel State Information (CSI)* must be fed back to the base station. For a case of a 4x4 MIMO channel, about 16 channel gains from each transmit antennas to each receiver antennas needs to be fed back. This can lead to overhead. To solve this issue a codebook is used. A codebook is a set of precoding matrices known by the transmitter and by the receiver. In an open-loop MIMO system, CSI is only known at the receiver. The receiver selects the best precoding matrix. While in a closed-loop MIMO system, the CSI is known at the transmitter and at the receiver. The receiver selects the best precoding matrix from the codebook and feds back the *Precoding Matrix Index* (PMI) to the transmitter. In this thesis, the focus is on open-loop MIMO system.

2.6 Theoretical channel capacity

In the previous section, it has been explained how to calculate the channel capacity for a SISO and MIMO systems. From (2.2) it is straightforward to compute the channel capacity for a SISO system. The table 2.2 gives the theoretical channel capacity for a SISO system for a single user.

Table 2.2 *SISO Channel capacity*

SNR [dB]	Channel Capacity [Mb/s]
0	14.952
10	51.725
20	99.34
30	149
50	248.35

From (2.7) it is straightforward to compute the channel capacity for a MIMO system. Here we consider MIMO (2x2) and MIMO (4x4) systems. The following tables 2.3 and 2.4 give the theoretical channel capacity for MIMO (2x2) and MIMO (4x4) systems.

Table 2.3 *MIMO (2x2) Channel capacity*

SNR [dB]	Channel Capacity [Mb/s]
0	29.904
10	103.45
20	199.11
30	298
50	496.7

Table 2.4 *MIMO (4x4) Channel capacity*

SNR [dB]	Channel Capacity [Mb/s]
0	59.808
10	206.90
20	398.21
30	596.12
50	993.4

Based on information in the tables above, we can get the following graphical representation of the theoretical performance bound of the channel capacity for a SISO and MIMO systems.

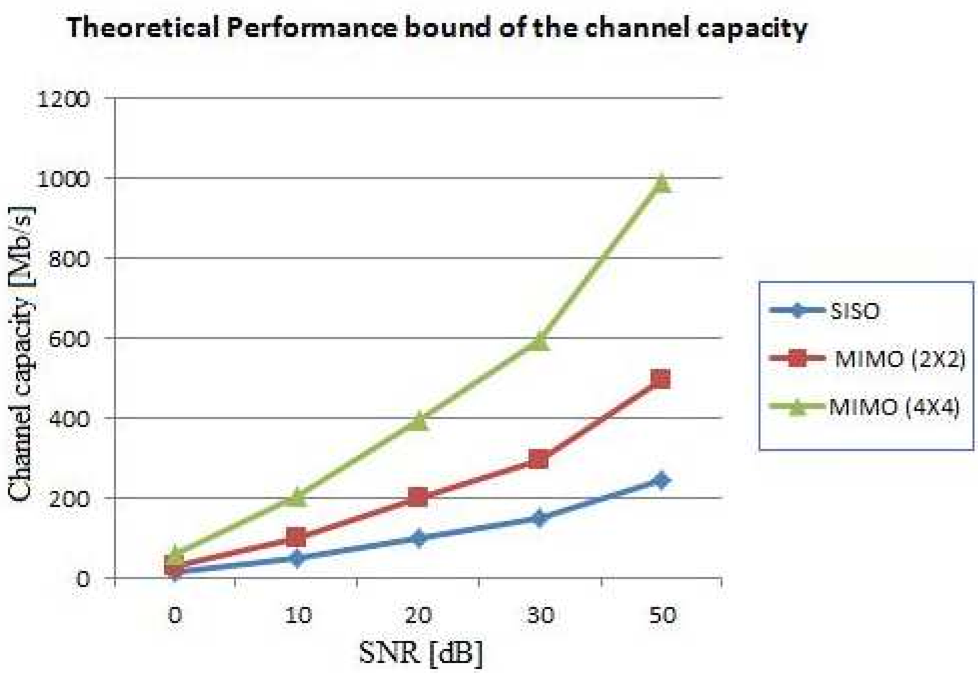

Figure 2.8 *Theoretical Performance bound of the channel capacity*

From this graph it is straightforward to see that the channel capacity increases with the number of antennas at the transmitter and at the receiver. Thus the channel capacity of a MIMO (4x4) system is two times higher than the channel capacity of a MIMO (2x2) system and the channel capacity of a MIMO (2x2) system is also two times higher than the channel capacity of a SISO system.

3 Related work

This chapter presents a description of the related works on downlink scheduling in LTE. We will explain the some existing scheduling algorithms. In section 3.1 the Best CQI scheduling algorithm will be discussed. Then in section 3.2 the Round Robin scheduling scheme will be reviewed.

3.1 Scheduling Methods

The scheduler controls the allocation of shared time-frequency resources among users at each time instant. The scheduler is located in the base station and assigned uplink and downlink resources. The scheduler determines to which user the shared resources (time and frequencies) for each TTI (1 ms) should be allocated for reception of DL-SCH transmission.

Link adaptation

Link adaptation (LA) compensates the variations in the instantaneous channel conditions. In situations with advantageous channel conditions, the data rate is increased and vice versa. To adjust the data rate, LA uses *Adaptive modulation and coding* (AMC). AMC matches the modulation and the channel coding scheme on resources assigned by the scheduler [3]. In situations with advantageous channel conditions, AMC selects a higher modulation order and coding rate and vice versa. This principle is illustrated in Figure 3.1.

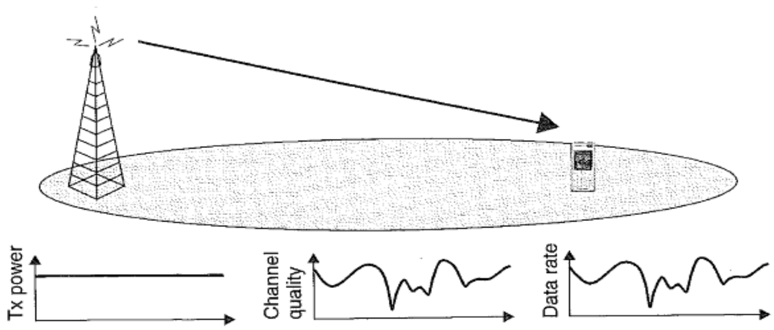

Figure 3.1 *Link Adaptation* [8].

In principle the base station periodically receives information from the terminal in the form of *Channel Quality Indicator* (CQI). The higher the CQI, the better the channel is. Thus based on the CQI received from the terminal, link adaptation can be performed.

The terminal reports the measured CQI to the BS by mapping the measured SNR according to Figure 3.2. In the LTE simulator, the mapping of the SNR to the CQI for a BLER of 0.1 is approximated through a linear function as shown in the figure.

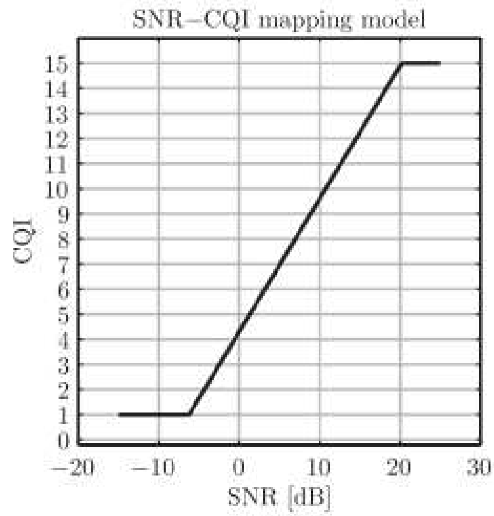

Figure 3.2 *SNR-CQI mapping model* [12]

The Table 3.1 contains the CQI index, the modulation scheme and channel coding rate corresponding to the CQI value.

Table 3.1 *CQI table* [10]

CQI index	Modulation	Coding rate	Efficiency [b/s/Hz]
0		Out of range	
1	QPSK	78/1024	0.1523
2	QPSK	120/1024	0.2344
3	QPSK	193/1024	0.3770
4	QPSK	308/1024	0.6016
5	QPSK	449/1024	0.8770
6	QPSK	602/1024	1.1758
7	16 QAM	378/1024	1.4766
8	16 QAM	490/1024	1.9141
9	16 QAM	616/1024	2.4063
10	64 QAM	466/1024	2.7305
11	64 QAM	567/1024	3.3223
12	64 QAM	666/1024	3.9023
13	64 QAM	772/1024	4.5234
14	64 QAM	873/1024	5.1152
15	64 QAM	948/1024	5.5547

3.1.1 Best CQI scheduling

As the name implies, this scheduling strategy assigns resource blocks to the user with the best radio link conditions as illustrated in Figure 3.3. In order to perform scheduling, terminals send *Channel Quality Indicator* (CQI) to the base station (BS). Basically in the downlink, the BS transmits reference signal (downlink pilot) to terminals. These reference signals are used by UEs for the measurements of the CQI. A higher CQI value means better channel condition.

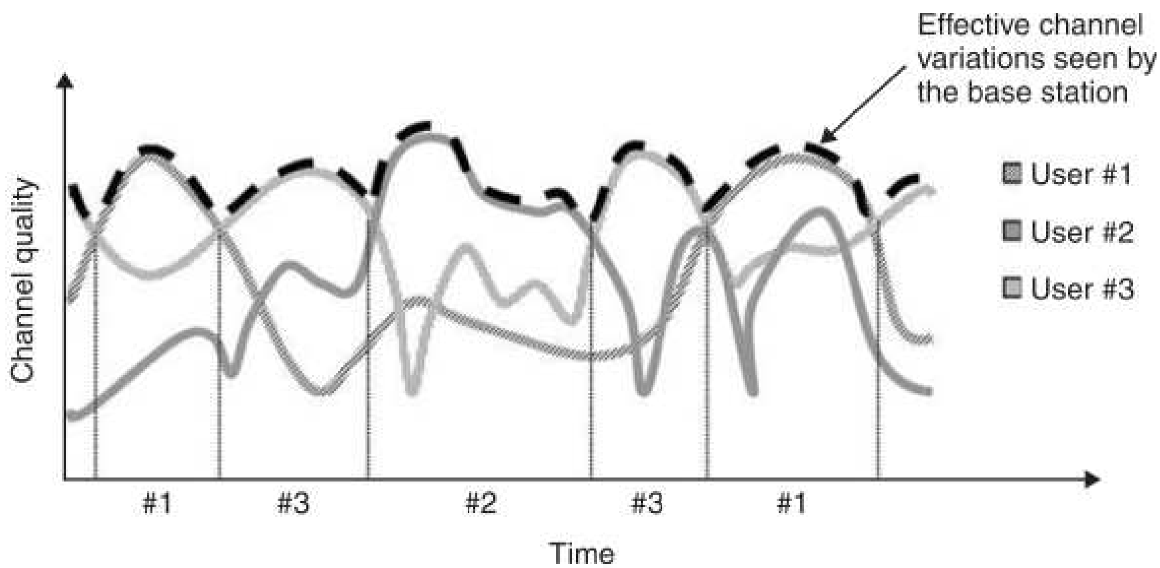

Figure 3.3 *Best CQI scheduling* [8]

Best CQI scheduling [4] can increase the cell capacity at the expense of the fairness. In this scheduling strategy, terminals located far from the base station (i.e. cell-edge users) are unlikely to be scheduled. The flowchart of the Best CQI scheduling is depicted in Figure 3.4

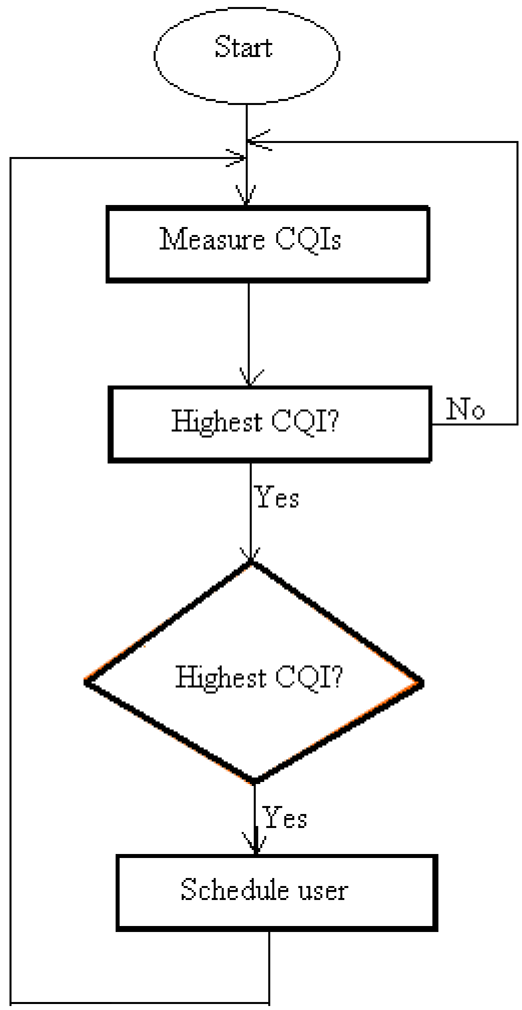

Figure 3.4 *Best CQI scheduling Flowchart*

3.1.2 Round Robin Scheduling

In this scheduling strategy the terminals are assigned the shared resources in turn (one after another). Thus every user is equally scheduled without taking the CQI into account as illustrated in Figure 3.5.

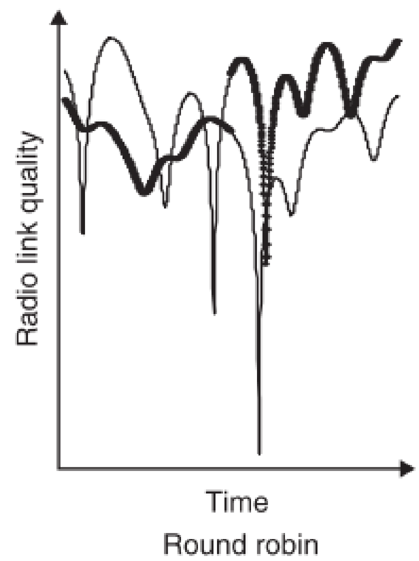

Figure 3.5 *Round Robin scheduling* [8].

The principal advantage of Round Robin scheduling is the guaranty of fairness for all users. Furthermore Round Robin is easy to implemented, that is the reason why it is usually used by many systems. Since Round Robin doesn't take the channel quality information into account, it will result in low user throughput. The flowchart of the Round Robin scheduling is shown in Figure 3.6.

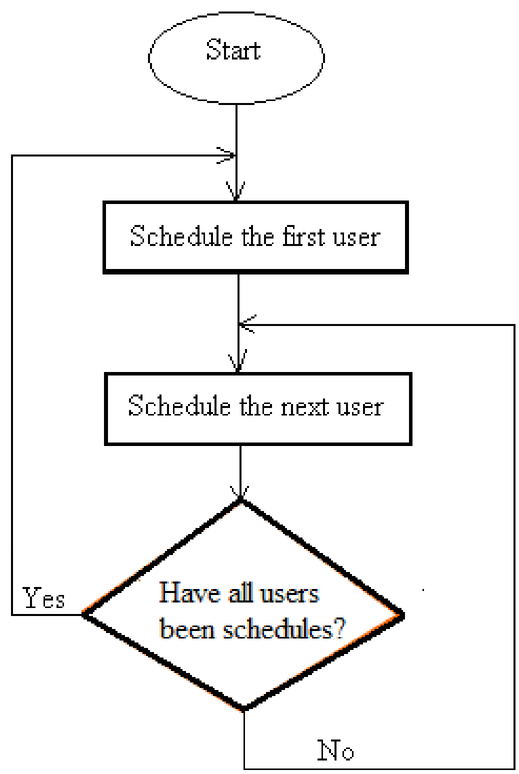

Figure 3.6 *Round Robin scheduling Flowchart*

4 The proposed new scheduling algorithm

In this chapter we introduce the proposed new scheduling algorithm for the downlink scheduling in LTE. We will explain how these scheduling scheme works. In section 4.1 the principle of the proposed new scheduling algorithm is explained. Then section 4.2 provides an illustration of the working of the scheduling scheme.

4.1 Principle

In order to find a trade-off between throughput and fairness we design a new scheduling algorithm that operates somewhere between the Best CQI scheduling and the Round Robin scheduling. The new scheduling algorithm will result in an acceptable throughput and provides some fairness between users. We propose a new scheduling algorithm that assigns the RB to the user that maximizes the CQI in the first slot period of each sub-frame; whereas in the second slot period the scheduler assigns the RB in turn to each user. In this way thus a compromise between the fairness and the throughput can be reached. The granularity of the proposed new scheduling algorithm is 1 resource block (RB). A resource block is the smallest element of resource allocation assigned by the BS scheduler. We have seen in the section 2.3 that one LTE frame is divided in 10 sub-frames of 1 msec duration. One subframe contains two slots periods of 0.5 msec duration. Figure 4.1 illustrates the flow chart of the proposed new scheduling algorithm. At the beginning of the scheduling process the BS compares the CQI from different terminals and selects the user with the highest CQI. If there is more than one terminal with the highest CQI, a random one is picked by the scheduler. In the first time slot the terminals with higher CQI are scheduled. In the second time slot the terminals are scheduled cyclically in turn. At the end of the second slot period the process begins again. Thus in the first slot of the second sub-frame the terminal with the higher CQI is selected and in the second time slot the terminals are assigned the RBs in turn.

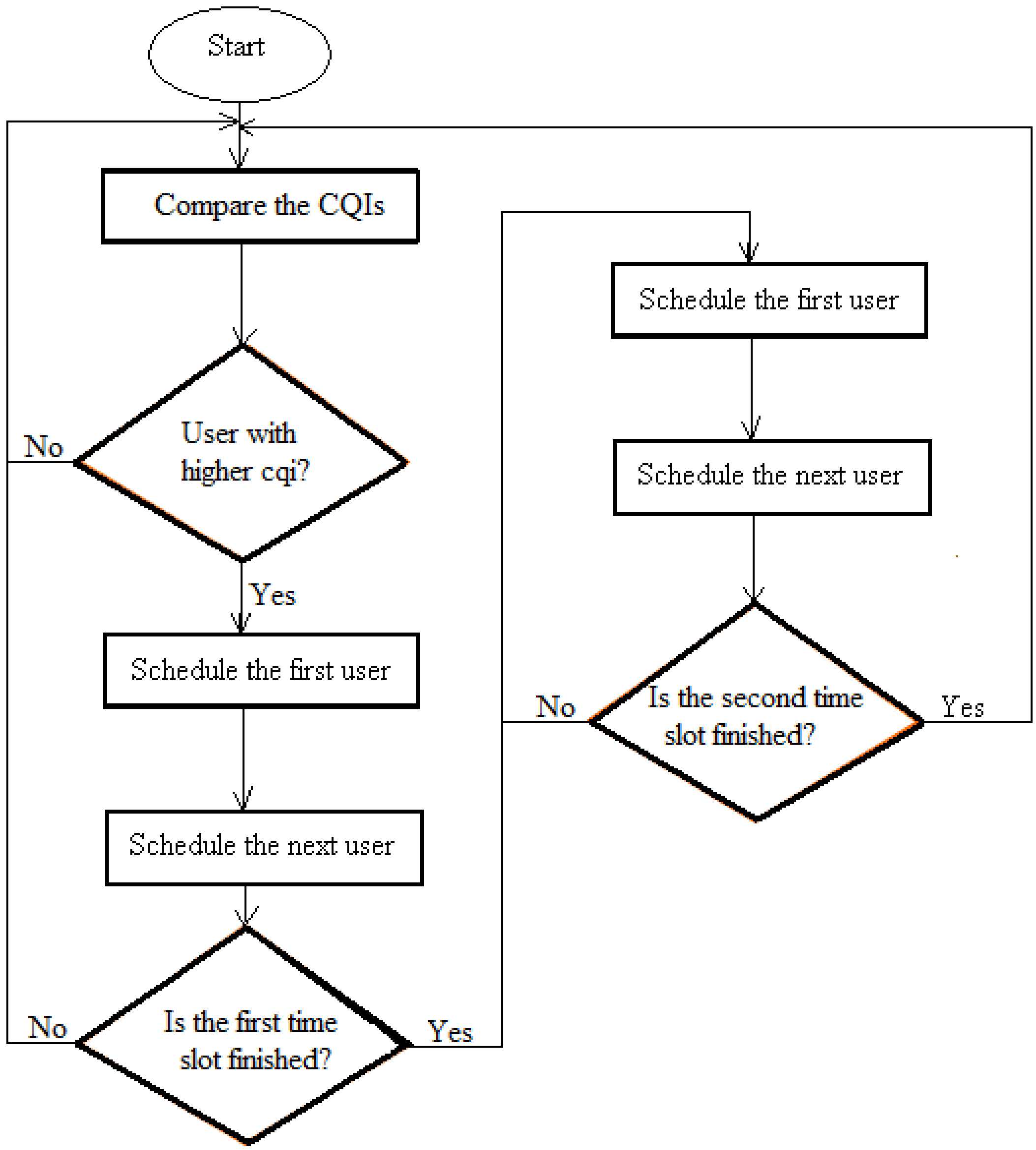

Figure 4.1 *Flowchart of the proposed new scheduling algorithm*

4.2 Illustration

The LTE operates in the bandwidth of 1.4 MHz up to 20 MHz. The number of RB ranges from 6 for 1.4 MHz bandwidth up to 100 RBs for 20 MHz bandwidth. In order to explain how the proposed new scheduling algorithm works, an illustration is given.
The main simulation parameters for the example under study are shown in the Table 4.1

Table 4.1 *Simulation Parameters*

Parameter	Value
Number of Equipments (UEs)	3
Number of base station	1
Bandwidth	1.4 MHz
Channel type	Ped B
Simulation length	1 sub-frame
Scheduling algorithm	The proposed new scheduling
Transmission scheme	SISO

The variable *UE_mapping_all_UEs* in the MATLAB code represents the mapping of RBs to users. For the example under consideration, the matrix with the name *UE_mapping_all_UEs* has 2 columns and 6 rows. The first and second columns of the matrix represent the first slot period and the second slot period of the subframe. Each column contains the RBs mapping to users. It is clear from the Figure 4.2 that each column has 6 RBs.

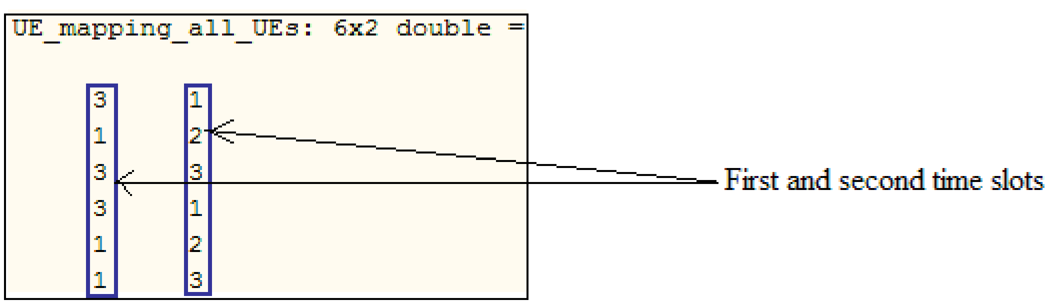

Figure 4.2 *Resources blocks mapping in the new scheduling algorithm*

In this example 3 users are considered and the selected bandwidth is 1.4 MHz. From the Table 2.1 we know that the number of RBs in a bandwidth of 1.4 MHz is 6. Since the MS3 has the highest CQI on RB1, MS3 is mapped to RB1, MS1 is mapped to RB2 and so on as depicted in Figure 4.2. Thus RB1 is assigned to MS3, RB2 to MS1, RB3 and RB4 to MS3 in the first time slot. The last two RBs in the first time slot are assigned to MS1. In this first time slot the RB is assigned to the user with the higher CQI on that RB. The second user is not scheduled because it has bad channel condition on these RBs. If the second user reports bad channel condition for a long period of time, it will not be scheduled for that period. Here the problem of unfairness has been exposed. In the second slot period the first 3 RBs are assigned cyclically in turn to users. Thus RB1, RB2, RB3 in the second slot period are mapped to MS1, MS2 and MS3 respectively. RB4, RB5 and RB6 are assigned to MS1, MS2 and MS3 respectively. Figure 4.3 illustrates the Resource blocks mapping for our example. We observe that the problem of unfairness for MS2 is resolved in the second slot period since two RBs are assigned to MS2 independently of its channel condition.

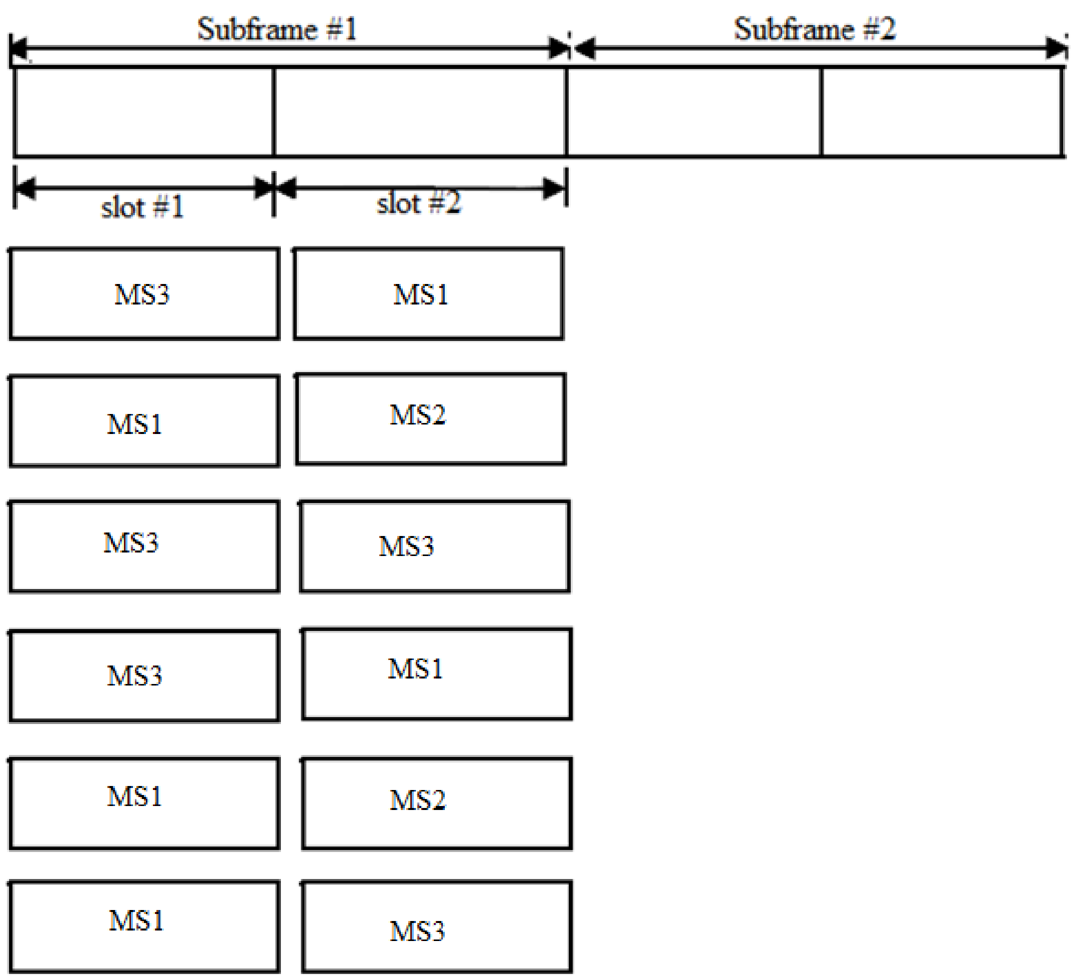

Figure 4.3 *Resources blocks mapping in the proposed new scheduling algorithm*

Table 4.2 compares the maximum throughput performances for the different scheduling algorithms namely: the Best CQI, the proposed new scheduling and the Round Robin. In this example we consider a scenario with 10 MS, SISO and the simulation length is 100 TTI. Furthermore the selected bandwidth is 20 MHz and the channel model is Pedestrian B.

Table 4.2 *Comparison of the throughput performances*

Scheduling Algorithms	Throughput [Mb/s]
Best CQI	43
Round Robin	12
The proposed new scheduling	33

The figure 4.4 depicts the SNR versus the cell throughput for different scheduling schemes: Round Robin, Best CQI and the proposed new scheduling algorithm.

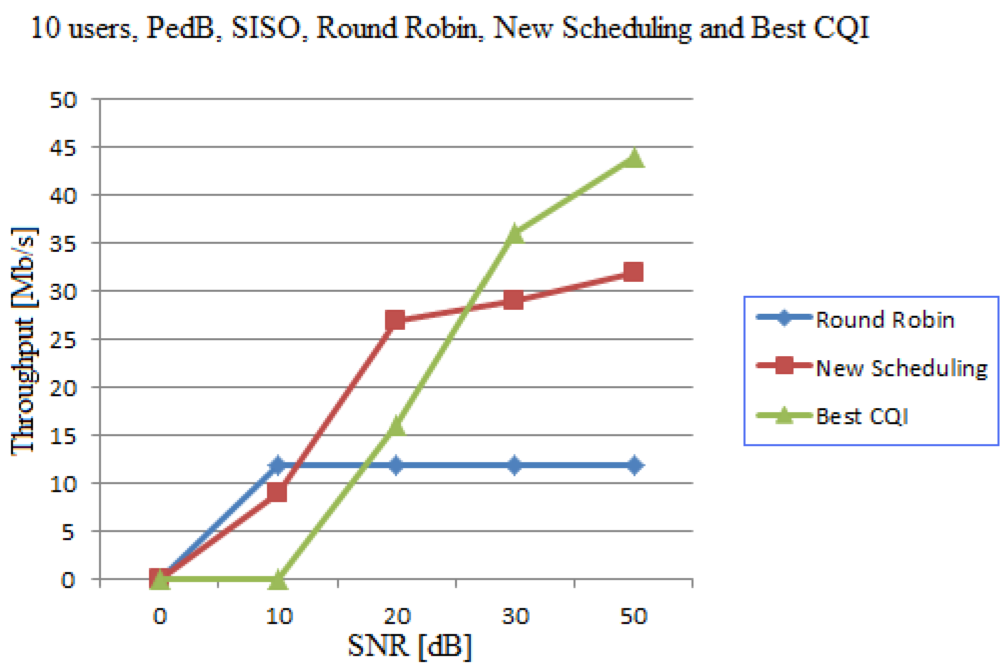

Figure 4.4 *Throughput for different scheduling schemes*

It is clear that the Round Robin scheduling performs worst since it does not take the channel conditions into account. The maximum cell throughput for the Round Robin scheduling is 12 Mb/s. It can be seen that our proposed new scheduling algorithm achieves better throughput than the Round Robin scheduling. In this example we can reach a maximum throughput of 33 Mb/s with the proposed new scheduling. The Best CQI scheduling achieves the highest throughput in the example but at the expense of the fairness as already explained. The maximum cell throughput for the Best CQI scheduling is 43 Mb/s. Thus our scheduler can be a trade-off between the throughput and the fairness because in a real system the fairness is more important than the highest throughput.

5 Simulation

This section investigates the performance of the LTE link level simulator in terms of throughput for different scenarios (different scheduling schemes, different antennas transmission system, different channel models [13] and different number of users). We will first start with the description of the LTE Link Level Simulator of the Vienna University [14]. Then graphical representations of the performance of these scheduling algorithms in terms of throughputs are plotted.

5.1 LTE Link Level Simulator overview

Link level simulations are carried out to evaluate the cell throughput. We have used the LTE Link Level Simulator v1.3r620 from the Vienna University of Technology, Austria [15]. Link level simulation enables us to emulate all the features of transmission between the base station and the terminal. This simulator is a MATLAB-based downlink physical-layer simulator for LTE. It can carry out single-downlink, single-cell multi-user and multi-cell simulations. Figure 5.1 depicts an overview of different possible simulation scenarios in the LTE simulator. But in this thesis the focus is on single-downlink, single-cell multi-user.

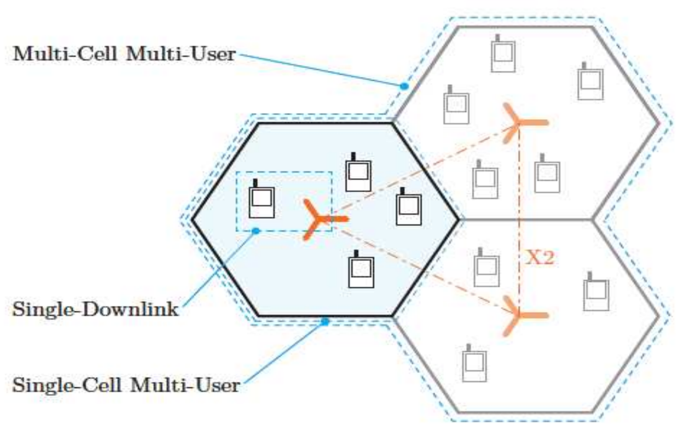

Figure 5.1: *overview of different simulation scenarios in the LTE simulator [12]*

5.2 MATLAB Code Problems

5.2.1 Round Robin scheduling

By the time the LTE Link Level Simulator was published in 2009 only one scheduling algorithm was available namely the Round Robin (RR) scheduling. The problem with the current implementation of the RR scheduling in the LTE simulator is that the RBs are not assigned in turn to users. For example in the case of 4 Mobile Stations (MS) and 6 RBs, the scheduler doesn't cyclically assigning a RB to MS1, MS2, MS3, MS4, MS1, MS2. The main simulation parameters for the example under study are shown in the Table 5.1

Table 5.1 *Simulation Parameters*

Parameter	Value
Number of Equipments (UEs)	4
Number of base station	1
Bandwidth	1.4 MHz
Channel type	Ped B
Simulation length	100 subframes
Scheduling algorithms	Round Robin (RR) CQI =7
Transmission scheme	SISO

The RR scheduling does not adapt the AMC mode according to the CQI-feedback. It always simulates with the cqi value set in the file *LTE_sim_batch.m* as cqi_i. By fixing the CQI to 7 we have assumed that channel conditions are the same on each RB during the simulation.

Before changes:

The example in the Figure 5.2 below explains the current implementation of the RR scheduling in the simulator. Here the variable *UE_mapping_all_UEs* in the MATLAB code represents the mapping of RBs to users. In this example 4 users are considered and the bandwidth is 1.4 MHz. From the Table 2.1 we know that the number of RBs in a bandwidth of 1.4 MHz is 6. We can see that the first three RBs are assigned to the first user and the next three RBs are mapped to second user in the first time slot. In the second time slot the first 3 RBs are assigned to the third user and the next 3 RBs are mapped to user 4.

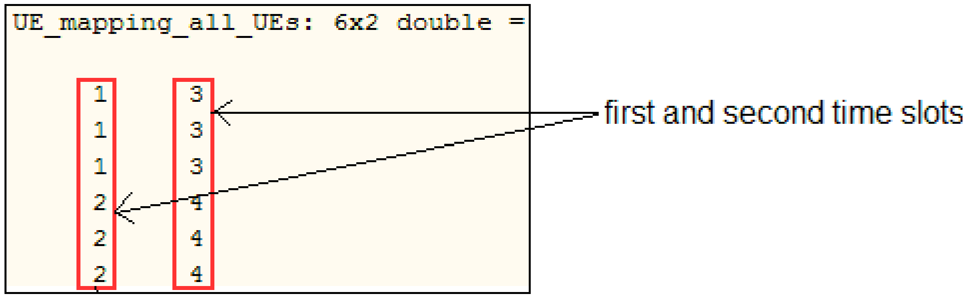

Figure 5.2 *Resources blocks mapping in Round Robin scheduling*

In a well-designed RR scheduling the RBs should be assigned cyclically to the users. With 4 MS and 6 RBs, the scheduler would cyclically assigned a RB to MS1, MS2, MS3, MS4, MS1 and MS2 until all the RBs are exhausted. From the Figure 5.2 we can observe that the implementation of RR scheduling is not correct.

Below is the simulation file with the name *roundRobinScheduler.m* for the simulation of Round Robin scheduling in the LTE Link Level Simulator.

```
classdef roundRobinScheduler < network_elements.lteScheduler
% www.nt.tuwien.ac.at

 properties
  end

  methods
      function obj = roundRobinScheduler(RB_grid_size,Ns_RB,UEs_to_be_scheduled,
                     scheduler_params,CQI_params)

             % Fill in basic parameters (handled by the superclass constructor)
obj=obj@network_elements.lteScheduler(RB_grid_size,Ns_RB,UEs_to_be_scheduled,
 scheduler_params,CQI_params);

             switch scheduler_params.assignment
                   case 'static'
                      obj.static_scheduler = true;
                      number_of_RBs_per_UE = floor(RB_grid_size*2 / obj.nUEs);

                      % Get a vector of scheduling params (one for each UE)
                      % initialized to the values that we want
                    obj.UE_static_params=
                    obj.get_initialized_UE_params(scheduler_params,CQI_params);

                     % Fill in the RB allocation grid for each user (and codeword)

                       UE_mapping_all_UEs = zeros(RB_grid_size,2);
                       for u_=1:obj.nUEs
                         % NOTE: Same RB assignment for both codewords.
                           UE_RBs = 1 + number_of_RBs_per_UE*(u_-1):
                           number_of_RBs_per_UE + number_of_RBs_per_UE*(u_-1);
                           cw_RB_grid = UE_mapping_all_UEs;
                           cw_RB_grid(UE_RBs) = u_;
                           UE_mapping_all_UEs = cw_RB_grid;

                       end
```

```
24             for u_=1:obj.nUEs
                    obj.UE_static_params(u_).UE_mapping=
                    (UE_mapping_all_UEs==u_);
                    obj.UE_static_params(u_).assigned_RBs =
                    squeeze(sum(sum(obj.UE_static_params(u_).UE_mapping,1),2));
                     end
                case 'dynamic'
                    obj.static_scheduler = false;

                    error('dynamic scheduler not yet implemented!!!!');
                otherwise
                    error('only static or dynamic schedulers supported');
            end
        end

function UE_scheduling =
scheduler_users(obj,subframe_corr,total_no_refsym,SyncUsedElements,UE_output,
UE_specific_data,cell_genie,PBCHsyms)
            if obj.static_scheduler
                UE_scheduling = obj.UE_static_params;
            else
                error('Dynamic scheduler not yet implemented.');
            end


obj.calculate_allocated_bits(UE_scheduling,subframe_corr,total_no_refsym,Sync
UsedElements,PBCHsyms);
        end
    end
end
```

<u>After changes:</u>

Thus some modifications have been made in the MATLAB code to make the Round Robin scheduling work correctly. In line 13 the variable *number_of_RBs_per_U*E representing the number of RBs per user was initialized in such a way that the number of RBs per user will be the same. Now the variable *number_of_RBs_per_U*E is initialized to one because this value allows us in line 23 to cyclically assign the RBs to users. Line 24 is the mapping of RBs to users. Below is the simulation file with the name *roundRobinScheduler.m* for simulation of Round Robin scheduling in the LTE Link Level Simulator after modifications.

```
classdef roundRobinScheduler < network_elements.lteScheduler
% www.nt.tuwien.ac.at

 properties
  end

  methods
      function obj =
roundRobinScheduler(RB_grid_size,Ns_RB,UEs_to_be_scheduled,scheduler_params,CQI
_params)

           % Fill in basic parameters (handled by the superclass constructor)
obj=obj@network_elements.lteScheduler(RB_grid_size,Ns_RB,UEs_to_be_scheduled,sc
heduler_params,CQI_params);

            switch scheduler_params.assignment
               case 'static'
                    obj.static_scheduler = true;
                    number_of_RBs_per_UE = 1;

                  % Get a vector of scheduling params (one for each UE)
                  % initialized to the values that we want
                 obj.UE_static_params =
                 obj.get_initialized_UE_params(scheduler_params,CQI_params);

                  % Fill in the RB allocation grid for each user(and codeword)
                  UE_mapping_all_UEs = zeros(RB_grid_size,2);

                    for u_=1:obj.nUEs
                         %NOTE: Same RB assignment for both codewords.
                        UE_RBs = 1 + number_of_RBs_per_UE*(u_-1):
                        number_of_RBs_per_UE + number_of_RBs_per_UE*(u_-1);
                        cw_RB_grid = UE_mapping_all_UEs;
                        cw_RB_grid(UE_RBs) = u_;
```

```
      cw_RB_grid(UE_RBs:obj.nUEs:(2*length(UE_mapping_all_UEs))) = u_;
      UE_mapping_all_UEs = cw_RB_grid;

         end

                % Assign the static scheduling parameters for each user
          for u_=1:obj.nUEs
              obj.UE_static_params(u_).UE_mapping=
              (UE_mapping_all_UEs==u_);
                obj.UE_static_params(u_).assigned_RBs=
               squeeze(sum(sum(obj.UE_static_params(u_).UE_mapping,1),2));
         end

         case 'dynamic'
                obj.static_scheduler = false;

                error('dynamic scheduler not yet implemented!!!!');
                otherwise
                error('only static or dynamic schedulers supported');
        end
    end
```

After the modifications of the MATLAB code we observe that RB1, RB2, RB3 and RB4 in the first slot period are mapped respectively to MS1, MS2, MS3 and MS4. RB5 and RB6 are assigned to MS1 and MS2 respectively. In the next slot period RB1, RB2 are assigned to MS3 and MS4 respectively. The new cycle begins again until the RBs are exhausted. Figure 5.3 illustrates the mapping of the RBs after modifications.

```
UE_mapping_all_UEs: 6x2 double =

     1      3
     2      4
     3      1
     4      2
     1      3
     2      4
```

Figure 5.3 *Resources blocks mapping in Round Robin scheduling*

5.2.2 Best CQI Scheduling

By the time the LTE Link Level Simulator was published only the Round Robin scheduling was provided. The work for Best CQI scheduling was in progress.

Before changes:

It was no possible to run the simulator with Best CQI as scheduling algorithm. At the end of the simulation, in the file name *simulation_results* we observe that there were no RBs assigned and we could compute the throughput. Furthermore the CQIs were not taken into consideration. The main simulation parameters for the example under study are shown in the Table 5.2.

Table 5.2 *Simulation Parameters*

Parameter	Value
Number of Equipments (UEs)	3
Number of base station	1
Bandwidth	1.4 MHz
Channel type	Ped B
Simulation length	100 subframes
Scheduling algorithms	Best CQI
Transmission scheme	SISO

Below are the main lines of the file *lteScheduler.m* for simulation of the Best CQI scheduling in the LTE Link Level Simulator.

```
classdef lteScheduler < handle
% Implements methods common to all the schedulers.
% Josep Colom Ikuno, jcolom@nt.tuwien.ac.at
% (c) 2009 by INTHFT
% www.nt.tuwien.ac.at

 properties
      maxCodewords = 2;  % Maximum number of codewords.
      static_scheduler   % Whether this scheduler is static or dynamic
      UEs                % List of UEs to schedule
      nUEs               % Total number of UEs -> length(UEs)
      UE_static_params   % In case this is a static scheduler.
       Ns_RB              % Number of symbols in one RB
       max_HARQ_retx      % Max num of HARQ retransmissions.
       attached_eNodeB    % eNodeB to which this scheduler is attached
       RB_grid_size       % Size of the Resource Block grid
       CQI_params         % CQI parameters for all possible MCSs
       zero_delay         % Specify whether there is zero delay for the CQI
       CQI_mapping_params % parameters needed to perform the CQI mapping
      UE_specific        % direct reference to the HARQ processes

  end

   methods
     .
     .
     .          Lines skipped
     .
```

```
function feedback_users_cqi_vec_all = get_all_UE_feedback(obj,UE_output)
            % Get feedback from all users. If we are using zero delay, then
            % calculate the CQIs from the genie SNRs. If not, use the
            % received UE feedback
            feedback_users_cqi_vec_all = zeros(obj.nUEs,obj.RB_grid_size);
            if obj.zero_delay
                % TODO: get genie information and calculate CQI
            else
                for u_=1:obj.nUEs
                    current_UE_feedback = UE_output(u_).CQI_feedback;
                    % It could be that there is no feedback (eg. Not yet
                    % arrived). Then set CQIs to all 0 (no transmission).
                    if isempty(current_UE_feedback)
                        feedback_users_cqi_vec_all(u_,:) = 0;
                    else
                        feedback_users_cqi_vec_all(u_,:)=
                            current_UE_feedback;
                    end
                end
            end
        end
    end

 methods (Abstract)
        % UE scheduling (to be implemented for each subclass
        UE_scheduling = scheduler_users(obj,subframe_corr,total_no_refsym,
SyncUsedElements,UE_output,UE_specific_data)
    end
     end
```

<u>After changes:</u>

We started to analyze the MATLAB code to determine what the current code was doing and from there we start to make modifications. After modifications the Best CQI scheduling works. The Best CQI scheduler assigns a RB to the user that has the highest CQI on that RB. The CQIs are randomly generated. Thus the CQIs are not generated based on the channel conditions. The user's feedback the CQIs to the BS and the BS assigned the resources to user with a higher CQI. Furthermore the higher the CQI, the higher the modulation order and the coding rate. At the end of the simulation we are able to compute the throughput.

Below are the main lines of the file *bestCqiScheduler.m* for simulation of the Best CQI scheduling in the LTE Link Level Simulator after modifications in the MATLAB code.

```
.
.
.
.

function UE_scheduling =
scheduler_users(obj,subframe_corr,total_no_refsym,
SyncUsedElements,UE_output,UE_specific_data,cell_genie,PBCHsyms)

UE_scheduling = obj.UE_static_params;

% dynamic assignment of RB to a user that has maximal CQI for this RB
UE_mapping_all_UEs = zeros(obj.RB_grid_size,2);

 feedback_users_cqi_vec_all = obj.get_all_UE_feedback(UE_output);

  % Obtain the vector of max CQIs
       max_users_cqi_vector = max(feedback_users_cqi_vec_all,[],1);

       for rb_= 1:obj.RB_grid_size

           % find maximum CQI
           max_UEs =
    find(max_users_cqi_vector(rb_)==feedback_users_cqi_vec_all(:,rb_));

         % If there is more than one UE with the maximum CQI,a random one is
          picked
           if(length(max_UEs)>1)

          max_user = max_UEs(ceil((rand(1)+realmin)*length(max_UEs)));

           else
               max_user = max_UEs;
           end

           UE_mapping_all_UEs(rb_,1) = max_user;
       end

.
.
.
.
```

.

Lines skipped

.

.

```
296 function feedback_users_cqi_vec_all = get_all_UE_feedback(obj,UE_output)
297          % Get feedback from all users.

298          feedback_users_cqi_vec_all = zeros(obj.nUEs,obj.RB_grid_size);

299          if obj.zero_delay

300                  UE_output = rand(obj.nUEs,obj.RB_grid_size);
301                  current_UE_feedback = UE_output;
302                  feedback_users_cqi_vec_all =
303                  ceil(current_UE_feedback.*15);

304          else

305          for u_=1:obj.nUEs
306                  current_UE_feedback = UE_output(u_).CQI_feedback;
307                  % It could be that there is no feedback (eg. Not yet
308                  % arrived). Then set CQIs to all 0 (no transmission).
309                  if isempty(current_UE_feedback)
309                      feedback_users_cqi_vec_all(u_,:) = 0;
310                  else
311                      feedback_users_cqi_vec_all(u_,:) =
312                        current_UE_feedback;
313                  end
314           end
315         end
316      end
317  end
```

In the file *lteScheduler.m*

In our example we have 3 users and the bandwidth is 1.4 MHz.
Line 300: A 3x6 matrix of random numbers ranging from 0 to 1 is generated and stores in the variable *UE_output*.
Line 301: The variable *UE_output* is given another name *current_UE_feedback*.
Figure 5.4 displays a 3 by 6 matrix of random real numbers.

```
current_UE_feedback: 3x6 double =

    0.2864    0.5121    0.7321    0.2395    0.8424    0.7939
    0.6871    0.7213    0.7498    0.5209    0.6629    0.4691
    0.1411    0.9288    0.4073    0.2191    0.8162    0.3095
```

Figure 5.4 *Matrix of random numbers*

Line 302: By multiplying the matrix *current_UE_feedback* by 15 and by rounding its elements to the nearest integers towards infinity we obtain a matrix of natural numbers ranging from 1 to 15 representing the CQIs. The results of this operation are saved in the variable *feedback_users_cqi_vec_all*. Thus this is how we have generated randomly the CQIs. Because we have 3 MS and 6 RBs the matrix containing the CQIs has 3 by 6 elements representing the CQIs. Figure 5.5 illustrates a 3x6 matrix containing the CQIs.

```
feedback_users_cqi_vec_all: 3x6 double =

     5     8    11     4    13    12
    11    11    12     8    10     8
     3    14     7     4    13     5
```

Figure 5.5 *CQIs randomly generated*

The first row of the matrix contains the CQIs of the first user on different RBs, the second and third rows contain respectively the CQIs of the second and third users on different RBs.

In the file *bestCqiScheduler.m*

Line 44: We get the vector of maximum CQI for each user in the variable *feedback_users_cqi_vec_all*. From the previous figure we observe that in the first column the highest CQI is 11 and the user that reports the highest the CQI on that RB is user 2. In the second column the highest CQI is 14 and the user that maximizes the CQI is user 3 and so on. In this way we can get a vector of maximum CQIs as show in Figure 5.6.

```
max_users_cqi_vector: 1x6 double =

    11    14    12     8    13    12
```

Figure 5.6 *Highest CQI on each column*

Line 51 – 55: If there is more than one UE with the maximum CQI, a random one is selected.
Line 56: The RBs are mapped to users. Since the MS2 has the highest CQI on RB1, MS2 is mapped to RB2, MS3 is mapped to RB2 and so one as depicted in Figure 5.7.

```
UE_mapping_all_UEs: 6x2 double =

     2     0
     3     0
     2     0
     2     0
     3     0
     1     0
```

Figure 5.7 *Resource blocks mapping*

By disabling line 17 in the file *LTE_load_parameters_dependent.m* below, it is possible to run the simulator with Best CQI as scheduling algorithm.

```
13 %% Additional check for the new (and not 100% developed yet) schedulers
14 if ~strcmp('round robin',LTE_params.scheduler.type) &&
15  ~strcmp('fixed',LTE_params.scheduler.type)
16    if LTE_params.UE_config.mode~=1
17        %error('For now only the RR and fixed scheduler is implemented for
18           non-SISO modes.');
19    end
20   end
```

5.3 Simulation Results and Analysis

In this section, the link level simulations are carried out to evaluate the performances of the downlink scheduling algorithms. We investigate the performance of the LTE link level simulator in terms of throughput for different scenarios (different scheduling methods, different antennas transmission system, different channel models and different number of users).

Parameter settings

Table 5.3 summarizes the essential simulation settings and parameters used for different simulations scenarios.

Table 5.3 *Simulations parameters*

Parameter	Value
Number of users	1,10, 25, 50 and 100
Number of base station	1
Bandwidth	20MHz
Channel type	Pedestrian B and Vehicular A
Simulation length	100 sub-frames
Scheduling algorithms	Round Robin, new scheduling and Best CQI
Transmission schemes	SISO, MIMO (2x2) and MIMO (4x4)

5.3.2 Simulation scenarios

Scenario 1

Case 1: Pedestrian B, SISO, MIMO, single user and new scheduling algorithm

In the first case we simulate a single user and we show the user throughput for different SNR values. We have plotted the throughput for different transmission schemes (SISO, MIMO (2x2), and MIMO (4x4)). The scheduling algorithm used is the proposed new scheduling. The duration of the simulation is 100 TTI; the selected bandwidth is 20 MHz. The channel type is Pedestrian B (PedB).

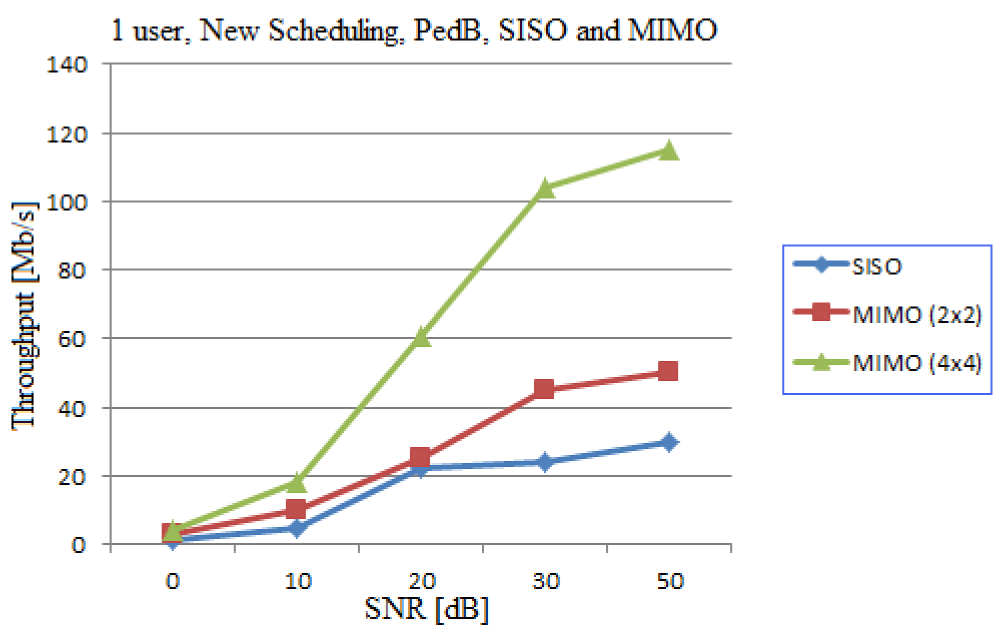

Figure 5.8 *SNR versus Throughput for single user.*

Figure 5.8 depicts the user throughput for different transmission schemes. We observe that the throughput of a SISO system is lower than the throughput of a MIMO (2x2) and the user throughput of a MIMO (2x2) system is lower than the throughput of a MIMO (4x4) system. Thus in other words, the higher the transmission schemes, the higher the throughput. To be more precise the throughput of a MIMO (4x4) system is two times higher than the throughput of a MIMO (2x2) system and the throughput of a MIMO (2x2) system is also two times higher than the throughput of a SISO system. The throughput increases with the SNR. Here we can reach a maximum throughput of 115 Mb/s.

Case 2: Pedestrian B, SISO, MIMO, single user and Round Robin

This second case intends to simulate a single user and shows the user throughput for different SNR values. The throughput for different transmission schemes (SISO, MIMO (2x2), and MIMO (4x4)) is plotted. Here the scheduling algorithm is Round Robin but with one user. The duration of the simulation is specified by the *Transmission Time Interval* (TTI). We set the simulation time to 100 TTI; the selected bandwidth is 20 MHz. The CQI is set to 7 in our simulation. The Round Robin scheduler does not adapt the AMC mode according to the CQI-feedback. It always simulates with the cqi value set in the file *LTE_sim_batch.m* as cqi_i.
In the rest of this report the CQI is fixed to 7 when running the simulation with Round Robin as scheduling algorithm. The channel type used is the Pedestrian B (PedB).

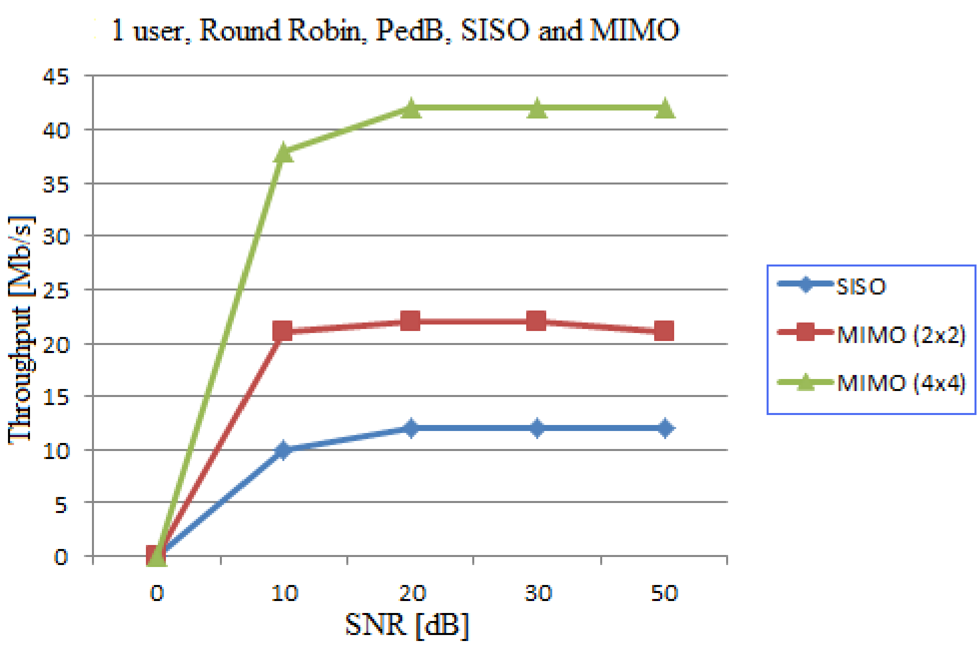

Figure 5.9 *SNR versus Throughput for single user.*

Figure 5.9 displays the relation between the SNR and the user throughput for different antenna schemes. The throughput of a SISO system is lower than the throughput of a MIMO (2x2) and the throughput of a MIMO (2x2) system is lower than the throughput of a MIMO (4x4) system. It is clear that the throughput of a MIMO (4x4) system is two times higher than the throughput of a MIMO (2x2) system and the throughput of a MIMO (2x2) system is also two times higher than the throughput of a SISO system. That is what we expect based on the theoretical results obtained in the chapter 2. Here we can reach a maximum throughput of 42 Mb/s.

Case 3: Best CQI, Pedestrian B, SISO, MIMO and single user

The third case simulates a single user. The throughput for different transmission schemes (SISO, MIMO (2x2), and MIMO (4x4)) is plotted. This time the scheduling algorithm is Best CQI but with one user. The duration of the simulation is set to 100 TTI, the bandwidth is 20 MHz, and the channel type used is the Pedestrian B (PedB).

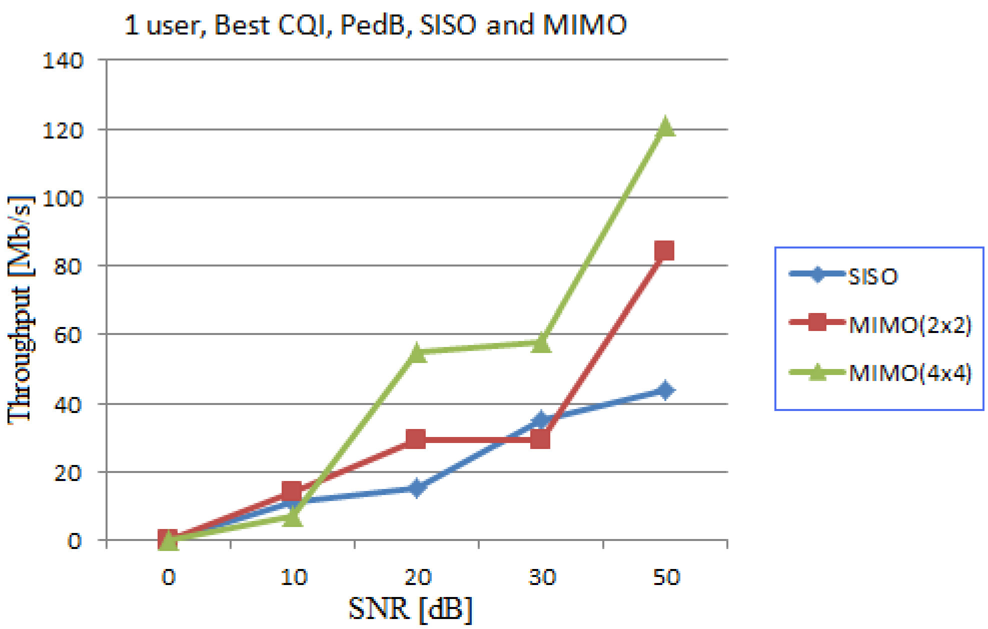

Figure 5.10 *SNR versus Throughput for single user.*

Figure 5.10 displays the SNR and the user throughput for SISO and MIMO systems. From this figure the UE throughput of a MIMO (2x2) system is higher than the throughput of a SISO system and lower than the throughput of a MIMO (4x4) system. Furthermore the throughput increases with the SNR. Here we can reach a maximum throughput of 121 Mb/s.

Scenario 2

Case 1: Vehicular A, SISO, MIMO, single user and new scheduling algorithm

In the first case we intend to simulate a single user and we show the user throughput for different SNR values. We have plotted the throughput for different antennas schemes (SISO, MIMO (2x2), and MIMO (4x4)). The scheduling algorithm used is the proposed new scheduling algorithm. The duration of the simulation is 100 TTI; the selected bandwidth is 20 MHz. The channel type is Vehicular A.

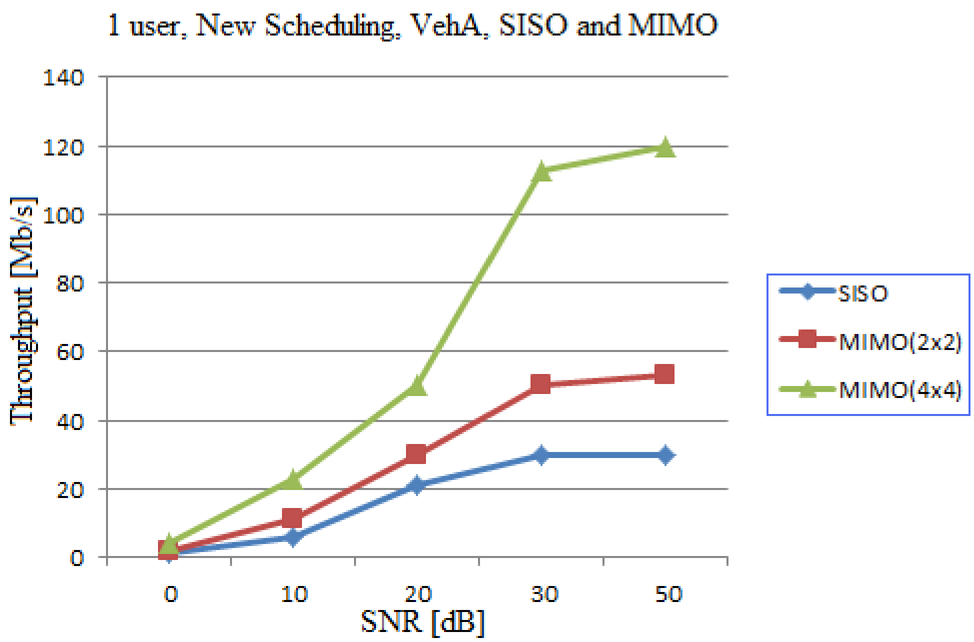

Figure 5.11 *SNR versus Throughput for single user.*

Figure 5.11 depicts the relation between the SNR and the user throughput for different transmission schemes. We observe that the throughput of a SISO system is lower than the throughput of a MIMO (2x2) and the throughput of a MIMO (2x2) system is lower than the throughput of a MIMO (4x4) system. Thus in other words, the higher the transmission schemes, the higher the throughput. The throughput increases with the SNR. Here we can reach a maximum cell throughput of 120 Mb/s.

Case 2: Round Robin, SISO, vehicular A and single user

In this scenario a SNR values versus the throughput for a single user is plotted for different antenna schemes (SISO, MIMO (2x2), and MIMO (4x4)). Again the scheduling algorithm is Round Robin (CQI =7) but with one user terminal. The RR scheduler does not adapt the AMC mode according to the CQI-feedback. It always simulates with the cqi value set in the file *LTE_sim_batch.m* as cqi_i. The simulation time is set to 100 TTI. The bandwidth is 20 MHz and the channel type is Vehicular A.

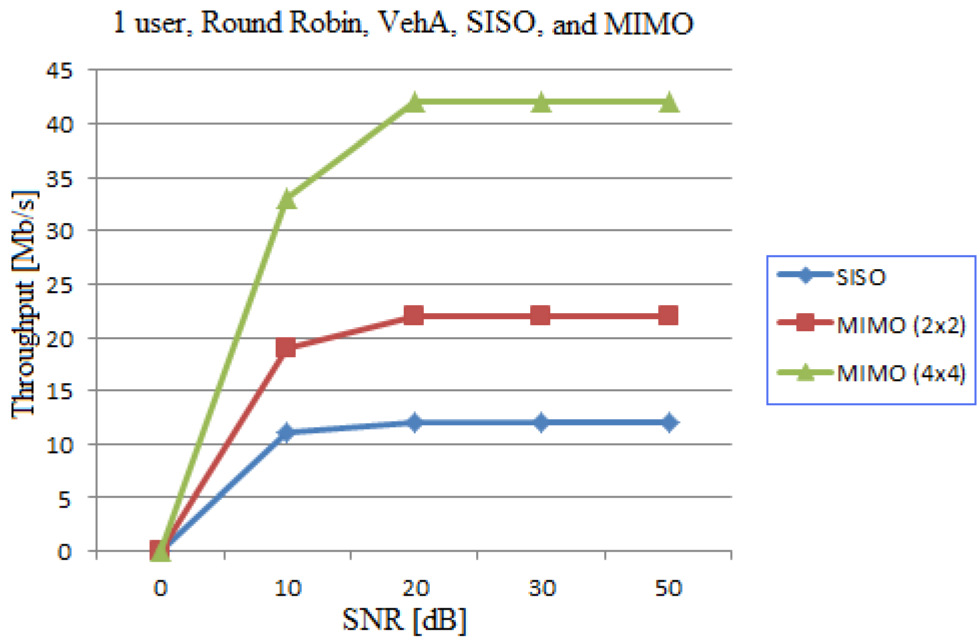

Figure 5.12: *SNR versus Throughput for single user.*

Figure 5.12 depicts the SNR versus the user throughput for SISO and MIMO systems. Again we observe that the throughput of a MIMO (4x4) system is two times higher than the throughput of a MIMO (2x2) system and the throughput of a MIMO (2x2) system is also two times higher than the throughput of a SISO system. Thus the throughput increases with the number of antennas at the transmitter and at the receiver. Here we can reach a maximum throughput of 42 Mb/s.

<u>Case 3:</u> Best CQI, SISO, MIMO, single use and Vehicular A

Here we simulate a single user throughput for different SNR values. The plot displays the throughput for different antenna schemes (SISO, MIMO (2x2), and MIMO (4x4)). The scheduling algorithm is Best CQI with one terminal. The simulation time is still set to 100 TTI. The bandwidth is 20 MHz and the channel model is Vehicular A.

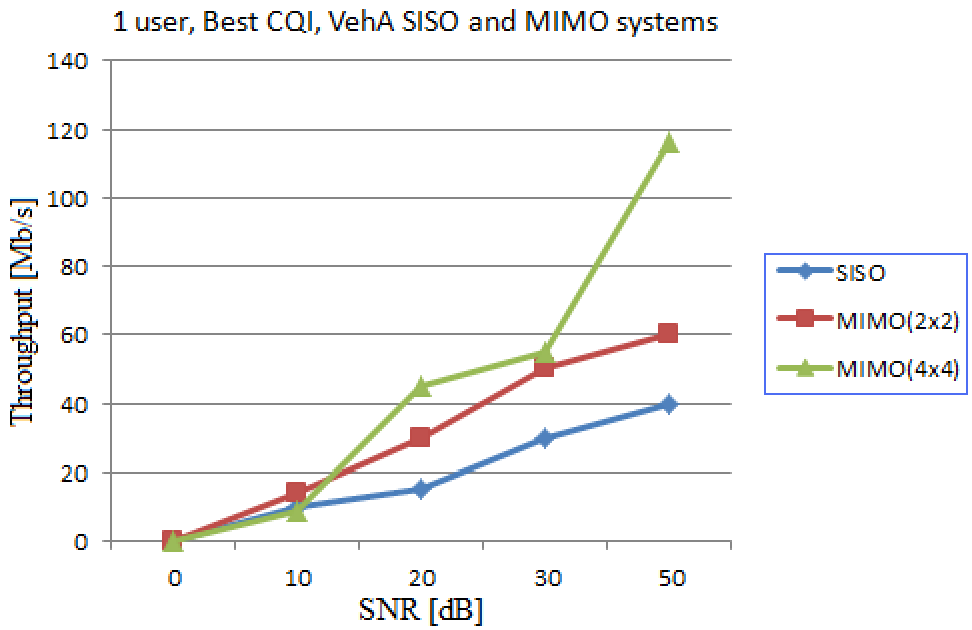

Figure 5.13 *SNR versus Throughput for single user.*

Figure 5.13 depicts SNR versus throughput for SISO and MIMO systems. Again from this Figure, it is easy to observe that the throughput of a MIMO (4x4) system is two times higher than the throughput of a MIMO (2x2) system and the throughput of a MIMO (2x2) system is also two times higher than the throughput of a SISO system. Furthermore the throughput increases with the SNR. Here we can reach a maximum throughput of 120 Mb/s.

Channel capacity and throughput analyze

Case 1: Channel Pedestrian B

Figure 5.14 compares the theoretical channel capacity for SISO and MIMO systems to the throughput results obtained from the LTE link level simulator. The section 2.6 has explained how to compute the theoretical channel capacity. Here the channel type is Pedestrian B. The throughput curves of the Best CQI, of the Round Robin and the ones of the new scheduling are plotted. The Round Robin scheduler does not adapt the AMC mode according to the CQI-feedback. It always simulates with the CQI value set in the file *LTE_sim_batch.m* as cqi_i. In our simulation we set the CQI to 7. From the plot we observe that the Best CQI scheduling has the highest throughput compared to the proposed new scheduling and to the Round Robin scheduling. It is clear that MIMO system increases the throughput and the system capacity.

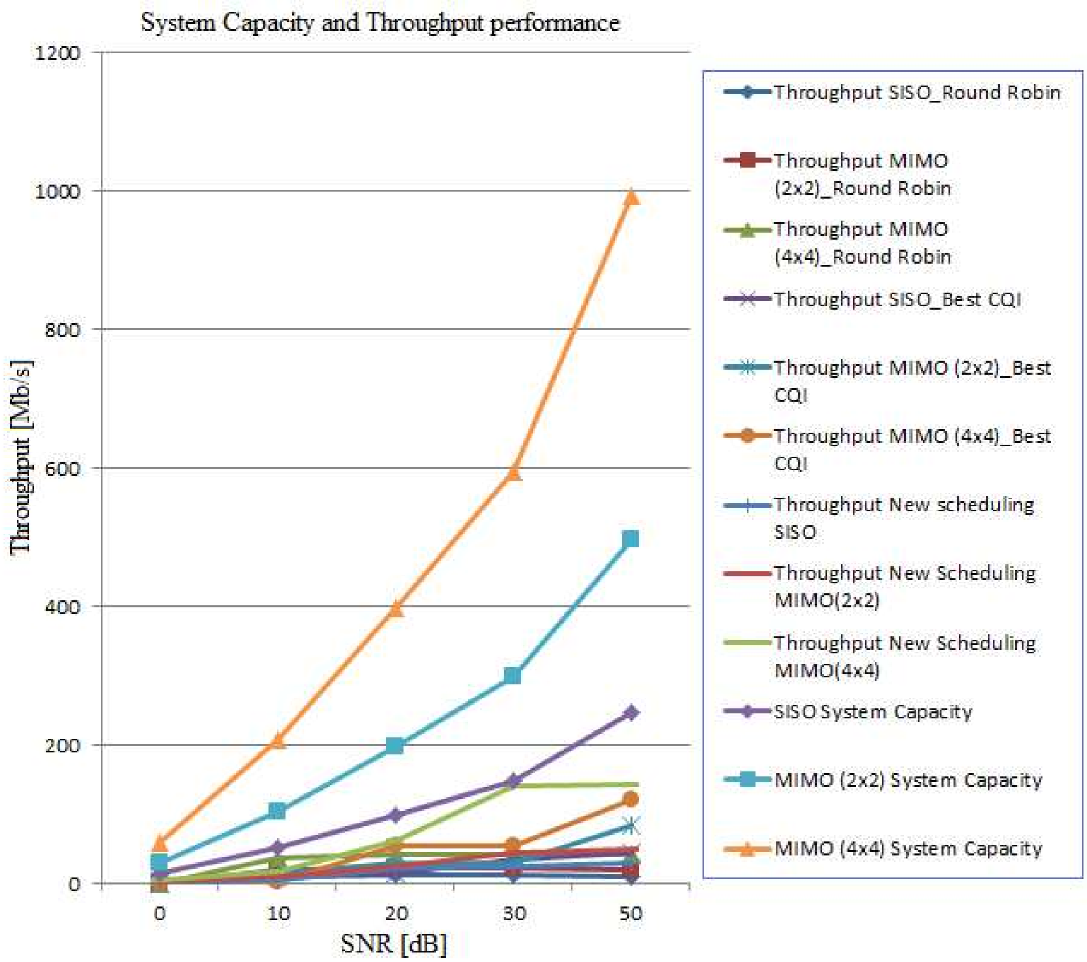

Figure 5.14 *Channel capacity and throughput for a single user.*

<u>Case 2:</u> Channel Vehicular A

This case is almost similar to previous one. But this time the channel is Vehicular A. The following plot depicts the channel capacity for SISO and MIMO systems and the throughput results obtained from the simulator.

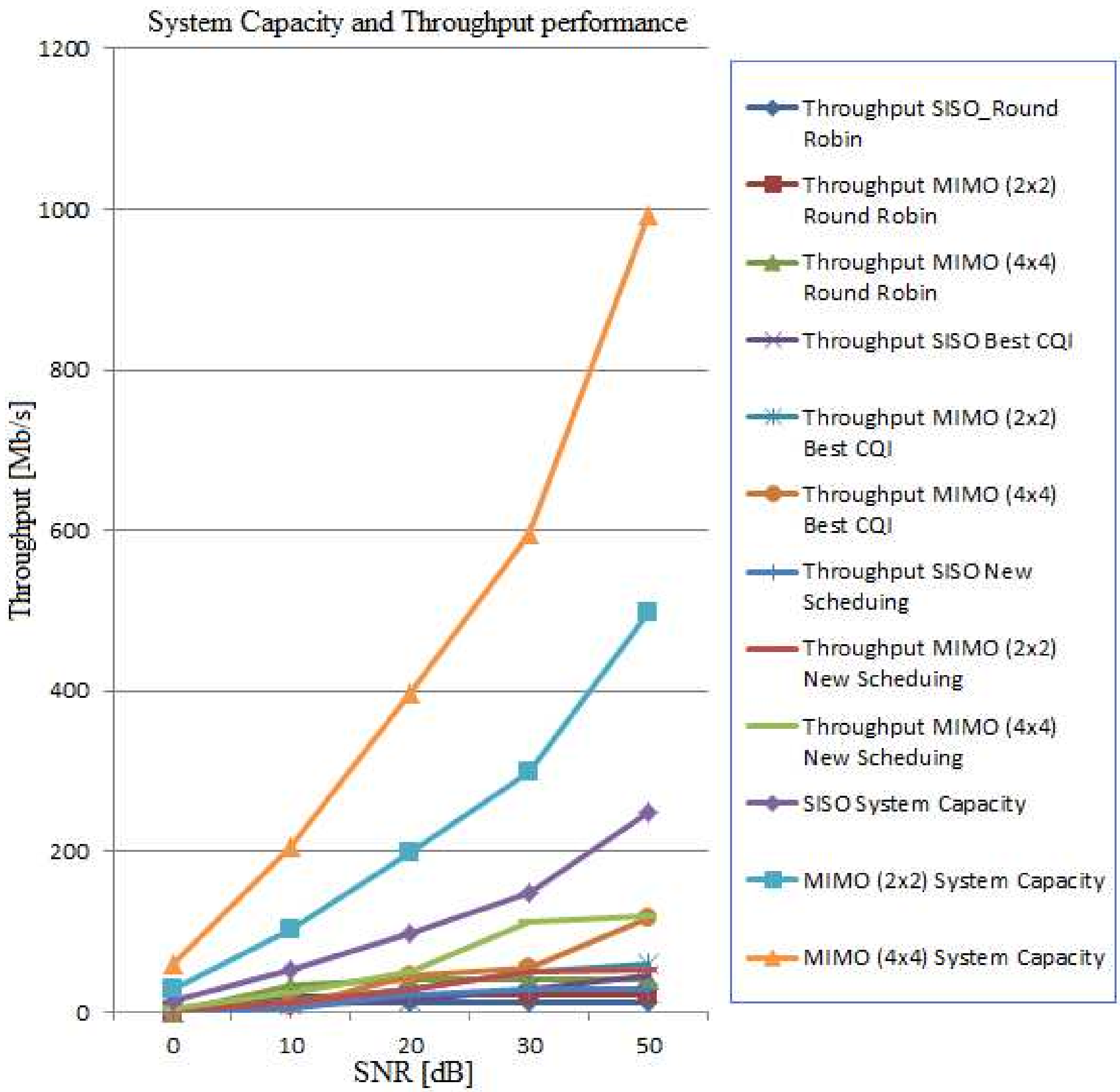

Figure 5.15 *Channel capacity and throughput for a single user.*

It can be observed that the Best CQI scheduling results in the highest throughput. From the plot we observe that the Best CQI scheduling has the highest throughput compare to the new scheduling and Round Robin scheduling. We can observe that MIMO system increases the throughput and the system capacity.

Scenario 3

Case 1: Best CQI, Pedestrian B, Multiple users and SISO

This scenario performs simulations for multiple users and depicts the SNRs versus the throughput. The throughput is shown only for a SISO system. This time the scheduling algorithm is Best CQI. Again the simulation time is set to 100 TTI, the bandwidth is 20 MHz, and the channel model used is the Pedestrian B.

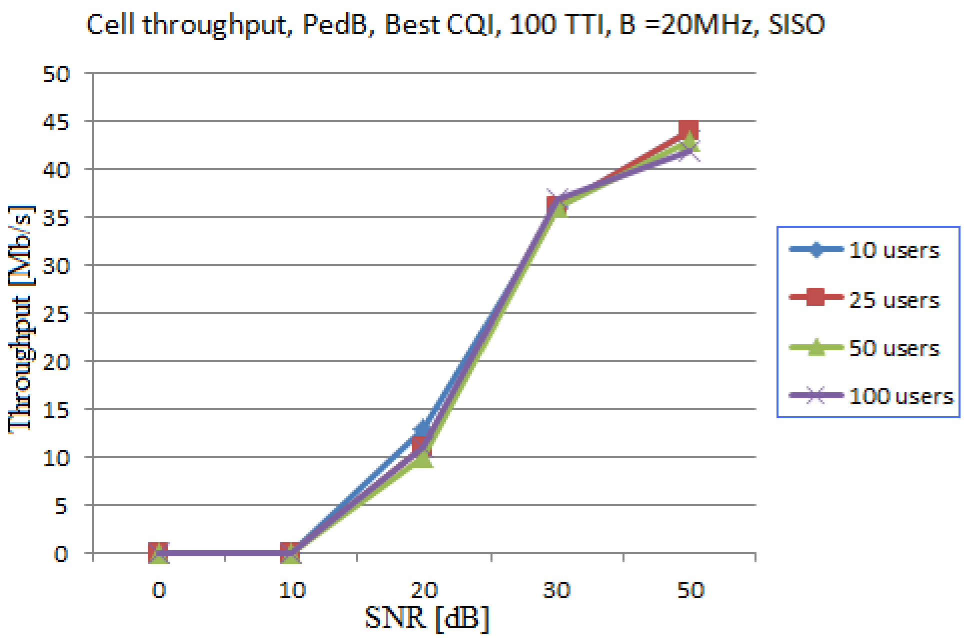

Figure 5.16 *SNR versus Throughput for multiple users.*

Figure 5.16 shows the SNR versus the throughput for a SISO system. The throughput is almost 0 for the SNR between 0 dB and 10 dB. This situation can be explained because the reported channel conditions are very bad for every user; this situation could result in a very low throughput (almost zero). From 10 dB, it can be seen that the throughput rapidly increases with the SNR. It is likely to find a user with a higher CQI on a given RB. That is why throughputs for different set of users are almost the same to each other in the plot. The maximum cell throughput in this scenario is 45 Mb/s.

<u>Case 2:</u> Best CQI, Pedestrian B, Multiple users and MIMO

This scenario simulates for multiple users the signal-to-noise ratio power values versus throughput. The throughput for a MIMO (2x2) system is shown. The scheduling algorithm is Best CQI which assigns a resource block to the user terminal that maximizes the CQI. The simulation time is set to 100 TTI. Again the bandwidth is 20 MHz and the channel type used is the Pedestrian B.

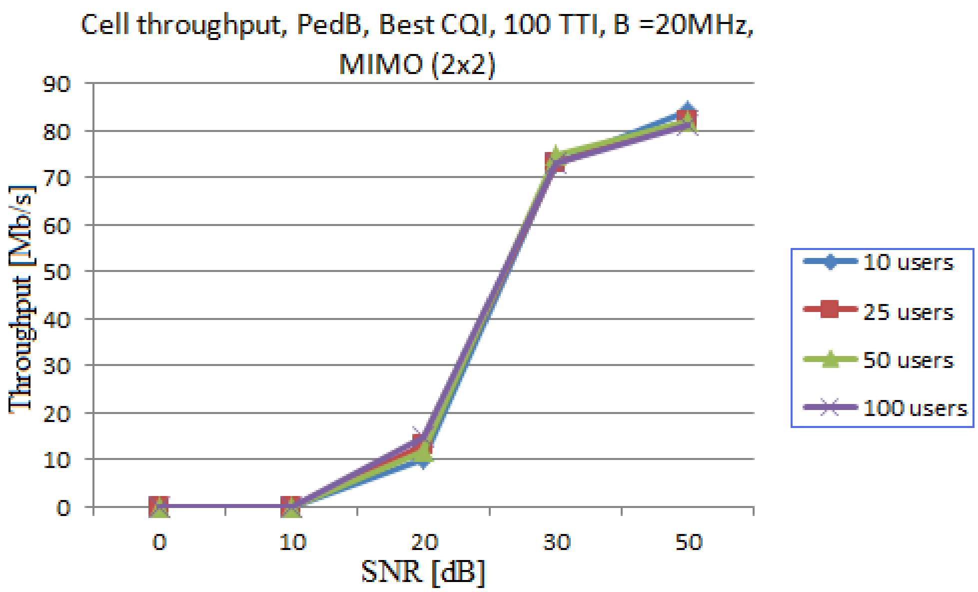

Figure 5.17 SNR *versus Throughput form multiple users.*

Figure 5.17 depicts the SNR versus the throughput for a MIMO system. The scheduling algorithm is Best CQI. As in the previous case the throughput is almost 0 for the SNR between 0 dB and 10 dB. This situation can be explained because the reported channel conditions are very bad for every user; this situation could result in a low throughput (almost zero). From 10 dB, it can be seen that the cell throughput increases with the SNR. The maximum cell throughput in this scenario is 84 Mb/s. That is 2 times higher than in the previous case (SISO system).

Scenario 4

<u>Case1:</u> Round Robin, SISO, Pedestrian B and Multiple users

This scenario simulates for multiple users the SNRs versus throughput. The throughput for a SISO system is shown. The scheduling algorithm is Round Robin (RR) and the CQI is set to 7. The RR scheduling does not adapt the AMC mode according to the CQI-feedback. It always simulates with the cqi value set in the file *LTE_sim_batch.m* as cqi_i. Thus we have set the cqi_i to 7 in the LTE simulator. The simulation time is set to 100 TTI, the bandwidth is 20 MHz, and the channel type used is the Pedestrian B.

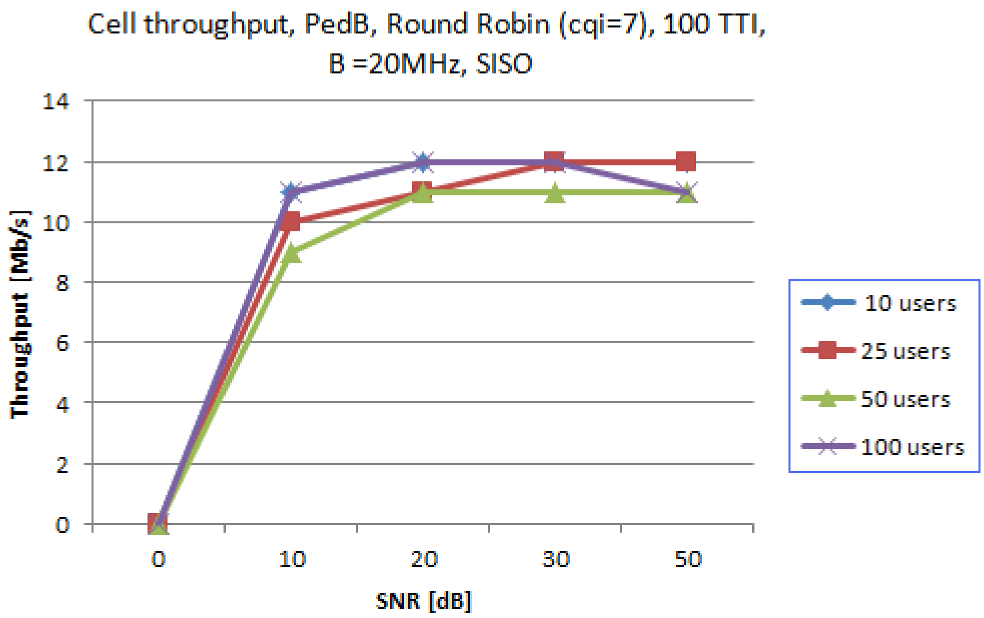

Figure 5.18 *SNR versus Throughput for multiple users.*

Figure 5.18 shows the SNR versus the throughput for a SISO system. From the plot, it can be seen that the cell throughput for different number of users (10 users, 25 users, 50 users and 100 users) is almost the same. From the Table 2.1 we know that there are 100 RBs in a bandwidth of 20 MHz. For the case of 10 users each user can be scheduled 10 times. When we have 20 users, each user can be scheduled 5 times. For 50 users, each user can be scheduled 2 times and if we have 100 users, each user can be scheduled one times. That is why the cell throughput for the different set of users is almost the same. The maximum cell throughput is 12 Mb/s.

<u>Case 2:</u> New scheduling algorithm, Pedestrian B, SISO and Multiple users

Multiple users are simulated and the SNR values versus throughput for different sets of users are plotted. Furthermore only a SISO system is considered. The scheduling algorithm is the proposed new scheduling algorithm. The simulation time is set to 100 TTI, the bandwidth is 20 MHz, and the channel type used is the Pedestrian B.

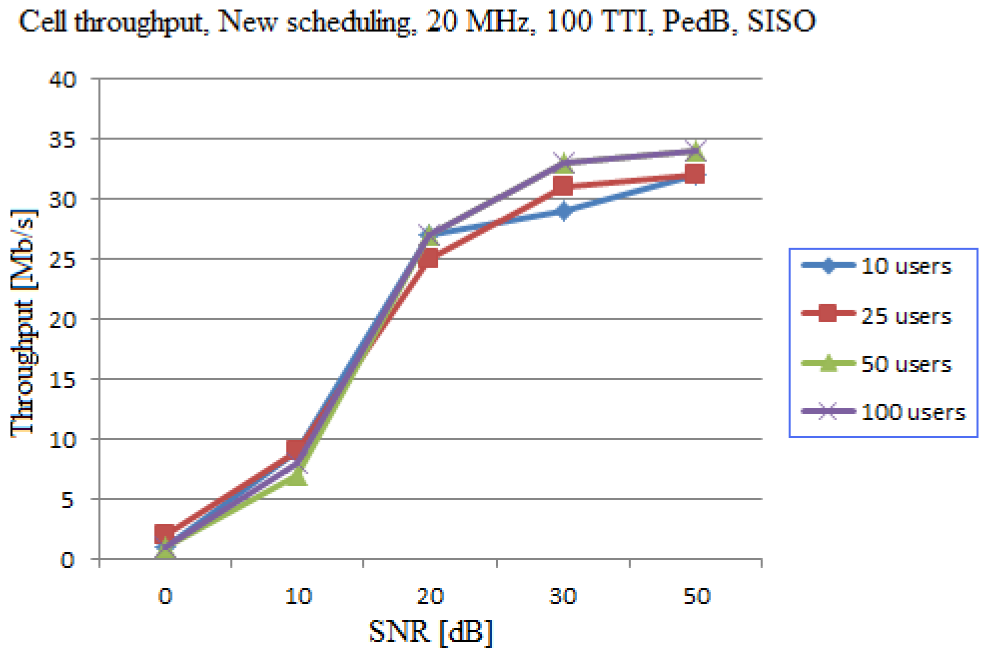

Figure 5.19 *SNR versus Throughput for multiple users.*

The graph in Figure 5.19 depicts the SNR versus the throughput for a SISO system. From the graph, it can be seen that the cell throughput for different sets of users (10 users, 25 users, 50 users and 100 users) increases with the SNR. The maximum cell throughput is 35 Mb/s. It is clear that the throughput in this case is higher than the throughput in the previous case where the scheduling algorithm is Round Robin.

Scenario 5

Case 1: Round Robin, MIMO (2x2), Pedestrian B and Multiple users

Again multiple users are simulated and we consider only a MIMO (2x2) system. The scheduling algorithm is Round Robin and the CQI is set to 7. Again the Round Robin scheduling does not adapt the AMC mode according to the CQI-feedback. It always simulates with the cqi value set in the file *LTE_sim_batch.m* as cqi_i. Thus we have set the cqi_i to 7 in the LTE simulator. The simulation time is set to 100 TTI, the bandwidth is 20 MHz, and the channel model used is the Pedestrian B.

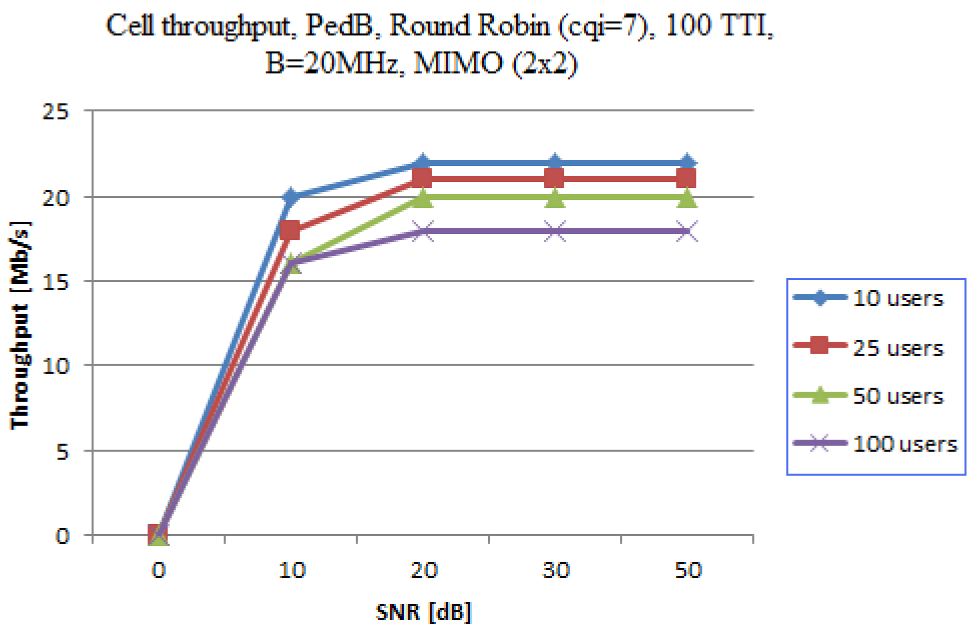

Figure 5.20 *SNR versus Throughput for multiple users.*

Figure 5.20 depicts the SNR versus the throughput for a MIMO (2x2) system. It is clear that the cell throughput for different set of users (10 users, 25 users, 50 users and 100 users) is almost the same. From the Table 2.1 we know that there is 100 RBs in 20 MHz bandwidth. For the case of 10 users each user can be scheduled 10 times. When we have 20 users, each user can be scheduled 5 times in a Round Robin way. For 50 users, each user can be scheduled 2 times in turns and if we have 100 users, each user can be scheduled one time. That is why the cell throughput for the different set of users is almost the same.

Case 2: Pedestrian B, MIMO 2x2 and new scheduling algorithm

Here Again multiple users are simulated and the SNR values versus throughput for different set of users is plotted. Here only a MIMO (2x2) system is considered. The scheduling algorithm is the proposed new scheduling algorithm. The simulation time is set to 100 TTI, the bandwidth is 20 MHz, and the channel model used is the Pedestrian B.

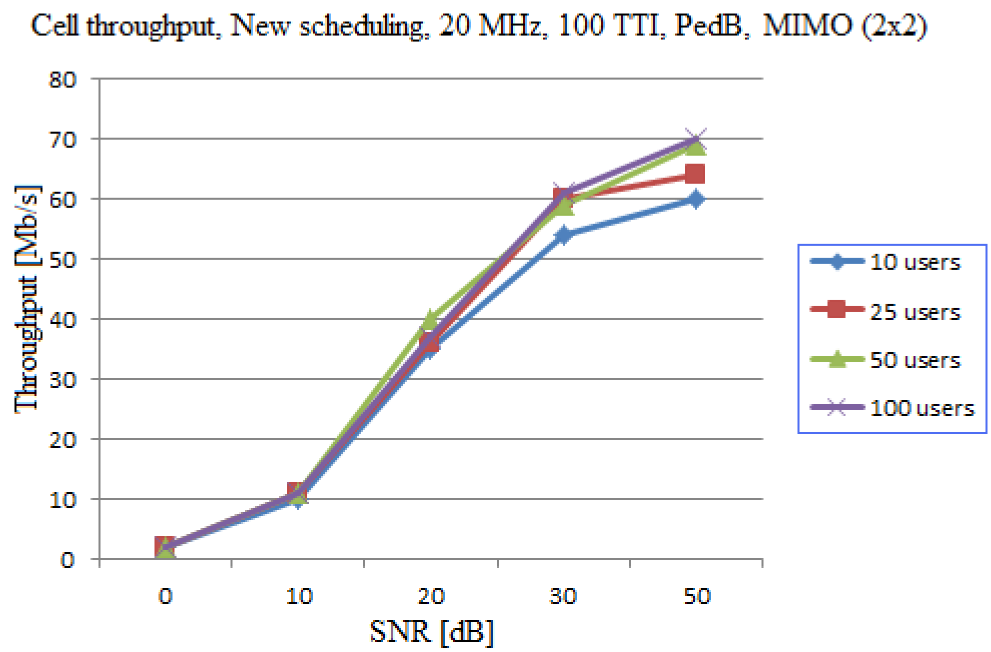

Figure 5.21 *SNR versus Throughput for multiple users.*

Figure 5.21 shows the SNR versus the throughput for a MIMO (2x2) system. We can see that the cell throughput for different sets of users (10 users, 25 users, 50 users and 100 users) increases with the SNR. The maximum cell throughput is 70 Mb/s.

Scenario 6

<u>Case 1:</u> Vehicular A, Best CQI, SISO and multiple users

Here multiple users are simulated and the SNR versus throughput for different set of users are plotted. Here only a SISO system is considered. The scheduling algorithm is Best CQI. The simulation length is set to 100 TTI, the bandwidth is 20 MHz, and the channel model used is the Vehicular A.

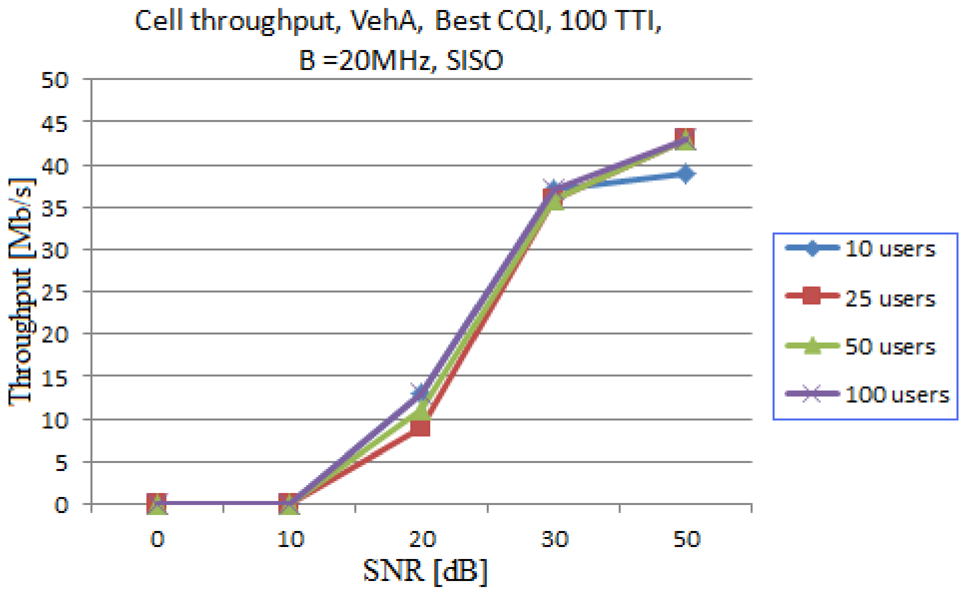

Figure 5.22 *SNR versus Throughput for multiple users*

Figure 5.22 depicts the SNR versus the throughput for a SISO system. The scheduling algorithm is Best CQI. Again we observe that the throughput increases with the SNR and we can reach a maximum cell throughput of almost 45 Mb/s.

<u>Case 2:</u> Vehicular A, Best CQI and MIMO (2x2)

In this scenario multiple users are simulated and the SNR values versus throughput for different set of users are plotted. We consider here only a MIMO (2x2) system. The scheduling algorithm is Best CQI. The simulation length is set to 100 TTI, the bandwidth is 20 MHz, and the channel model used is the Vehicular A.

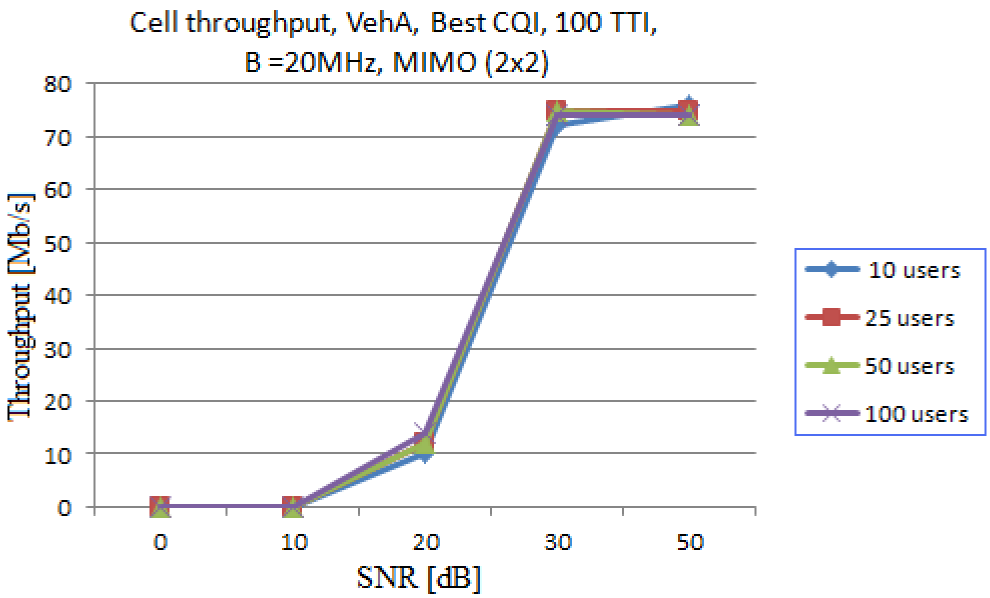

Figure 5.23 *SNR versus Throughput for multiple users.*

This graph depicts the SNR versus the throughput for a MIMO system. The scheduling algorithm is Best CQI. It can be seen that the throughput increases with the SNR and we can reach a maximum cell throughput of almost 75 Mb/s. The throughput is two times higher than in the throughput in the previous case.

Scenario 7

Case 1: Vehicular A, Round Robin, SISO and Multiple users

This scenario simulates for multiple users the SNRs versus throughput. The throughput for a SISO system is considered. The scheduling algorithm is Round Robin and the CQI is set to 7. The simulation time is set to 100 TTI, the bandwidth is 20 MHz, and the channel model used is the Vehicular A.

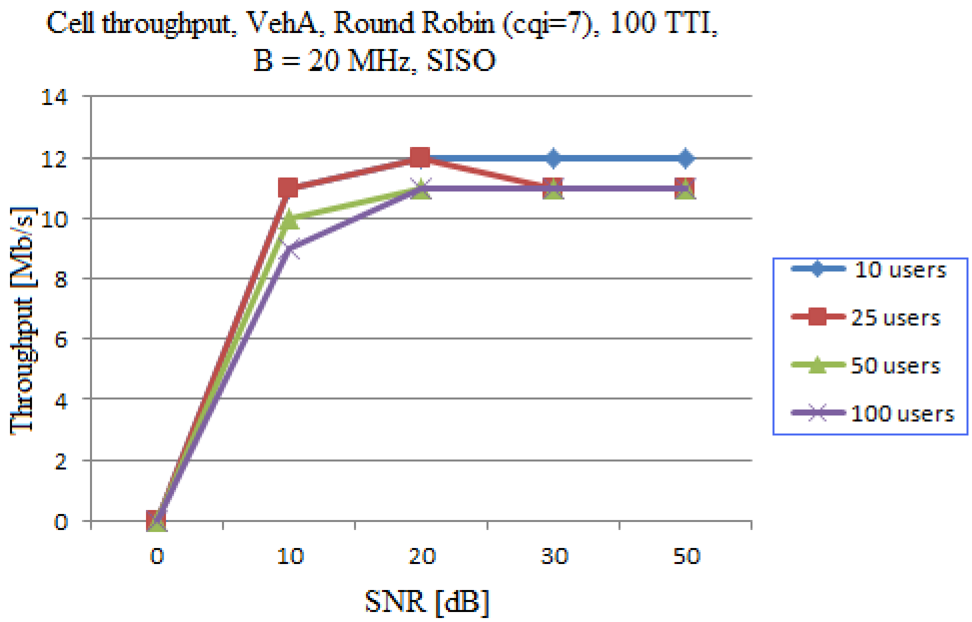

Figure 5.24 *SNR versus Throughput for multiple users.*

Figure 5.24 depicts the SNR versus the throughput for a MIMO (2x2) system. The scheduling algorithm is Round Robin. The CQI is set to 7. We can observe that the throughput for different set of users (10 users, 25 users, 50 users and 100 users) is almost the same. With 100 RBs in a bandwidth of 100 MHz when we have 10 users, each user can be scheduled 10 times in turns. For 20 users, each user can be scheduled 5 times in turns. For 50 users, each user can be scheduled 2 times. For 100 users, each user can be scheduled one time. The maximum cell throughput is 12 Mb/s.

<u>Case 2:</u> Vehicular A, Round Robin (CQI=7), MIMO (2x2) and Multiple users

Again multiple users are simulated. The throughput for a MIMO (2x2) system is considered. The scheduling algorithm is Round Robin and the CQI is set to 7. Furthermore we assume perfect channel condition. The simulation time is set to 100 TTI, the bandwidth is 20 MHz, and the channel model used is the Vehicular A.

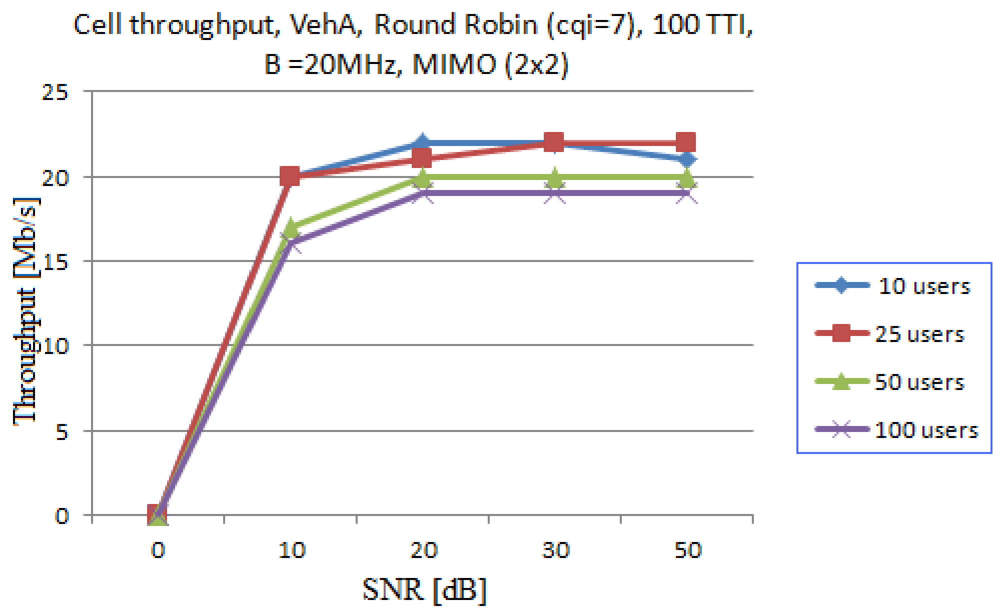

Figure 5.25 *SNR versus Throughput for multiple users.*

Figure 5.25 shows the SNR versus the throughput for a MIMO (2x2) system. The scheduling algorithm is Round Robin and the CQI is set to 7. Again the Round Robin scheduling in the LTE simulator always simulates with the cqi value set in the file *LTE_sim_batch.m* as cqi_i. Thus we have set the cqi_i to 7. It is obvious that the cell throughput for different set of users (10 users, 25 users, 50 users and 100 users) is almost the same. The maximum cell throughput is 22 Mb/s that is two times higher than in the previous case.

Scenario 8

<u>Case 1:</u> Vehicular A, New Scheduling algorithm, SISO and Multiple users

Here multiple users are simulated. The throughput for a SISO system is considered. The scheduling algorithm is the proposed new scheduling. The simulation time is set to 100 TTI, the bandwidth is 20 MHz, and the channel model used is the Vehicular A.

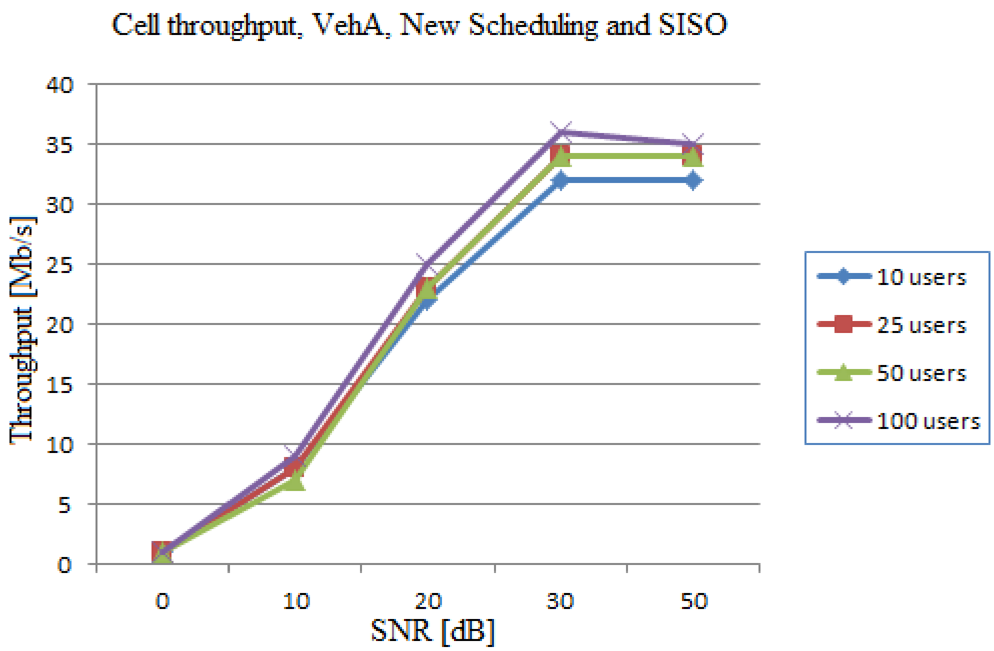

Figure 5.26 *SNR versus Throughput for multiple users.*

Figure 5.26 shows the SNR versus the throughput for a SISO system. The maximum cell throughput is 36 Mb/s.

<u>Case 2:</u> Vehicular A, New Scheduling, MIMO (2x2) and multiple users

Multiple users are simulated. The throughput for a MIMO (2x2) system is considered. The scheduling algorithm is the proposed new scheduling algorithm. The simulation time is set to 100 TTI, the bandwidth is 20 MHz, and the channel model used is the Vehicular A.

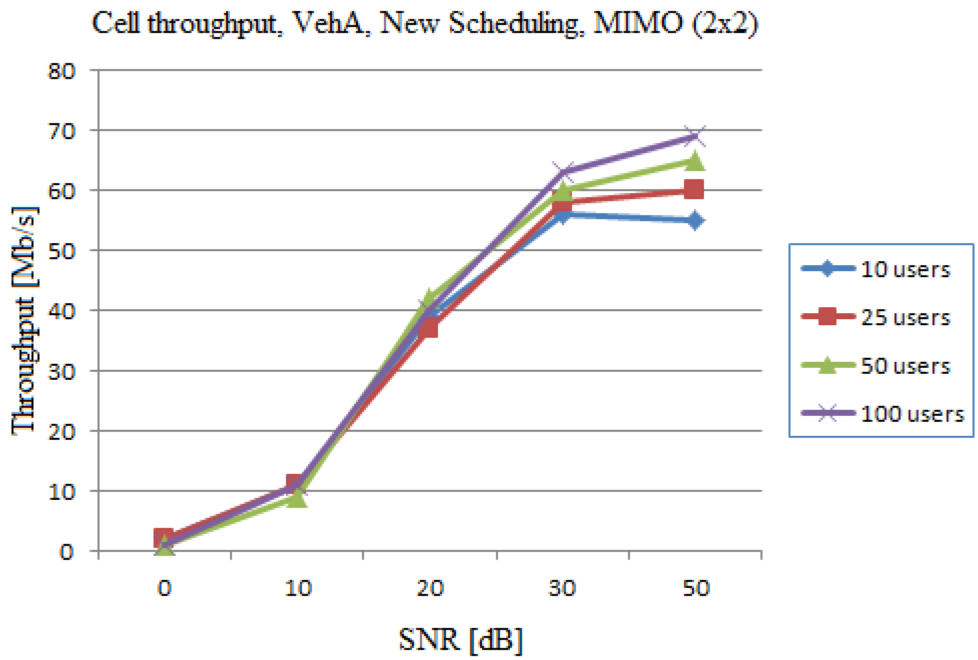

Figure 5.27 *SNR versus Throughput for multiple users.*

Figure 5.27 shows the SNR versus the throughput for a MIMO (2x2) system. The throughput increases with the SNRs. The maximum cell throughput is 70 Mb/s almost 2 times higher than in the SISO case.

Case 3: (Pedestrian B, SISO, MIMO (2x2), Best CQI, New scheduling algorithm
and Round Robin scheduling

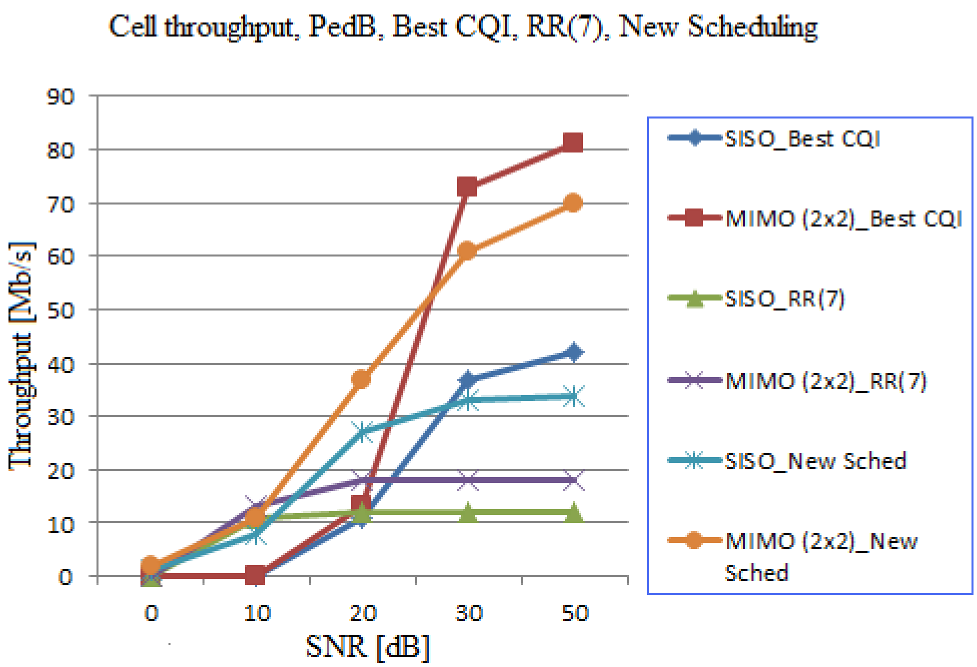

Figure 5.28 *SNR versus Throughput for multiple users.*

Figure 5.28 displays the throughputs for different scheduling schemes. Furthermore SISO and MIMO systems are considered. The total number of users is in the cell is fixed to 100. Here the channel type is Pedestrian B. The TTI is fixed to 100. We compare the cell throughput for the different scheduling algorithms namely: Best CQI, the proposed new scheduling and Round Robin. We can observe that the cell throughput of the Best CQI scheduling is the highest in this example. The throughput of the proposed new scheduling algorithm is higher than the throughput of Round Robin. Furthermore it is clear that MIMO systems increase the throughput.

6 Conclusions and future work

6.1 Conclusion

In this thesis an overview of the Long term Evolution of the UMTS is presented. LTE intends to support high peak data rates (100 Mb/s in the downlink and 50 Mb/s in the uplink), to improve the system capacity and coverage. It also efficiently supports packet data transmission, etc. OFDM has been adopted as the downlink transmission scheme of LTE. LTE is the future of Mobile broadband. It is expected that in 2014, 80% of broadband users will be mobile broadband subscribers and they will be served by HSPA and LTE networks

I have done research on the LTE downlink scheduling algorithms. The scheduler is a very important element of the base station. It assigns the resource blocks to different users. I have worked on two scheduling algorithms: Best CQI and Round Robin scheduling. As the name implies, the Best CQI scheduling assigns the resource blocks to the user with the higher CQI. In Round Robin scheduling the terminals are assigned the resource blocks in turn (one after another). I have investigated the impact of the scheduling schemes on the throughput and on the fairness. The Best CQI scheduling maximizes the throughput by scheduling the user with the good channel quality and the Round Robin scheduling is fair since it equally schedules the terminals.

We have proposed a new scheduling algorithm that assigns the resource blocks to the user with the highest CQI in the first slot period of each sub-frame whereas in the second slot period the scheduler assigns the resource blocks in turn to each user. The new scheduling algorithm can be seen as compromise between the throughput and the fairness. The novel scheduling scheme has been implemented and tested to check whether it reaches its goal.

These scheduling algorithms have been implemented in a MATLAB-based Link Level Simulator of the Vienna University. A comparative analysis between the scheduling algorithms based on their throughputs for different scenarios (different scheduling methods, different antennas transmission system, different channel models and different number of users) was carried out. We can see that the throughput of the Best CQI scheduling is the highest. The new scheduling algorithm has a better throughput performance than the Round Robin scheduling. Furthermore the new scheduling algorithm is fairer than the Best CQI.

I have computed the theoretical channel capacity for a SISO and MIMO systems. Multi-antenna techniques have been used to improve the throughput. Thus we have used MIMO (2x2) and MIMO (4x4). The theoretical channel capacity and the throughput results obtained from the simulator have been plotted. It is obvious that the throughput increases when MIMO is used.

Two ITU-channel types have been used: The Pedestrian B and the Vehicular A channel.
I have examined the impact of the channel delay on the throughput. The Vehicular channel has a higher delay than the Pedestrian channel. We observe that when Round Robin scheduling is used the throughput is almost the same for both channel types. That is what I had expected since Round Robin doesn't take the channel condition in account. But we can see that in general the throughput is different when Best CQI scheduling or the new scheduling algorithm are used.

6.2 Future work

More research still can be done in the LTE downlink scheduling because it is a very interesting field. The first step in finding a trade-off between throughput and fairness is the proposed new scheduling algorithm. Future work can be done in the order to optimize the throughput in the proposed new scheduling algorithm.

Depending on the goal of the scheduling algorithm we want to design, we may choose to improve the throughput, the fairness or both of them. If we want to favor the throughput we can improve the Best CQI scheduling and the new scheduling algorithm. But if we favor the fairness we can improve the new scheduling algorithm or Round Robin scheduling. MIMO is one of the technologies to increase the throughput. More advanced and complex techniques can be also designed with the same goal. One of these techniques consists of placing a relay between the base station and the mobile station.

Abbreviations

Acronym	Description
3GPP	Third Generation Partnership Project
AMC	Adaptive Modulation and Coding
ARQ	Automatic Repeat request/query
AWGN	Additive White Gaussian Noise
BCQ	Best CQI
BER	Bit Error Rate
BLER	Block Error Rate
BS	Base Station
CP	Cyclic Prefix
CQI	Channel Quality Indication
CSI	Channel State Information
DL	Downlink
FDD	Frequency-Division Duplex
FEC	Forward Error Correction
GP	Guard Period
HARQ	Hybrid ARQ
HSPA	High Speed Packet Access
ICI	Inter Carrier Interference
IFFT	Inverse Fast Fourier Transform
ISI	Inter-Symbol Interference
ITU	International Telecommunication Union
LA	Link Adaptation
LOS	Line-Of-Sight
LTE	Long-Term Evolution
MAC	Medium Access Control
MIMO	Multiple Input Multiple Output
OFDM	Orthogonal Frequency Division Multiplexing
PMI	Precoding Matrix Index
QAM	Quadrature Amplitude Modulation
RAN	Radio Access Network
RB	Resource Block
RE	Resource Element
RLC	Radio Link Control
RR	Round Robin
RRM	Radio Resource Management
SINR	Signal to Interference and Noise Ratio
SISO	Single Input Single Output
SNR	Signal-to- Noise Ratio Power
TB	Transport Bock
TD	Transmit Diversity

TDD	Time Division Duplex
TTI	Transmission Time Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
UpPTS	Uplink part
UTRA	Universal Terrestrial Radio Access
UTRAN	Universal Terrestrial Radio Access Network

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