THE REPUBLIC OF TURKEY
BAHÇEŞEHİR UNIVERSITY

PERFORMANCE EVALUATION OF THE LTE DOWNLINK SCHEDULING ALGORITHMS

M.S. Thesis

COŞKUN DENİZ

ISTANBUL, 2015

THE REPUBLIC OF TURKEY
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ABSTRACT

PERFORMANCE EVALUATION OF THE LTE DOWNLINK SCHEDULING ALGORITHMS

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Computer Engineering

Thesis Supervisor: Asst. Prof. Vehbi Çağrı Güngör

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Long Term Evolution is the latest wireless broadband technology which enables the mobile users to achieve high throughputs with low latency. LTE employs OFDM technology which provides resources in both for frequency and time domain. The radio resource allocation is performed by using a scheduling algorithm for downlink and uplink by the base station. At the present, there are many scheduling algorithms with different objectives.

In this thesis, we propose a LTE Downlink scheduling algorithm and investigate the performance of the new algorithm with other scheduling algorithms in terms of throughput and fairness metrics. We employ different simulation setups to observe the changes in the performance metrics under different network scenarios. The simulation results indicate that the proposed scheduler increases the edge throughput and fairness while limiting degradation in the system throughput between 0 to 2 percent with respect to the other schedulers.

Keywords: LTE, Scheduling, Resource Allocation, Radio Resource Management

ÖZET

LTE KULLANICI YÖNLÜ ZAMAN ÇIZELGELEME ALGORITMALARININ PERFORMANS DEĞERLENDIRMESI

Coşkun Deniz

Bilgisayar Mühendisliği

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LTE kullanıcılara yüksek veri hızları ve düşük gecikme sağlayan kablosuz geniş bant teknolojisidir. LTE hem frekans hem de zaman alanında kaynak sağlayan OFDM teknolojisini kullanır. Radyo kaynağı atama işlemi aşağı ve yukarı yön için zaman çizelgeleme algoritmaları kullanılarak baz istasyonu tarafından gerçekleştirilir. Hâlihazırda farklı amaçları olan pek çok zaman çizelgeleme algoritması bulunmaktadır.

Bu tezde, yeni bir zaman çizelgeleme algoritması öneriyoruz ve önerdiğimiz algoritmayla beraber diğer zaman çizelgeleme algoritmalarının veri kapasitesi ve adillik ölçütlerine göre performans değerlendirmesini yapıyoruz. Farklı simülasyon ayarları kullanılarak farklı ağ senaryoları altındaki performans ölçütlerindeki değişimi gözlemliyoruz. Simülasyon sonuçları, önerilen zaman çizelgeleyicinin uç veri kapasitesini ve adilliği arttırdığını, bununla beraber sistem kapasitesindeki azalmanın diğer zaman çizelgeleyicilere göre yüzde 0 ve 2 arasında kalmasını sağladığını gösteriyor.

Anahtar Kelimeler: LTE, Zaman Çizelgelemesi, Kaynak Atama, Radyo Kaynak Yönetimi

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ABBREVIATIONS

3GPP	:	Third Generation Partnership Project
AMC	:	Adaptive Modulation and Coding
ARQ	:	Automatic Repeat Request
AWGN	:	Additive White Gaussian Noise
BER	:	Bit Error Rate
BLER	:	Block Error Ratio
CDMA	:	Code Division Multiple Access
CLSM	:	Closed-Loop Spatial Multiplexing
CN	:	Core Network
CP	:	Cyclic Prefix
CQI	:	Channel Quality Indicator
CSI	:	Channel-State Information
EPC	:	Evolved Packet Core
E-UTRAN	:	Evolved Universal Terrestrial Access Network
EV-DO	:	Evolution-Data Optimized
FDD	:	Frequency Division Duplexing
FEC	:	Forward Error Correction
FFT	:	Fast Fouirer Transform
FSTD	:	Frequency Switched Transmit Diversity
GPRS	:	General Packet Radio Service
GSM	:	Groupe Spécial Mobile
HARQ	:	Hybrid Automatic Repeat Request
HSPA	:	High Speed Packet Access
IDFT	:	Inverse Discrete Fourier Transform
ISI	:	Inter-Symbol Interference
ITU	:	International Telecommunication Union
LMMSE	:	Linear Minimum Mean Square Error
LTE	:	Long Term Evolution
MAC	:	Media Access Control

MBSFN	:	Multicast-Broadcast Single-Frequency Network
MCS	:	Modulation and Coding Scheme
MIMO	:	Multiple Input Multiple Output
MME	:	Mobility Management Entity
MMSE	:	Minimum Mean Square Error
OFDM	:	Orthogonal Frequency-Division Multiplexing
OFDMA	:	Orthogonal Frequency-Division Multiple Access
OLSM	:	Open-Loop Spatial Multiplexing
PAPR	:	Peak-to-Average-Power-Ration
PCCC	:	Parallel Concatenated Convolutional Code
PDCP	:	Packet Data Convergence Protocol
PDN	:	Packet Data Network
PF	:	Proportional Fair
PGW	:	Packet Gateway
PHY	:	Physical Layer
PMI	:	Precoding Matrix Indicator
QPP	:	Quadrature Permutation Polynomial
RAN	:	Radio Access Network
RB	:	Resource Block
RE	:	Resource Element
RI	:	Rank Indicator
RLC	:	Radio Link Control
RR	:	Round Robin
RRC	:	Radio Resource Control
RRM	:	Radio Resource Management
SC-FDMA	:	Single-Carrier Frequency-Division Multiple Access
SFBC	:	Space-Frequency Block coding
SGW	:	Serving Gateway
SINR	:	Signal-to-Interference-plus-Noise Ratio
SM	:	Spatial Multiplexing
TB	:	Transport Block

TDD	:	Time Division Duplexing
TTI	:	Transmission Time Interval
TxD	:	Transmit Diversity
UE	:	User Equipment
UTRAN	:	Universal Terrestrial Access Network
WCDMA	:	Wideband Code Division Multiple Access
WIMAX	:	Worldwide Interoperability for Microwave Access

1. INTRODUCTION

In this chapter, an overview of the thesis background will be provided and the motivation and the scope of the thesis will be given.

1.1 BACKGROUND

In the past years, mobile broadband technology has been introduced to the world. Mobile broadband technology has brought new features to mobile networks and it enabled the mobile users with rich multimedia experiences. With new multimedia services, mobile broadband traffic has increased 10 fold since 2011 and it is expected that it will increase 10 fold until 2019 (Cisco, 2015). A global standards-developing organization Third-Generation Partnership Project (3GPP) has started to work on new access technology to meet the mobile traffic demand. 3GPP has standardized the new network technology in Release 8 in December 2008 and they have developed it with the new releases since then.

The new mobile technology is classified as fourth generation mobile technology and it is specifically named as LTE-Long Term Evolution. It has a flat architecture according to the previous mobile networks. LTE consists of two networks; Evolved-Universal Terrestrial Radio Access Network (E-UTRAN) and Evolved Packet Core (EPC). Unlike the third generation (3G) mobile technologies which mostly use Code Division Multiple Access (CDMA), E-UTRAN is the new air interface system between eNodeB and user equipments. Orthogonal Frequency-Division Multiple Access (OFDMA) and Single-Carrier Frequency Division Multiple Access (SC-FDMA) are used for downlink and uplink respectively in E-UTRAN architecture. High data rates and low latency targets can be achieved by using OFDMA and SC-FDMA. These multiple access schemes are based on Orthogonal Frequency-Division Multiplexing (OFDM).

OFDM provides radio resource in both frequency domain and time domain. A radio frame consists of 10 subframes and each subframe is 1 ms long. OFDM consists of multiple subcarriers, each having same bandwidth, 15 KHz, in the frequency domain. A

Resource Block (RB) is a resource unit in both frequency and time domain. RB is essential transmission unit which consists of 12 subcarriers in half subframe duration (0.5 ms). Radio resources are allocated to users in each Transmission Time Interval (TTI) which is 1ms length. Resource allocation is specifically called as scheduling and scheduler is responsible for this process at the MAC layer. A scheduler can assign resources in both frequency and time domains. 3GPP did not put any standard for the scheduling process therefore scheduling algorithms are not a part of the specifications. The manufacturers and the mobile operators implement different scheduling algorithms to increase the system efficiency. Implementation of the appropriate algorithms is a very important task and it has great impact on the overall performance of the system.

1.2 GOAL OF THESIS

The goal of this thesis is to investigate the throughput and fairness performance of the proposed scheduler with the essential schedulers such as Proportional Fair, Round Robin, MaxMin and Best CQI. The proposed scheduling algorithm takes edge throughput metric consideration at first place. The purpose of the new scheduler is to increase the edge throughput without sacrificing the system throughput. Since the edge users mostly have poor channel condition and low spectral efficiency, giving additional resources to the edge users to increase their data rates causes dramatic decreases in the system throughput. To achieve higher edge throughputs without giving additional resources to the edge users, the proposed scheduler gives the priority to use the RB with high spectral efficiency while trying to avoid the use of the RB with low spectral efficiency. Average and particular spectral efficiency values are used to give priority to the specific time-frequency time slots for the specific users.

To be able to evaluate the performance of the scheduling algorithms, we simulate the LTE environment under several scenarios with different parameters such as antenna configuration, antenna type, network topology, mobility, carrier frequency, channel model and the number of UEs. Vienna LTE System Level Simulator [2] has been employed to simulate the LTE environment.

1.3 RELATED WORK

There are many studies in literature related to LTE scheduling algorithms. They propose and investigate existing scheduling algorithms in terms of various parameters. The priorities and objectives vary for designing a scheduling algorithm. System throughput, fairness, QoS, power efficiency and delay constraints are the main objectives of the scheduling algorithms. However, these objectives are generally conflicts with each other; there is mostly a trade-off among them. Therefore, it is difficult to obtain better performance in an objective without having performance degradation in others. In the researches, it is often focused on improving one performance metric while keeping the other metrics as much as constants. Some of the related scheduling algorithms proposed in the researches are given below. For convenience, the symbols used throughout the paper are listed in Table 1.1.

Table 1.1: A list of symbols used in this paper

Description	Symbol
Number of Resource Block	N_{RB}
Number of user	N_{UE}
Resource Block per user	RB_N
User index	U
User	m
Subcarrier	n
Unscheduled users	UE
CQI feedback	CQI
Instantaneous data rate	R, r
Average data rate	T
Window size	t_c
Spectral efficiency	$C_{n,m}$
Average spectral efficiency	C_{mean}
Pseudo-CQI feedback	$PCQI$

One of the mostly investigated scheduling algorithms is the Proportional Fair scheduling algorithm. It was introduced for code-division-multiple-access high-data-rates systems which was supporting only time-domain scheduling for CDMA systems. Kim and Han (Kim & Han 2005) extended PF algorithm from time-domain to multicarrier transmission systems. Their modification enabled PF to support scheduling in frequency domain. Based on their work, Sun et al. (Sun et al. 2006) proposed an optimal PF algorithm for systems using OFDMA and proposed a PF algorithm wıth low complexity. Their results show that the proposed algorithm reduced the computational complexity while showing similar performance to the optimal PF scheduling algorithm. The algorithm is introduced in the next chapter. Kwan et al. (Kwan et al. 2009) introduced a PF scheduler and a Max-Rate scheduler which tries to keep the system throughput as high as possible. They compared the schedulers in terms of average user throughput and found that PF performance showed uniformity in average throughput with minor bit rate degradation relative to the Max-Rate scheduler.

Since the LTE imposed the same modulation and coding scheme for the all resources of a user in a single TTI, Schwarz et al. (Schwarz et al. 2010) derived a linearization model for multi-user scheduling based on Channel Quality Indicator (CQI) feedback. Their purpose was to find the mean CQI index for all radio resources of users with a simple linearized method. Besides that, they proposed a scheduler called Approximate Maximum Throughput (AMT) algorithm and compared it to PF, Best CQI, MaxMin and Kwan Max Rate scheduler. MaxMin scheduler achieves the highest fairness with maximizing the minimum throughput of the users. The proposed scheduler shows better performances when the number of users is small and similar performance when the number of users is large.

Schwarz et al. (Schwarz et al. 2011) also proposed an scheduler which can be adjusted to obtain specific fairness performance in this study. Adjustable fairness enables the network to achieve a desired fairness goal. They used a method which is based on sum utility maximization of the α-fair utility functions. To achieve the specific fairness target, an appropriate α value should be found, which is obtained from the observed CQI probability mass function.

AlQahtani and Alhassany (Alqahtani & Alhassany 2013) proposed a new scheduling algorithm and compared it with Best CQI and Round Robin (RR). The algorithm is shown Table 1.2.

Table 1.2: The scheduling algorithm of Alqahtani & Alhassany

Algorithm 1: (Alqahtani & Alhassany 2013)	
1.	**Input:** Number of RB, N_{RB}, number of users N_{UE}
2.	**Compute:** RB per UE, RB_N
3.	**if** $CEIL(RB_N) = FLOOR\ (RB_N)$
4.	assign the same number of RB, RB_N to each user
5.	**else** assign the same number of RB, RB_N, to each user and distribute extra RB (RBS) to the users randomly
6.	**Compute:** user index, U = rand(N_{UE})
7.	**for each** U
8.	**select** RB or RBS with maximum CQI
9.	**assign** RB or RBS to the user U
10.	**Output:** RB allocation matrix, $RBxUE$

Table 1.3: The scheduling algorithm of Gavrilovska & Talevski

Algorithm 2: (Gavrilovska & Talevski 2011)	
1.	**Input:** Unscheduler users in previous TTI, UE_m, CQI feedbacks of the UEs, $CQI_{n,m}$, where n is subcarrier and m is the user id.
2.	**Compute:** argmax**(**$CQI_{n,m}$), find n, m index
3.	**for each** m
4.	**assign** RB_n to user m and extract it from UE_m
5.	if $UE_m = 0$
6.	**break**
7.	**end**
8.	**if** there is unassigned RB_n
9.	UE_m equals to all users
10.	**go to** Step 2
11.	**Output:** RB allocation matrix, $RBxUE$

The scheduler behaves as RR until the all users obtain the same number of RB. After that, it behaves like Best CQI algorithm, the residue of the RB is assigned to the user with the highest CQI. Throughput performance achieved by the new scheduler is between RR – Best CQI. Fairness metric is declined almost 20 percent relative to RR. PF algorithm is not in the scope of this work, thus fairness comparison with PF is not available. Gavrilovska and Talevski presented a new Best CQI scheduler to overcome the fairness problem in the existing Best CQI scheduler (Gavrilovska & Talevski 2011). The results show that system throughput was improved with new scheduler and there was no user with throughput degradation. Their algorithm is shown in Table 1.3

Escheikh et al. (Escheikh et al. 2014) proposed a new scheduling algorithm to increase system throughput. They aimed to enable a fair trade off between fairness and throughput. The new scheduler was compared with existing scheduler i.e. RR, Best CQI and MY SCH Not Fair. They observed significant improvements in system throughput. Fairness performance was not presented in the work.

Bechir et al. (Bechir et al. 2014) introduced a new scheduling algorithm and compared it with RR, PF and Best CQI algorithms. The new scheduler was more complex than PF and it performed better than PF in terms of system throughput. While the system throughput was increasing, fairness metric was decreasing up to 20 percent comparing with RR and PF. The algorithm is given in below.

Table 1.4: The scheduling algorithm of Bechir et al.

Algorithm 3: Bechir et al.	
1.	**Input:** CQI in terms of required data rate $R_m(n)$
2.	**for each** n
3.	**Compute:** $R_m(n)$ and $T_m(n)$
4.	**find** (m^*, n^*) =arg$max(R_m(n)/T_m(n))$
5.	Schedule user m on n subcarrier. User m will not have permission to be scheduled until $N_{RB}\ x\ N_{UE}$
6.	**Output:** RB allocation matrix, $RBxUE$

Finally, S. Assaf (Assaf 2014) investigated the prioritization capabilities in LTE networks and the proposed an algorithm that lead to have priority access for some users following their QoS Class Identifier (QCI). He modified the Proportional Fair scheduler and implemented prioritization capabilities to it.

1.4 OUTLINE OF THESIS

The rest of this thesis is organized as follows:

The new features that 3GPP introduced with LTE will be explained in Chapter 2. The physical entities and the protocol stacks of the LTE network will be covered in this section in addition.

In Chapter 3, a deep look will be taken at the physical layer of the LTE downlink. Essential concepts such as OFDM, Channel Coding and Rate Matching, Link adaptation and MIMO will be explained. The frame and resource structures of the transmission scheme will also be given in detail.

In Chapter 4, the principles of the scheduling mechanism will be given and the importance of the scheduling mechanism will be emphasized. Besides that, the well-known scheduling algorithms will be explained such as Round Robin, Proportional Fair, Best CQI and MaxMin. In addition, the proposed scheduling algorithm will be described.

In Chapter 5, the detailed information will be given about the simulation environment. Transmitter, Receiver, Channel Model and other specifications will be explained and capabilities of the simulator will be shown.

In Chapter 6, the results of the different scheduling algorithms under different simulation scenarios will be given. And finally, the results of the simulations will be evaluated in the Chapter 7.

2. LONG TERM EVOLUTION

In 2008, 3GPP has introduced Long Term Evolution (LTE) in Release 8. The main purpose of LTE is to enhance the radio access network to support new services. Some of the motivations for the evolvement are listed below (Tara, 2011):

i. Demand for higher throughputs and quality of service
ii. Cost saving
iii. To be sure the continuity of competitiveness of the 3G system for the future
iv. Optimization for Packet Switch network
v. Simplicity in network
vi. not to perform technology fragmentation for TDD and FDD band operation

2.1 FEATURES OF LTE

OFDM is the one of the important features of LTE. To achieve high level strength against frequency selective fading channels and multipath interference, OFDM is employed in the air interface. Channel-aware radio resource allocation and MIMO are the other benefits of OFDM. High Peak-to-Average-Power-Ratio (PAPR) is the main disadvantage of OFDM. High PAPR has negative effect on the power efficiency. Therefore, SC-FDMA is employed in uplink transmission to obtain low PAPR. Orthogonality in the frequency domain and MIMO are also available with SC-FDMA.

LTE provides flexible bandwidths starting from 1.4 MHz up to 20 Mhz. TDD and FDD are available for all the bandwidths. Bandwidth scaling can be done automatically with respect to users roaming across different serving cells. LTE has capability providing high throughputs. For 20 MHz bandwidth, LTE supports 100Mbps downlink and 50Mbps uplink for single-input single-output antenna configuration. Spectrum efficiencies are 5 bps/Hz for downlink and 2.5 bps/Hz for uplink. It can support 300 Mbps and 150 Mbps for downlink and uplink respectively by operating 4x4 MIMO.

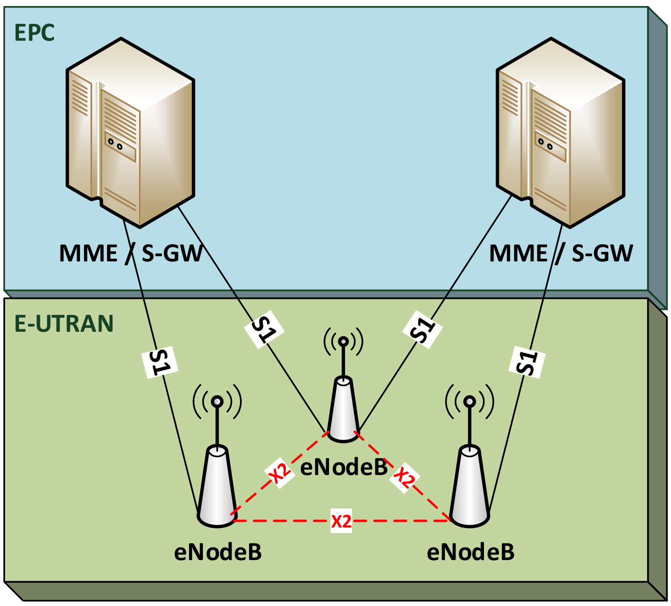
LTE supports Adaptive Modulation and Coding (AMC). AMC is a strong mechanism which is used to maximize throughput in poor channel conditions. Modulation and coding scheme change with respect to the channel condition. Highest modulation is selected at first and then it is downgraded when channel quality decreases and upgraded when channel quality increases.

In terms of mobility, E-UTRAN is optimized for speeds less than 15 km/h. High performances can be achieved up to 120 km/h and link can be maintained for speeds up to 350 km/h. By depending on the frequency band, link can be maintained up to 500 km/h.

Latency is less than 50-100 ms for control plane and 10 ms for user plane. One-way latency is 5 ms and Round Trip Times (RTT) is 10 ms.

2.2 LTE ARCHITECTURE

Figure 2.1: LTE Network Architecture



Source: **3GPP**

Network architecture of LTE consists of Core Network (CN) and a Radio Access Network (RAN). Figure 2.1 shows the overall architecture of the LTE network.

2.2.1 Core Network

The main responsibility of the Core Network is to control UEs and establishment of bearers. Core network consists of following logical entities: Serving Gateway (S-GW), Mobility Management Entity (MME), Packet Data Network Gateway (P-GW) (Shahrear, 2013).

S-GW is the point of interconnect between access network and EPC. S-GW deals with user plane, delivers user data packets and it behaves as a mobility anchor point for the mobile terminals that move among eNodeBs and for other 3GPP accesses such as GSM/GPRS and HSPA. S-GW keeps information of the bearers when the user is at IDLE mode. There is a logical interface between S-GW and the PDN Gateway logically (Alcatel-Lucent, 2013).

P-GW works as an interface between EPC and the external packet networks. P-GW routes packets from and to the PDNs. UE IP address allocation is done by P-GW. It is responsible for QoS enforcement on transport level, charging support, packet filtering and packet screening. PDN GW also behaves as mobility anchor point for non-3GPP access technologies such as EV-DO, WiMAX and CDMA2000 (Firmin, 2011).

Mobility Management Entity (MME) controls the signaling processes between UE and EPC. Its responsibilities include UE tracking in idle mode, paging process, connection and release of bearers between EPC and UE. It also handles the most of the security operations (Zumerle, 2011).

2.2.2 Radio Access Network

Radio access network of LTE is specifically named Evolved Universal Terrestrial Radio Access Network (E-UTRAN). It consists of single type of element, eNodeB. S1-MME is the interface between eNodeB and MME and S1-U the interface between eNodeB and S-GW. eNodeBs are connected to each other by interface X2. Its main purpose is enhancing the handover procedure between eNodeBs. It also takes role in Radio Resource Management (RRM) scenarios such as Inter-cell Interference Coordination (ICIC).

Functional responsibilities of E-UTRAN can be summarized in four functions: radio resource management, header compression, encryption and decryption of the data packets, data exchange with the EPC.

Radio Resource Management (RRM) is a set of functions, i.e. Scheduling, Link Adaptation (power control and AMC), handover, Inter-Cell Interference Coordination. RRM mainly controls assigning and sharing the radio resources to meet QoS requirements of the services. RRM is responsible to use the system resource as much as efficient while meeting QoS requirements.

IP header Compression is a mechanism which is the function of compressing the recurrent part of the IP packet headers at the transmitter node and recovering them at the receiver node. Header compression helps to improve the efficiency of radio resource usages especially for the small-packet sized applications such as Voice over IP, messaging and gaming services

Security in E-UTRAN ensures that the transmitted data over the air is encrypted in the transmitter side and decrypted at the receiver side as well. Data exchange with EPC is handled by using the S1-MME and S1-U interfaces. Connectivity covers the signaling among eNodeB, MME and S-GW.

2.2.3 Protocol Architecture

Radio protocols consist of two types of protocols; User Plane, Control Plane. The user plane protocol stack is shown in Figure 2.2. The entire information transmitter and received by UE is transported through the user plane.

Figure 2.2: User Plane Protocol Stack

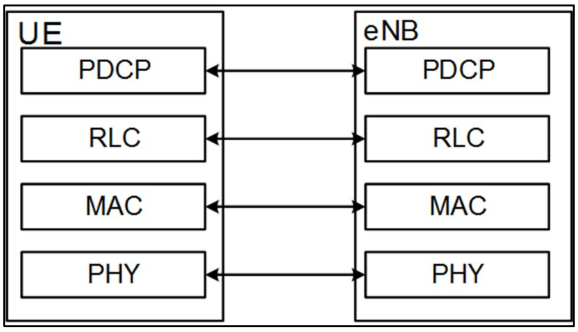
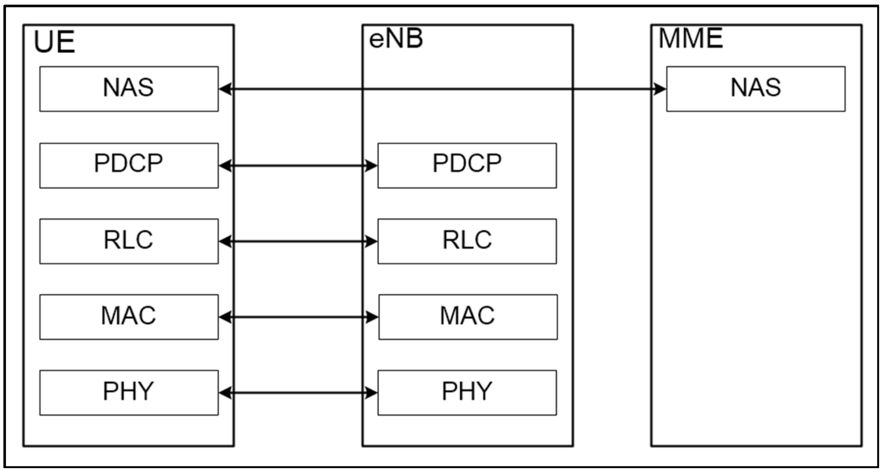


Figure 2.3 Control Plane Protocol Stack



PDCP, RLC, MAC and PHY are layers responsible for header compression, ciphering, scheduling and ARQ/HARQ operations.

Connections among the UEs, network and radio bearers are managed by control plane. Figure 2.3 shows control plane protocol stack of E-UTRAN. Functionalities of the layers are listed below.

RRC layer, at the C-plane level, is responsible for the control of the radio resources over the air interface. RRC layer in eNodeB and the UE send and receive signaling message to establishing and managing the connection between them. Managements of Connections, Radio bearers, mobility and signaling are done at the RRC layer.

i. Connection Management: Establishment, modification and release functions of the connections between UE and eNodeB are handling by RRC layer. UE and eNodeB have to make RRC connection to exchange signaling messages; otherwise UE cannot operate in the network.
ii. Radio Bearer Management: Establishment, configuration and release of the radio bearers which are the used to transport user data between eNodeB and UE are managed at RRC layer. RRC layer also manages a radio bearer to handle the quality of service to required data that user.
iii. Mobility Management: RRC layer is responsible for mobility management which is performed according to channel quality, location and user load on a cell.
iv. Signaling Connection: To transport the signaling messaging of the higher layer, the RRC layer provides bearer services. RRC enables signaling bearer services to transport the higher layer's signaling message. Higher layer signaling covers control message exchanges between the UE's higher layer and the EPC.

PDCP layer is responsible to perform IP header compression and security function at the user and control plane. Security function is to provide ciphering and deciphering to disable non-authorized access to user plane data. For control plane data, it provides integrity verification and protection of the transmitted data. Header compression mechanism is based on Robust Header Compression (ROHC). The purpose of the header compression is to provide efficient way to use the radio resource by not sending of unnecessary bytes through the air.

RLC layer, at the U-Plane and C Plane, RLC is responsible for segmentation/concatenation, retransmission functionality for error-free transmission. The air interface is a lossy environment, Automatic Repeat reQuest (ARQ) technique is used to obtain a reliable communication. RLC also performs reordering the packets to provide in-order transmission of the data packets. There is one RLC entity for a radio bearer in the UE.

Figure 2.4: PDCP/RLC/MAC layers for Downlink

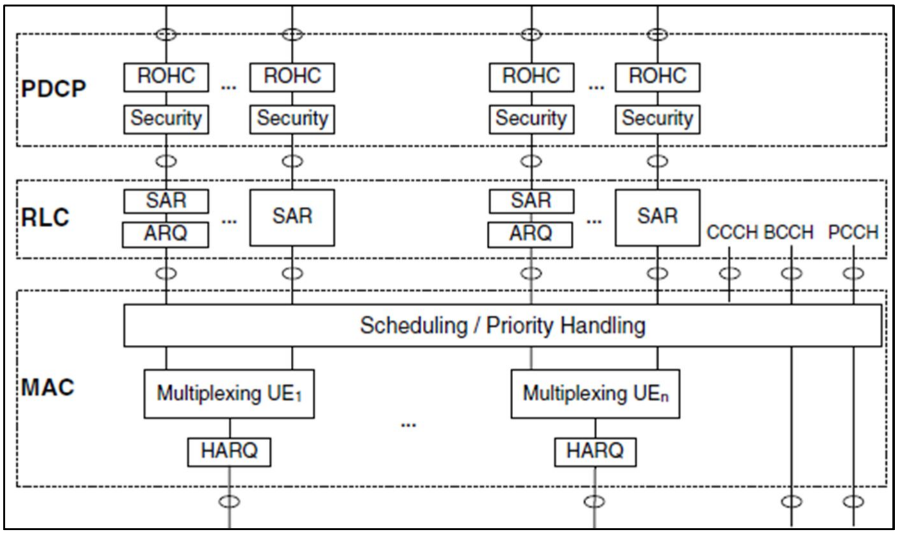
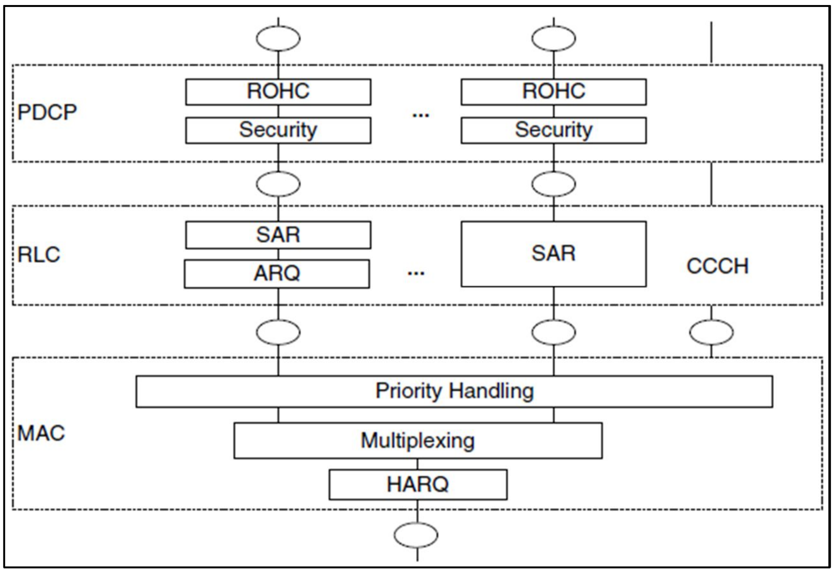


Figure 2.5 PDCP/RLC/MAC layers for Uplink



MAC layer, MAC layer performs multiplexing of logical channels, uplink and downlink scheduling operations and it provides Hybrid-ARQ. MAC performs scheduling function basically by controlling the upper layers access radio resource. MAC layer performs the resource allocation to UEs. The aim is to provide the quality of service needs for the each UE. Logical Architecture of the PDCP/RLC/MAC layers are shown in Figure 2.5 and 2.6 for downlink and uplink respectively.

3. LTE PHYSICAL LAYER FOR DOWNLINK

3.1 ORTHOGONAL FREQUENCY DIVISION MULTIPLEXING

The LTE physical layer employs OFDM which is a multi-carrier transmission scheme. Basic idea in OFDM is to obtain a wideband signal by using large number of parallel narrowband carriers. One of the main advantages of OFDM is its strength against the frequency selective fading and inter-symbol interference. In a single carrier system, the link may be failed totally; however in multi-carrier system, only some of subcarriers may be failed due to the frequency selective fading.

A basic OFDM signal is represented in below;

$$x(t) = \sum_{i=0}^{N_c-1} x_i(t) = \sum_{i=0}^{N_c-1} a_i^{(n)} e^{j2\pi k\Delta f t} \tag{3.1}$$

Where Δf is the subcarrier bandwidth, f_i is the i_{th} subcarrier frequency, $x_i(t)$ is i_{th} modulated subcarrier with frequency f_i and $a_i^{(n)}$is the symbol applied to the i_{th} subcarrier during the n_{th} OFDM symbol the during time interval $nT_u < t < (n+1)T_u$. T_u denotes the modulation-symbol time for the each subcarrier. OFDM uses block based transmission scheme, which indicates that modulated symbols, N_c, are transmitter in parallel during each symbol interval. Symbols can be modulated by using different modulation alphabet, such as QPSK, 16QAM, or 64QAM. For LTE, Δf is 15 kHz, and i depends on the system bandwidth.

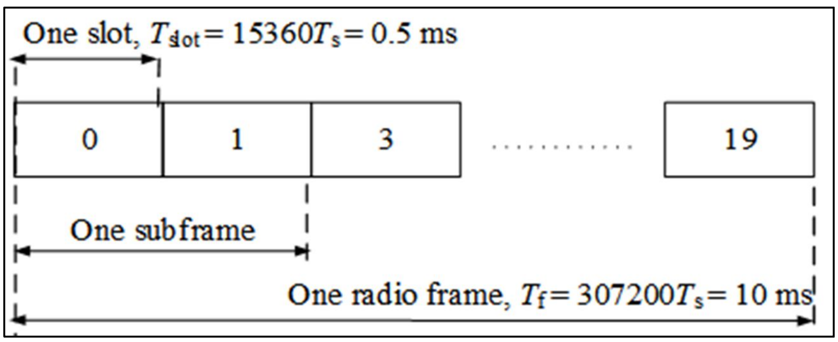
Modulation and demodulation of the OFDM signal would require implementing the large number of sinusoidal signal generators for the large number of subcarriers. This type of implementation would become highly expensive and complicated. However, the OFDM signal can be found by calculating the real part of the inverse discrete Fourier transform (IDFT) of the original complex-valued data. Fast Fourier Transform is a computationally efficient algorithm that can be implement to calculate IDFT of the signal.

The orthogonality of subcarriers can be maintained completely after demodulation process by an FFT if there is no Inter-Symbol Interference on the received signal. In wireless channel, multipath delays cause inter-symbol interference among OFDM symbols and result the distortion on orthogonality. When the delay spread is small, the effect of ISI is negligible. However in most cases, the delay spread is large to distort the orthogonality of the subcarriers and it causes losses on the original signal. To overcome multipath distortion, the symbol is extended with a guard band. This guard band is called Cyclic Prefix (CP). The duration of an OFDM symbol is defined as $T_s = T_u + T_g$, where T_g is the guard band. The guard band should be chosen as T_g is longer than multipath delay to eliminate the ISI efficiently.

3.2 FRAME STRUCTURE

Radio frames are structured in 10 ms length for downlink and uplink transmissions. There are two types of frame structures are supported in E-UTRAN: Type-1 for FDD and Type-2 for TDD.

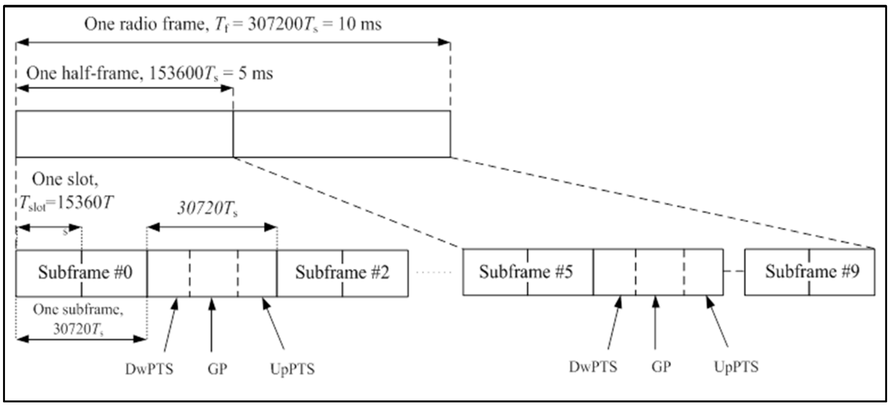
Figure 3.1: FDD Frame Structure, Type-1



Downlink and Uplink transmission both have 10 sub-frames available for FDD scheme. Downlink and uplink are allocated at different bands in the frequency domain. The UE can send and receive simultaneously for full duplex FDD while it cannot in half duplex FDD mode.

Type-2 frame structure is used for TDD. A single frame consists of two half-frames. Each half-frame consists of five subframes. Each subframe is defined as two slots, and each slot is 0.5 ms.

Figure 3.2: TDD Frame Structure, Type-2



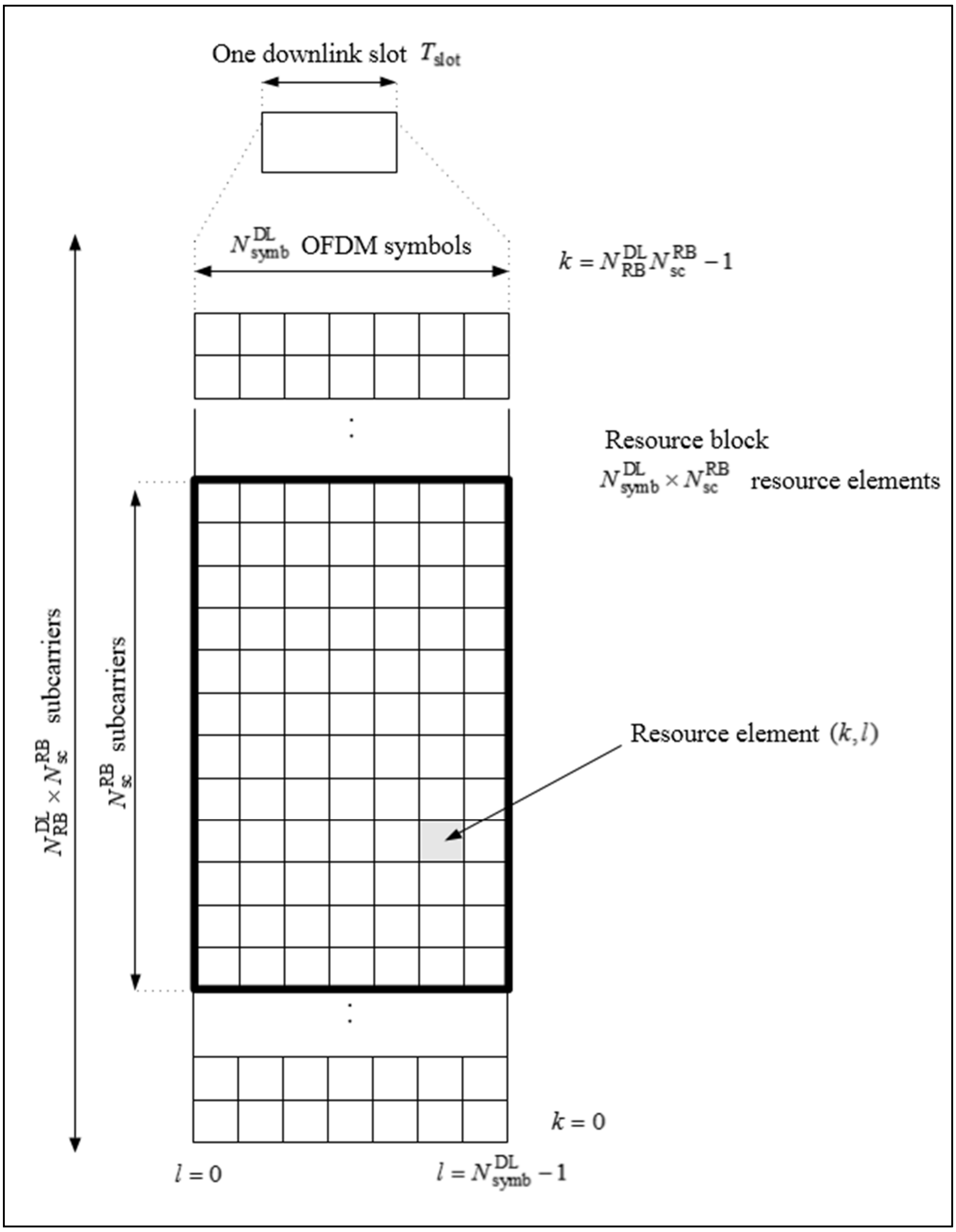
Source: 3GPP

The uplink-downlink configurations in a cell may vary among the frames and controls in which subframes uplink or downlink transmissions may take place in the current frame. The uplink-downlink configuration in the current frame is obtained according to Section 13 in (Access, 2015).

3.3 RESOURCE STRUCTURE

The resource grid shown in Figure 3.3 is the structure that represents the physical resources of the LTE. The resource grid has both frequency and time domain. The smallest time-frequency slot in the resource grid is called a Resource Element (RE). It consists of typically 12 sub-carriers with 6 or 7 OFDM symbols. The resource grid structure consists of large number of REs and the quantity of resource elements depend on the system bandwidth which has been set on the eNodeB.

Figure 3.3: LTE Physical Resource Structure



Source: 3GPP

Table 3.1: Resource Element Configuration

	Subcarrier Spacing	Number of Subcarriers	Number of Symbols
Normal CP	15 KHz	12	7
Extended CP	15 KHz	12	6
	7.5 KHz	24	3

The number of OFDM symbols in a resource element depends on the type of the cyclic prefix. There are 7 OFDM symbols in normal cyclic prefix and 6 OFDM symbols in extended cyclic prefix.

As it can be seen from the Table 3.1, subcarrier spacing can be set 15 kHz and 7.5 kHz. Subcarrier spacing is set to 7.5 kHz only for the Multicast-broadcast single-frequency network (MBSFN) transmission with extended cyclic prefix.

A physical resource block (PRB) is the smallest unit that can be allocated for a UE, and it consists of $N_{\mathrm{symb}}^{\mathrm{DL}} \times N_{\mathrm{sc}}^{\mathrm{RB}}$ resource elements. The quantity $N_{\mathrm{RB}}^{\mathrm{DL}}$ depends on the system bandwith. Maximum and minimum number of resource blocks are 110 and 6 respectively. The relation among $N_{\mathrm{RB}}^{\mathrm{DL}}$, channel bandwidth is given the Table 3.2.

Table 3.2: Channel Bandwidth vs. Number of Users

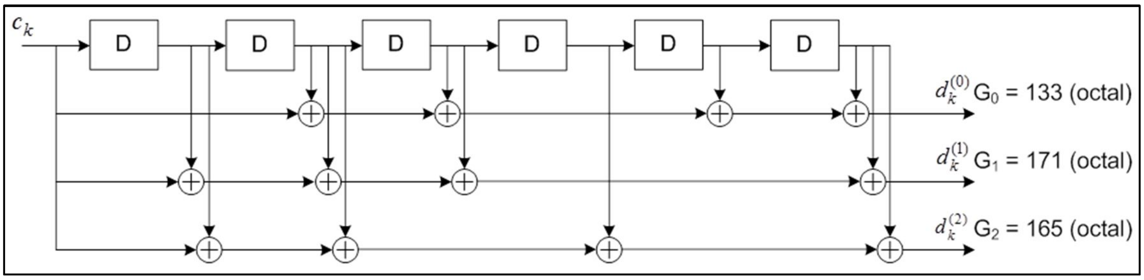
Channel Bandwidth [MHz]	Number of RBs	Effective Channel Bandwidth [MHz]
1.4	6	1.08
3	15	2.7
5	25	4.5
10	50	9
15	75	13.5
20	100	18.0

3.4 CHANNEL CODING AND RATE ADAPTATION

Channel coding provides mechanisms to recover the signal transmitted through the wireless channel. For LTE downlink, error detection and correction, rate matching and interleaving techniques are applied in the channel coding process. There are two error correction methods, FEC and ARQ in LTE. FEC is based on adding redundancy bits to data which can be done by convolution code. ARQ is based on retransmitting the packet in case error detection. Tail-biting convolution coding and Turbo coding is used for coding the channel.

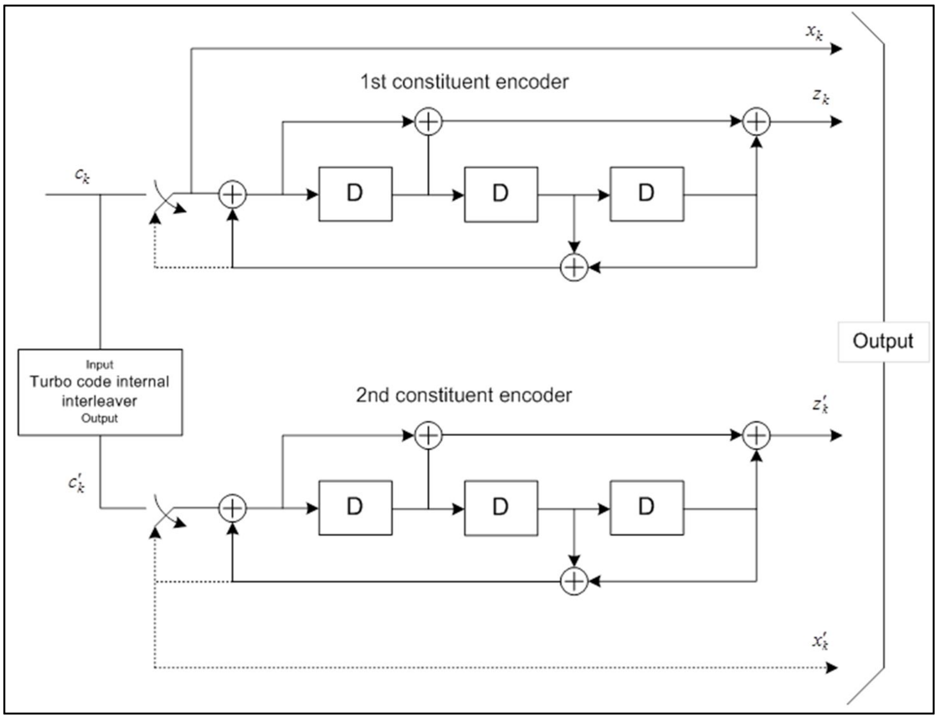
Block diagram of a tail biting convolutional code is shown in the Figure 3.5. Its constraint length is 7 and coding rate is 1/3.

Figure 3.4: The structure of turbo coding



Source: 3GPP

Figure 3.5: The structure of turbo encoder rate 1/3

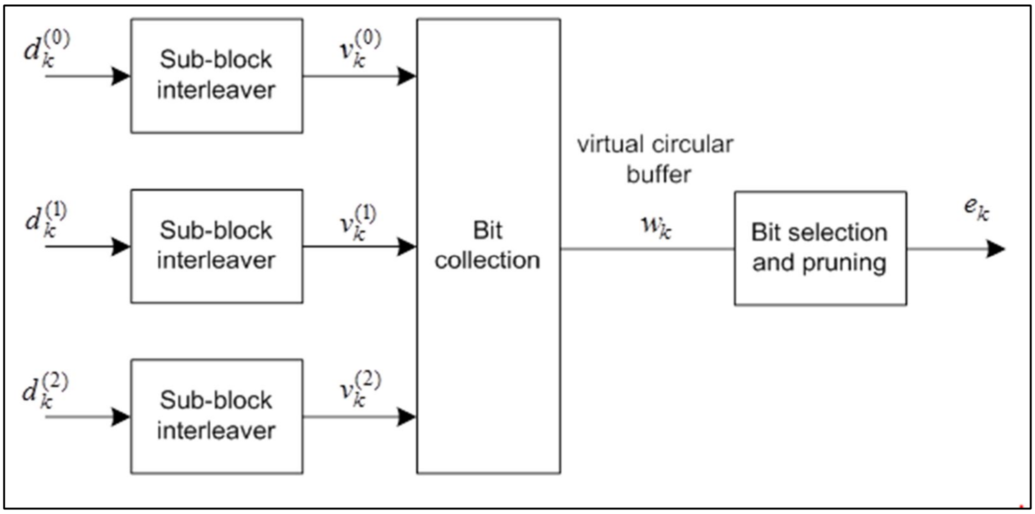


Source: 3GPP

The scheme of the turbo encoder in LTE is Parallel Concatenated Convolutional Code (PCCC) with two eight-state constituent encoders and one turbo code internal interleaver, with a coding rate of 1/3. The encoder for the turbo codes is systematic which means that all the input data passes to the output transparently and recursive which means that it has feedback mechanism. It was decided to employ a new contention-free internal interleaver based on Quadrature Permutation Polynomial (QPP) (Sun & Takeshita, 2005). The QPP interleaver requires a little memory and it provides parallelization in high level due to its maximum contention-free feature which substantially reduces the encoder-decoder complexity (Takeshita, 2006) (Ghosh, et al., 2010). Figure 3.6 depicts the structure of the encoder.

Coding rate of turbo coder is 1/3 and in order to obtain the preferred coding rate, Rate matching process is need after coding stage. Rate matching stage has following steps; interleaving, bit collection and bit selection. Interleaving is performed in order to increase the ability of error protection codes to correct for burst errors. After interleaving, there is the bit collection stage to place the systematic and parity bits in the right order for the decoder. As a final step, the bit selection stage is needed in order to repeat or puncture some of the parity bits to create the required payload.

Figure 3.6: The Structure of Rate Matching mechanism



Source: 3GPP

3.5 LINK ADAPTATION

Link adaptation mechanism is the ability of modification of the modulation and coding scheme according to the channel condition. It is based on Adaptive Modulation and

Coding (AMC) technique. AMC helps the UE and eNodeB adapting to the channel conditions by switching between the modulation schemes and coding rates. The main purpose of the AMC is to maximize the transmission capacity and cell coverage while minimizing the data error rate. AMC deals with two parameters such as; Modulation scheme and coding rate. Robustness of modulation schemes against the noise and interference decreases when the modulation order increases. Lower order modulation schemes provide high availability under the poor channel conditions. However, high order modulation schemes provide high data rates under good channel conditions. Therefore AMC chooses the most appropriate modulation scheme concerning SINR of the received signal. Similar to the modulation scheme, code rate is set lower for poor channel condition and it is set higher for good channel condition. Different coding rates are provided by applying puncturing or repetition to the original code.

Table 3.3: CQI vs Modulation

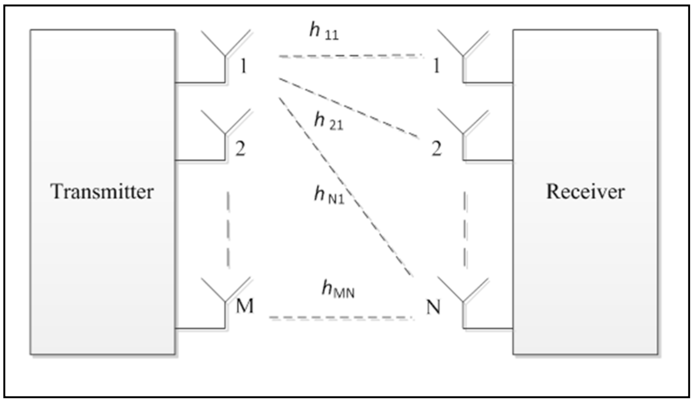
CQI	Modulation Alphabet	Code rate x 1024	Spectral efficiency
0	out of range		
1	QPSK	78	0.1523
2	QPSK	120	0.2344
3	QPSK	193	0.3770
4	QPSK	308	0.6016
5	QPSK	449	0.8770
6	QPSK	602	1.1758
7	16QAM	378	1.4766
8	16QAM	490	1.9141
9	16QAM	616	2.4063
10	64QAM	466	2.7305
11	64QAM	567	3.3223
12	64QAM	666	3.9023
13	64QAM	772	4.5234
14	64QAM	873	5.1152
15	64QAM	948	5.5547

For the downlink, the eNodeB decides the modulation scheme and coding rate with respect to the downlink channel conditions. CQI is the feedback information sent by the UE and is major input to the modulation selection mechanism. CQI is used to interpret the optimum data rate that can be achieved through the channel. In Table 3.3, a list of CQI indexes and their corresponding modulation schemes and code rates are given.

3.6 MIMO

Multiple-Input-Multiple-Output (MIMO), is a multi-antenna transmission mechanism and it is the one of the important concepts of E-UTRAN. MIMO enables the LTE air interface to reach significantly high data throughputs. LTE supports downlink transmission for one, two and four transmit antennas. Transmit Diversity (TxD) and Spatial multiplexing (SM) transmission schemes can be used in order to increase data throughput and diversity.

Figure 3.7: M x N MIMO System



Transmit diversity is specifically effective for transmission scenarios such as time-varying channel and low SNR conditions. Transmit diversity is performed by using Space-Frequency Block coding (SFBC) when two eNodeB antennas are in use. SFBC is the frequency domain version of Space-Time Block Codes (Ghosh, et al., 2010). These code types are designed to retain the orthogonality of the transmitted signals and to obtain the optimum SNR using linear receiver. When four transmit antennas are in use; Frequency Switched Transmit Diversity (FSTD) is based on SFBC. By using FSTD with SFBC, four antennas are grouped in two pairs. The modulation symbols are transmitted by pair with an alternating way between two pairs of antenna ports such as 0, 2 and 1, 3.

Spatial multiplexing has different properties from diversity scheme. If the receiving and transmitting sides have multiple antennas, multiple data streams can be set up between two sides. Increasing the number of streams also increases the data throughput. In SM, z, the transmitted vector which is the modulated data symbols, is multiplied by a precoding matrix W of size $N_a \times N_L$ where N_a is the number of antennas and N_L denotes the number of layers. Length of z is the number of layers. Output vector of the multiplication, x, is sent over the channel.

$$\begin{bmatrix} z^{(0)}(i) \\ \vdots \\ z^{(n-1)}(i) \end{bmatrix} = W(i) \begin{bmatrix} y^{(0)}(i) \\ \vdots \\ y^{(n-1)}(i) \end{bmatrix} \tag{3.1}$$

Open-loop Spatial Multiplexing, as a Spatial Multiplexing scheme, uses CDD with a fixed precoder matrix for the two and four antennas. CDD works as block-based and it applies cyclic shifts for the different antennas. CDD shifts the time-domain signal and transmits the copies of the signal over the different antennas. Precoding for spatial multiplexing is defined in below (Access, 2009).

$$\begin{bmatrix} z^{(0)}(i) \\ \vdots \\ z^{(n-1)}(i) \end{bmatrix} = W(i)D(i)U \begin{bmatrix} y^{(0)}(i) \\ \vdots \\ y^{(\upsilon-1)}(i) \end{bmatrix} \tag{3.2}$$

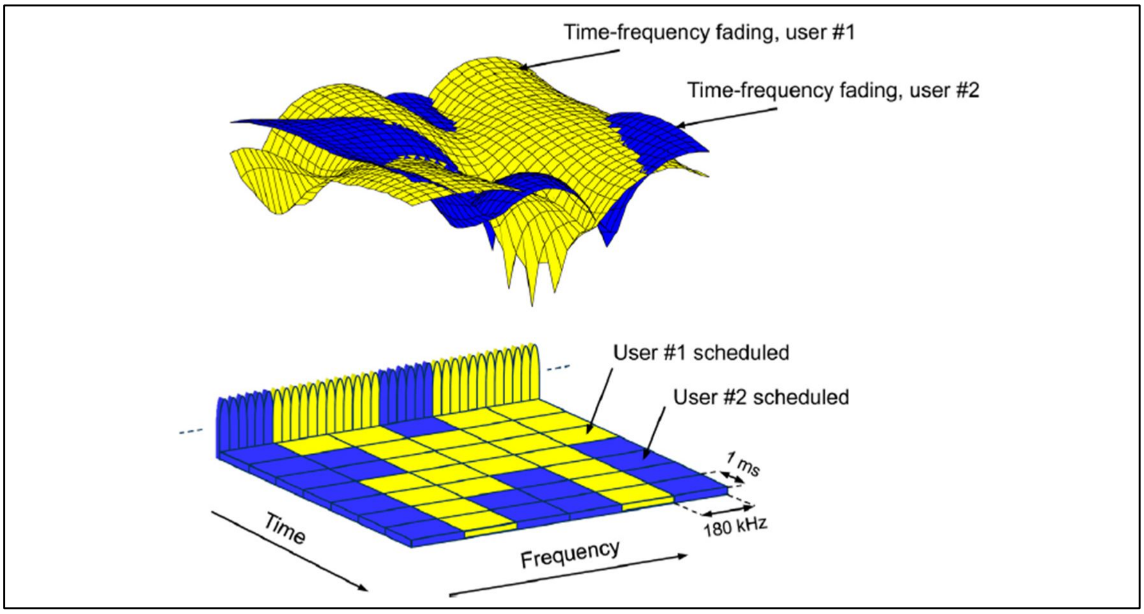
where D represents the supporting cyclic delay diversity, i is the time instant.

Close-loop Spatial Multiplexing uses not the CDD but the measurements on the reference signals. eNodeB chooses an optimum rank and precoder matrix then the information about the rank and the precoder matrix is reported back to the eNodeB from the UEs in the form of Rank Indication (RI) and Precoder-Matrix Indication (PMI). In order to simplifying the operation, a UE sends the most appropriate index from a predefined codebook to the eNodeB. The most appropriate precoder can be chosen as to achieve highest the capacity based on the receiver abilities. Under the optimum channel conditions, the UE generally indicates the precoder that results in a transmission with an effective SNR following most closely the largest singular values of its estimated channel matrix. The advantage of the closed-loop precoding can be seen in interference-free, low mobility scenarios while OLSM performs in case of high mobility better.

4. SCHEDULING

Scheduling is the one of the most important step in the Radio Resource Management in LTE. Scheduling is responsible for the user selection and resource allocation among the active users at the each time instant. OFDMA enables scheduling process to be performed in both for frequency and time domain. Scheduling is performed at every transmission time interval. For each TTI, two successive RB are assigned to a user.

Figure 4.1: Channel dependent scheduling in frequency and time domain



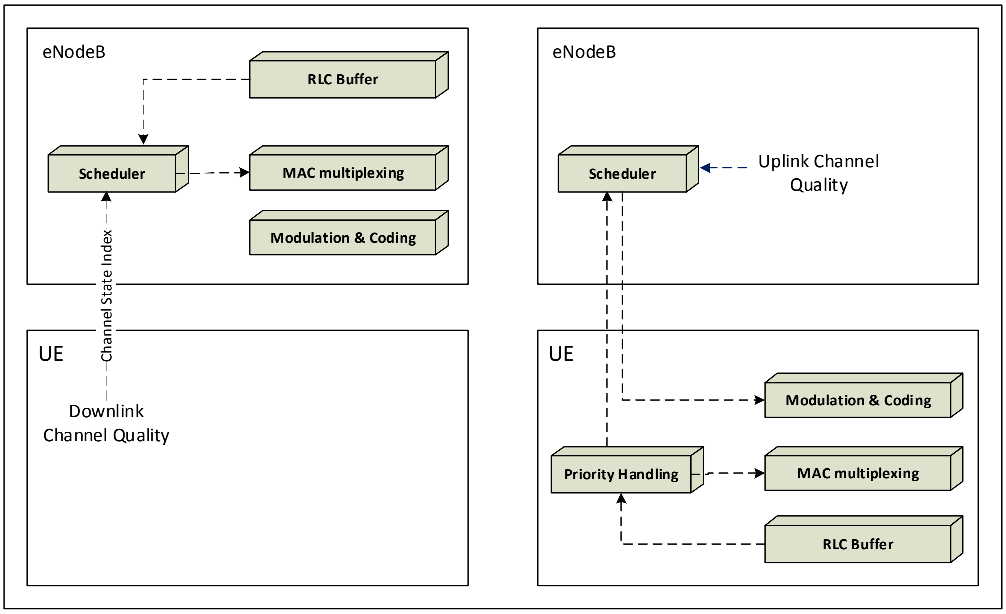
Source: (Dahlman, et al., 2010)

Scheduling function is handled by the eNodeB both for uplink and downlink transmission. The UE is responsible for providing channel-state reports that contain channel quality in the downlink. Scheduler assigns resources to the UEs with respect to the channel-states reports named as Channel-State Information (CSI). The diagram can be seen in the Figure 4.2.

The main purpose of a scheduler is to achieve the highest system throughput while satisfying the users' requirements. Scheduling algorithms are not standardized by 3GPP. The scheduling algorithm is implemented with respect to vendor or operator's choice. Since system efficiency is directly related with the scheduling strategy, it is extremely important to use appropriate strategy according to the system and users' requirements.

Basically, two different scheduling categories exist for the radio resource management. Channel independent and channel dependent scheduling. Channel independent schedulers don't take channel conditions into consideration. Channel status reports are not required in the scheme. Channel independent scheduling is inefficient for wideband wireless communication systems where frequency selective fading is the serious problem.

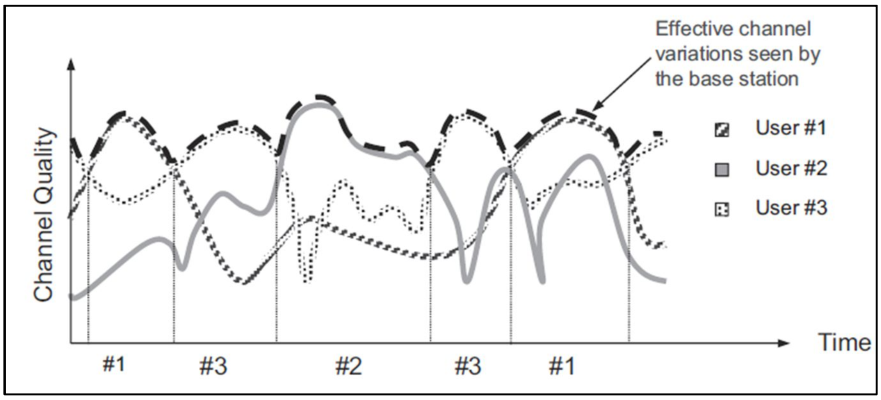
Figure 4.2: Transport Diagram for a) Downlink b) Uplink



Due to the fading channels, another type scheduling strategy, channel dependent scheduling needs to be implemented to achieve the efficient radio resource management. As mentioned in the previous section, a RB, the smallest resource assigned to the user, has 180 kHz-bandwidth and it is located at the bandwidth within a range from 1.4Mhz to 20Mhz. It is a challenging subject to find optimum RB allocation for user, since in the frequency domain, each RB will be have different fading characteristics for each user in a TTI. (Figure 4.1)

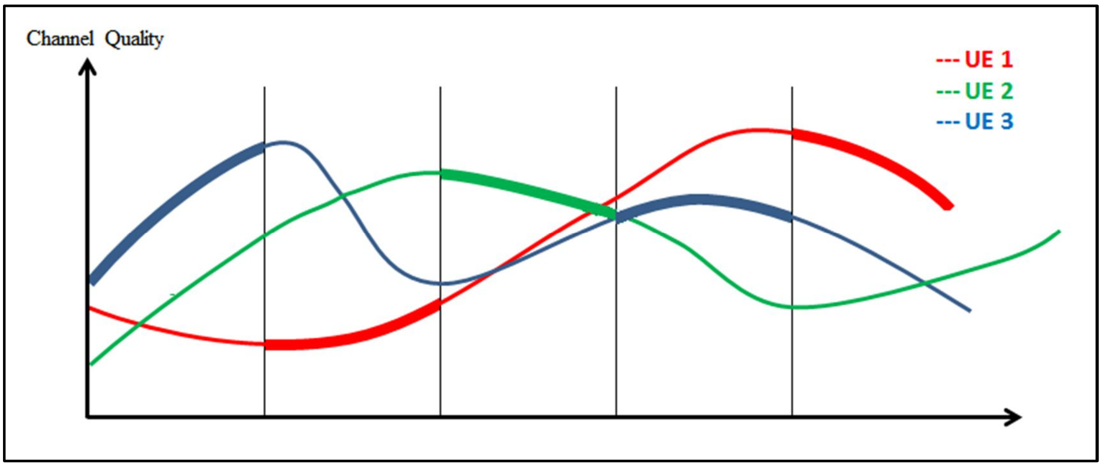
Channel dependent scheduling is performed by using the feedback from the UE which is called CQI. UE reports CQIs for each RB. The scheduler decides user selection and resource allocation with respect to the users' CQIs and other requirements such as fairness and QoS parameters. However, transport block size does not depend on each CQI separately. eNodeB applies a mapping procedure and selects a Modulation and Coding scheme (MCS) with respect to the CQIs. After MCS is selected, TB size is determined.

Figure 4.3 Effect of Channel Condition on Scheduling



4.1 ROUND ROBIN

Figure 4.4: Round Robin Scheduling



Round Robin (RR) is a channel-independent scheduling algorithm that used commonly in LTE network. In RR algorithm, shared resources are allocated to the users in turn sequentially. When all users are assigned a resource, it starts from the first user to assign resources recursively. RR algorithm does not take any other parameters into consideration therefore it is the one of the simplest scheduling algorithms.

In Figure 4.4, the resources are allocated using RR algorithm. As seen that users can be assigned on the fading channels therefore throughput can be low and high BER can be observed in the transmission. The lack of channel awareness causes low efficiency in the resource management. RR provides high fairness however there is fairness only in terms of the number of RB that is assigned to each user.

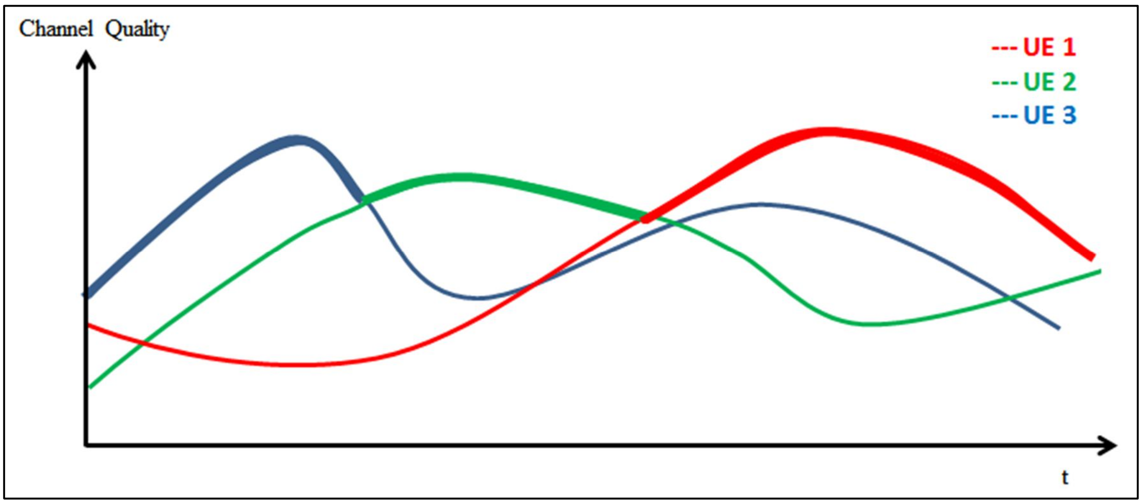
4.2 BEST CQI

Best CQI aims to choose the user with best channel condition for a particular RB in a time interval. This algorithm performs efficiently in terms of the system throughput. However, there is a lack of fairness from the point of the user throughput. Only the users with high CQIs, (or highest CQI) will be able to send/receive data in this algorithm. Mathematical expression of this algorithm is:

$$\mathrm{k} = \arg\max_i R_i \qquad (4.1)$$

where R_i is the instantaneous data rate for user i.

Figure 4.5: Best CQI Scheduling



As seen from Figure 4.5, the UE having highest channel quality is scheduled until the channel quality of the other users is greater than scheduled user. Only a couple of users can exploit all the resources in Best CQI case. The users that are close to the eNodeB will use almost all resources and edge users will be out of connection.

4.3 MAXMIN

MaxMin algorithm aims to maximize the minimum throughput of the UEs. In this algorithm, it is not possible to increase the throughput of a user without decreasing another. Maximizing the throughput brings fairness to the system. However, to maximize the minimum user throughput, scheduler assigns large amount of resources to the users with low throughput. Since these users mostly have poor channel quality and low spectral efficiency, MaxMin algorithm causes significant decrease in system throughput. To find a balance between fairness and overall system efficiency, Proportional Fair algorithm is present.

4.4 PROPORTIONAL FAİR

Proportional Fair algorithm provides high fairness by exploiting the channel variations to improve spectral efficiency. Resources are assigned according to a metric that is determined by instantaneous and average throughput of a user.

$$m^*(n) = \underset{m=1,2,\ldots,M}{argmax} \frac{R_m(n)}{T_m(n)} \tag{4.2}$$

where $R_m(n)$ is the instantaneous data rate for the m_{th} user in the n_{th} subframe. $T_m(n)$ is the mean throughput for the "m_{th}" user in a past window. In each subframe, $T_m(n)$ is updated with respect to:

$$T_m(n+1) = \begin{cases} (1 - \frac{1}{t_c} T_m(n) + \frac{1}{t_c} R_m(n) & m = m^*(\mathrm{n}) \\ (1 - \frac{1}{t_c} T_m(n) & m \neq m^*(\mathrm{n}) \end{cases} \tag{4.3}$$

where t_c is the window length. Window length can be modified to obtain fairness over a predetermined time horizon. When t_c gets smaller, the gain decreases since the scheduler has less time to wait for the peaks. Larger $\mathrm{t_c}$ makes the scheduler to wait for peak rates and to obtain gain in throughput at the expense of the latency.

Implementation of the proportional fair algorithm in the simulator is done according to the paper. In the paper, proportional fair algorithm is divided by three steps (Sun et al. 2006):

Step 1:

For each unassigned subcarrier n and each user k, compute the following formula

$$\frac{r_{k,n}}{(t_c-1)T_k+\sum_{n=1}^{N}\rho_{k,n}r_{k,n}} \tag{4.4}$$

where $r_{k,n}$ is the instantaneous data rate of user of the RB n and T_k is the average data rate of the user and $\rho_{k,n} \in \{0,1\}$ is the vector indicating whether the RB n is allocated to user k or not.

Step 2:

Choose the pair

$$(k^*,n^*) = \underset{k,n}{argmax}\left(\frac{r_{k,n}}{(t_c-1)T_k+\sum_{n=1}^{N}\rho_{k,n}r_{k,n}}\right) \tag{4.5}$$

and allocate subcarrier n^* to user k^*.

Step 3:

Repeat step 1 and step 2 until all subcarriers are assigned to users, then update T_k for each user.

4.5 PROPOSED SCHEDULING ALGORITHM

In a mobile network, the users are distributed in the field around a serving base station. The distance between the user and the base station user affects the channel quality of the user. Signal to Noise Ratio (SNR), throughput and delay are affected as well. The users that are close to the cell border have low SNR, low throughput and high BER in the transmission.

As mentioned in the previous section, the proportional fair algorithm assigns resources according to a metric which is calculated by dividing instantaneous data rate by the average data rate. The instantaneous data rate depends on the Transport Block (TB) size which is calculated by using the MCS index. The MCS index is calculated from the SNR value of the channel. The UEs cannot send the SNR values directly but they send an indicator, CQI. Therefore the MCS index is selected based on the CQI values. In wireless broadband communications every users experience the fading channels. For a TTI, a user can report CQI from 1 to 16 for each individual RB. However, only single MCS is used in a TTI for a user. In other words, the same modulation and coding scheme is applied on the all of the RBs regardless of CQI.

The purpose of the new algorithm is to increase the edge throughput without obtaining any degradation in system throughput. To achieve this goal, the scheduler gives the priority to the users to be allocated in time-frequency slots within their above-the-average spectral efficiency. By applying this methodology, the scheduler can keep the MCS index as high as possible for all users. In addition, this method gives advantage to the users who have poor channel conditions over the users with high channel quality. To keep the MCS index higher, RBs must not selected if their CQIs are lower than the average even their metrics are high. To do that, the following algorithm is applied to the users within each TTI. The PF algorithm is applied after Step 8 in the proposed algorithm.

Table 4.1: Proposed Scheduling Algorithm

Algorithm : Proposed Scheduler	
1.	**Input:** CQI feedbacks of the UEs, $CQI_{n,m}$
2.	**Compute:** Coding efficiencies, $C_{n,m}$, and Average Spectral efficiency $C_{mean,m}$ according to the CQI feedback for a TTI of the UEs
3.	**for each** user m
5.	**if** $C_{n,m}$ greater than $C_{mean,m}$
6.	$PCQI_{n,m}$ equals to $CQI_{n,m} + 1$
7.	**else**
8.	$PCQI_{n,m}$ equals to $CQI_{n,m} - 1$
9.	**for each** n
10.	**Compute:** $R_m(n)$ and $T_m(n)$, using $PCQI_{n,m}$
11.	**find** (m^*, n^*) =arg$max(R_m(n)/T_m(n))$
12.	**Output:** RB allocation matrix, $RBxUE$

In Figure 4.6, the process of obtaining the Pseudo-CQI is shown for a single user. Each cell represents a RB in frequency and time domain. The user has reported CQIs between 6 and 12. (a) In each TTI, CQIs are converted to the spectral efficiency. (b) Then, the average spectral efficiency is calculated and resources which are greater and less than the mean spectral efficiency are detected. RBs that have greater spectral efficiency than the average spectral efficiency are highlighted green. In the next step, CQI values of the highlighted RBs are incremented by one and the CQI values of the gray RBs are decremented by one. (c) After Pseudo-CQI feedback is obtained, PF algorithm is applied and PF metrics are calculated according to Pseudo-CQI table for RB. The resource assignment is completed by using the PF metrics.

Figure 4.6: Obtaining Pseudo-CQI feedback

Frequency Domain

(a)

11	7	12	11	10	10	10	11	10	6
12	9	9	12	11	6	8	11	11	9
6	12	11	10	11	7	12	7	7	12
12	12	6	6	8	6	6	9	10	8
10	7	8	11	10	6	9	9	10	10
6	12	12	12	7	11	8	10	7	7

(b)

3,322	1,477	3,902	3,322	2,731	2,731	2,731	3,322	2,731	1,176
3,902	2,406	2,406	3,902	3,322	1,176	1,914	3,322	3,322	2,406
1,176	3,902	3,322	2,731	3,322	1,477	3,902	1,477	1,477	3,902
3,902	3,902	1,176	1,176	1,914	1,176	1,176	2,406	2,731	1,914
2,731	1,477	1,914	3,322	2,731	1,176	2,406	2,406	2,731	2,731
1,176	3,902	3,902	3,902	1,477	3,322	1,914	2,731	1,477	1,477

(c)

12	6	13	12	11	11	11	12	11	5
13	8	8	13	12	5	7	12	12	10
5	13	12	9	12	6	13	6	6	13
13	13	5	5	7	5	5	8	11	7
11	6	7	12	11	5	10	8	11	11
5	13	13	13	6	12	7	11	6	6

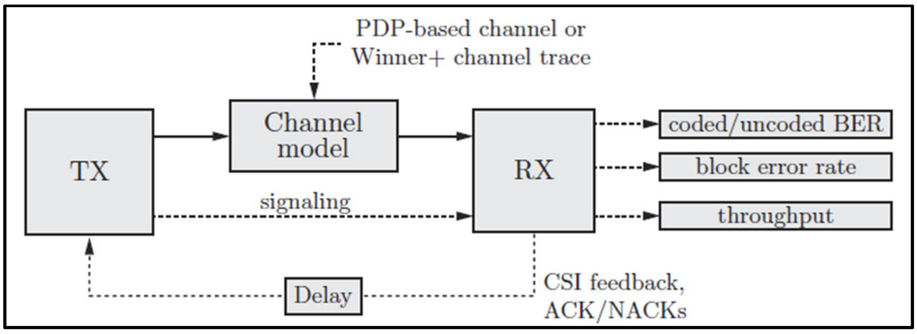
Time Domain

5. SIMULATION ENVIRONMENT

In this section, the Vienna LTE System Level simulator will be described in detail and its capabilities will be presented with the examples.

The structure of the simulator has basically three components such as transmitter, receiver and the channel model. Transmission is realized from transmitter to receiver (only downlink) and propagation medium is simulated using Channel model component. Signaling flows towards to receiver and it is assumed that uplink feedback assumed to be error-free.

Figure 5.1: Structure of LTE link level simulator

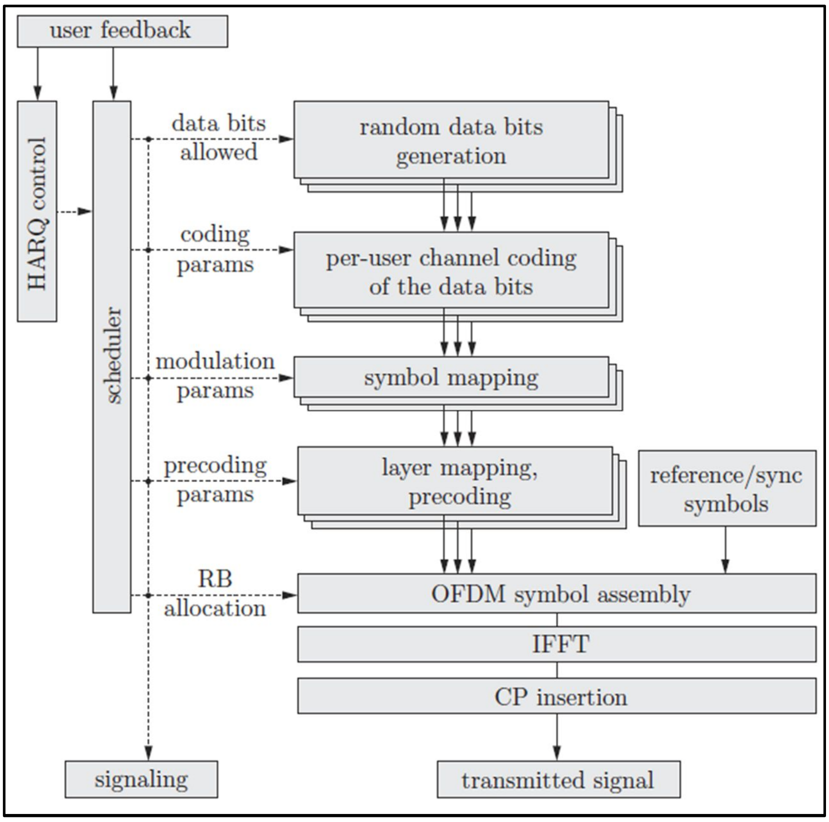


Coding schemes, HARQ information, scheduling and precoding parameters are sent from transmitter to the receiver by means of signaling data. Channel state information that contains CQI, PMI and RI values are sent from receiver to the transmitter in the uplink.

5.1 TRANSMITTER

Figure 5.2 shows the block diagram of the transmitter. The Scheduling algorithm allocates Resource Blocks to UEs and selects modulation and coding scheme, MIMO mode and pre-coding for all attached users. Depending on the type of the scheduling, frequency, time, spatial and multi-user diversities are adaptively set with respect to the channel conditions.

Figure 5.2: LTE downlink transmitter structure



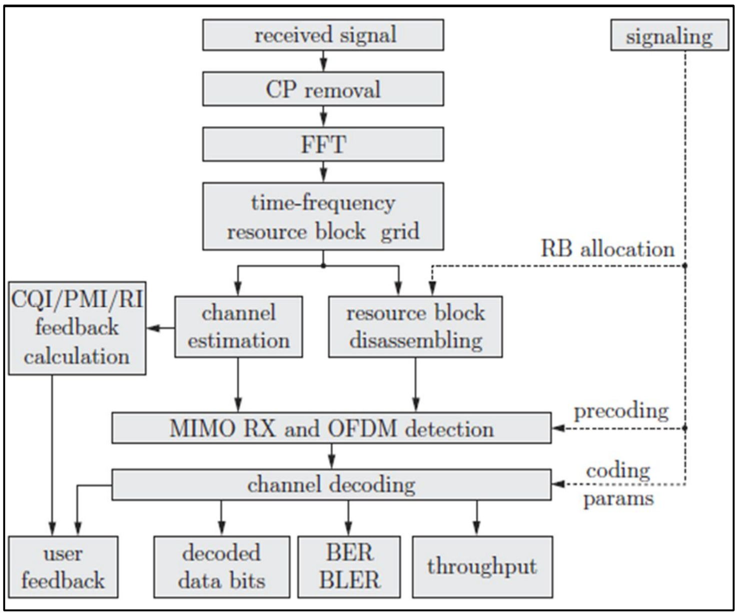
5.2 CHANNEL MODEL

The Vienna LTE link level simulator is able to simulate both block and fast-fading channels. The channel is assumed to stay constant during the one TTI in the block-fading channel. In every transmitted signal, time-correlated channel impulse responses are generated for the fast fading. Following channel models are supported by the simulator:

i. ITU Pedestrian A & B
ii. ITU Vehicular A & B
iii. Additive White Gaussian Noise (AWGN)
iv. Flat Rayleigh fading
v. Winner Phase II+

The most improved channel model among these models is the Winner Phase II+ (P Kyösti, 2007) which is a 3GPP spatial channel model can support additional features such as 3D antenna patterns.

Figure 5.3: LTE downlink receiver structure



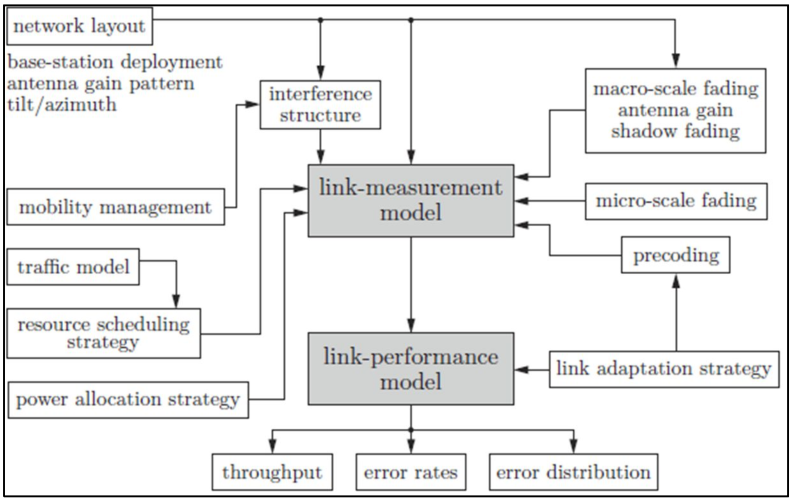
5.3 RECEIVER

Figure 5.3 depicts the block diagram of the receiver at the UE. After the RBs dissembled in the resource block disassembling module, signal detection algorithms such as soft sphere decoding, Zero-Forcing and Linear Minimum Mean Squared Error (LMMSE) are employed for signal decoding process. The data is obtained after decoding process, also BER, BLER and throughput statictic are obtained after decoding process. Channel estimation is done by using one of the following channel estimator algorithms: Least Squares (LS), Minimum Mean Squared Error (MMSE), Approximate LMMSE (Simko, et al., 2010) and genie-driven perfect channel knowledge.

5.4 LTE SYSTEM LEVEL SIMULATOR

LTE System Level simulator consists of three parts: Link-measurement model and link-performance model. The link quality measurements are calculated by link-measurement model. Link-measurement model enables the resource management and link adaptation. Link quality of each subcarrier is measured for every TTI. The UE calculates CQI, PMI and RI feedbacks for link adaptation. The scheduler allocates users and assigns resources to users for radio resource management. Link performance model estimates BLER based on the user feedbacks and modulation and coding scheme.

Figure 5.4: Block diagram of LTE System Level Simulator

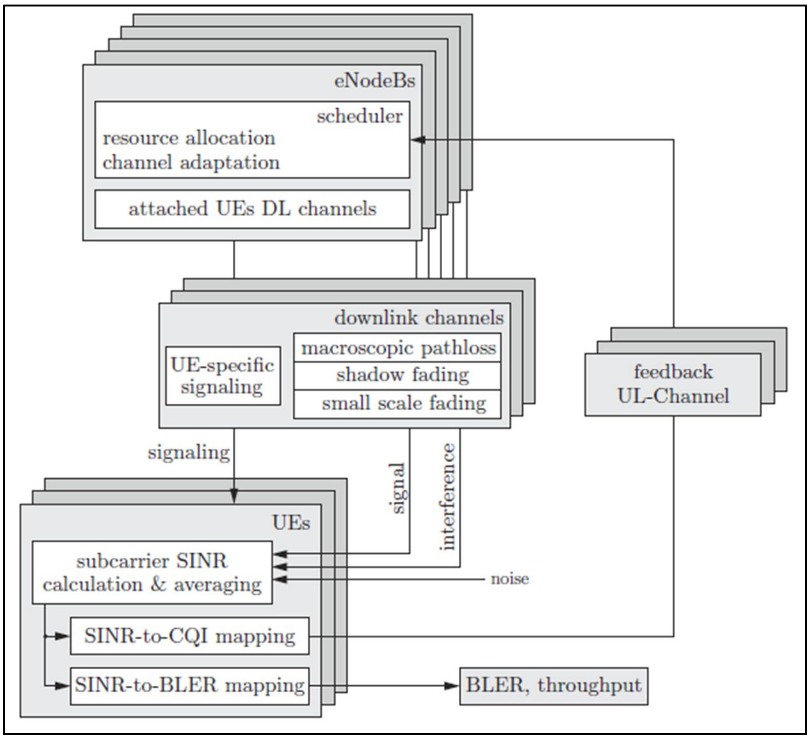


Implementation-based representation of the simulator is shown in the Figure 5.5. Each class objects represents a network element. Interactions of the classes are described in below.

Topology contains eNodeBs (three-sector with three schedulers) and the UEs. Traffic model assumes as full buffers in the downlink. Resource allocation and MCS and precoding matric calculations are done by scheduler for each UE that connected to the eNodeB.

At the user side, link measurement model calculates SINR of the assigned subcarrier. The SINR is calculated with respect to interference and noise levels depending on the cell layout and small-scale fading.

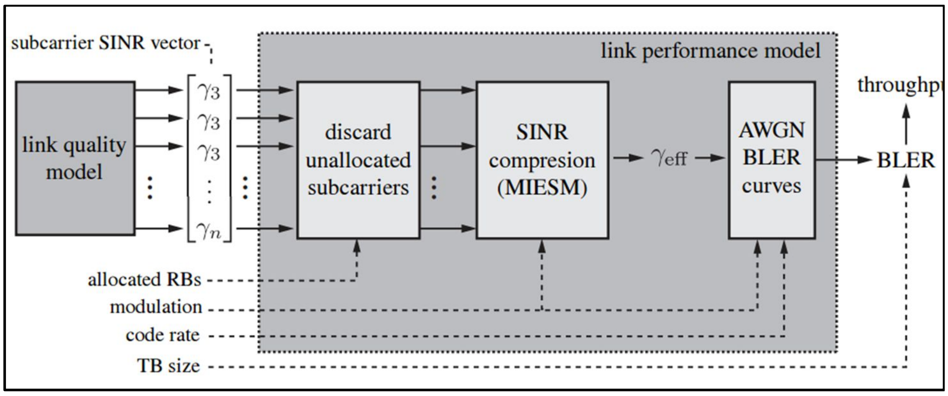
Figure 5.5: Implementation of the LTE System Level Simulator



The CQI feedback is calculated with respect to the SINRs of RBs (subcarriers) and the target BLER. SINR-to-CQI mapping (Ikuno, et al., 2010) is employed for CQI generation. Scheduler decides the appropriated modulation and coding scheme (MCS) to stay below the BLER threshold. For the scenarios that covers high mobility cases, computation and signaling can cause the feedback delay. If the channel quality changes during the delay, performance degradation occurs eventually.

An algorithm called Mutual Information Effective Signal to Interference and Noise Ratio Mapping (MIESM) (Kim, et al., 2004) (Tsai & Soong, 2003) (Wan, et al., 2006) is employed to obtain AWGN-equivalent SINR (y-AWGN). y-AWGN is mapped to BLER by using AWGN performance curves (Ikuno, et al., 2010). The BLER value is used to predict the probability for computing ACK/NACKs which are required with the Transport Block size to compute system throughput. (Figure 5.6).

Figure 5.6: Link performance model for the LTE System Simulator

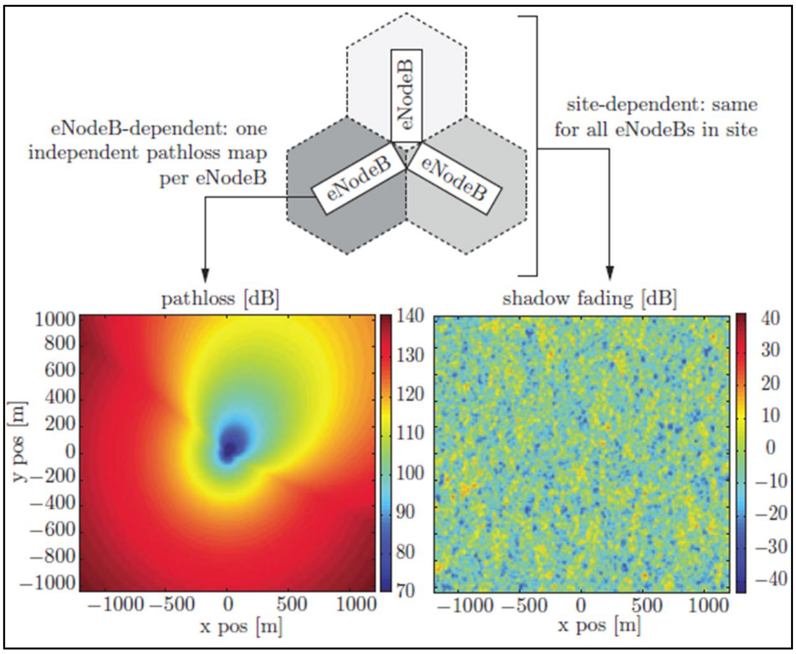


5.5 LARGE-SCALE AND SMALL SCALE AND SHADOW FADING

The large-scale fading (path loss) and shadow fading are modeled as location-dependent maps. The large-scale fading is calculated with respect to the channel models in (Access, 2006) (Access, 2008) and mixed with the antenna pattern of the corresponding eNodeB (Ikuno, et al., 2010). Shadow fading is calculated from log-normal random distribution by using a low-complexity variant of the Cholesky decomposition (Claussen, 2005). Large-scale and shadow fading maps can be seen in Figure 5.7.

Small-scale fading are depending on the time. The calculation of the small-scale fading is based on the transmitter precoding, the small-scale fading, MIMO channel matrix and the receive filter (Figure 5.7). A linear Zero Forcing receiver is used to model the receiver.

Figure 5.7: Path loss and shadow fading maps obtained from simulator



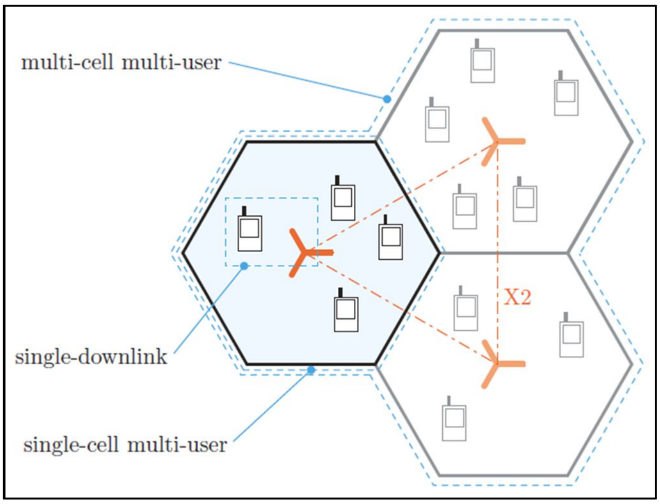
5.6 SIMULATION SCENARIOS

Three types of simulation exist in the scope of the Vienna LTE Simulator: Single Downlink, Single-cell Multi-user and Multi-cell Multi-user.

Single-downlink simulation covers the transmission data from single eNodeB and single UE. In this scenario, channel tracking/estimation, synchronization, MIMO gains, AMC and feedback optimization, receiver structures, (not taking scheduling into account), channel encoding/decoding mechanism are available to investigation (Mehlführer, 2011).

Single-cell Multi-user simulation covers connections between single eNodeB and many UE. This scenario enables the investigation of scheduling algorithm additional to the single-downlink scenario.

Figure 5.8: Simulation Scenarios



Multi-cell Multi-user simulation covers the radio links between multiple eNodeBs and multiple UEs. This scenario demands high number of computations and it provides more realistic investigation of interference-aware receiver techniques, interference management and interference alignment, and network-based algorithms such as joint resource allocation and scheduling.

6. PERFORMANCE EVALUATION

The simulations focus on the throughput and fairness performance of the different scheduling algorithms. A summary of the simulation parameters of the related work is given in Table 6.1. As seen in the table, the parameters will be changed for the each scenario.

Table 6.1: Simulation scenarios of the related work

Related Work	Scheduling algorithms	Number of Users (per cell)	Cell Topology	Mobility (km/h)	Antenna Type	Antenna Configuration
(Mehlführer et al. 2011)	BCQI, RR, PF, RF, MM	20	SC[1]	3	D[2]	1x1
(Assaf 2014)	PF, PS	10,20	MC[3]	3	D	2x2
(Gavrilovska & Talevski 2011)	BCQI, My_SCH_Fair, My_SCH_not_Fair	8	SC	3,30	D	1x1
(Schwarz et al. 2011)	BCQI, AMT, KMT, RR, MM	2,25	SC	30	N/S[4]	1x1
(Schwarz et al. 2011)	BCQI, RR, PF, RF, MM, PS	2,15	SC	N/S	N/S	1x1
(Alqahtani & Alhassany 2013)	BCQI, RR, PS	10,20,30,40,50	SC	N/S	N/S	1x1
(Escheikh et al. 2014)	BCQI, RR, My_SCH_Fair	15,35	SC	3	N/S	2x2
(Bechir et al. 2014)	BCQI, PF, RR, PS	5,10,15,20,25	SC	3	N/S	1x1
(Ikuno et al. 2013)	FFR, PF, RR	30	MC	5	D	4x4
Proposed Scheduler	BCQI, RR, PF, MM, PS, FFR	10,20,…,80	SC & MC	5,30,100	D & O[5]	1x1,2x2,4x4

6.1 SCENARIO 1

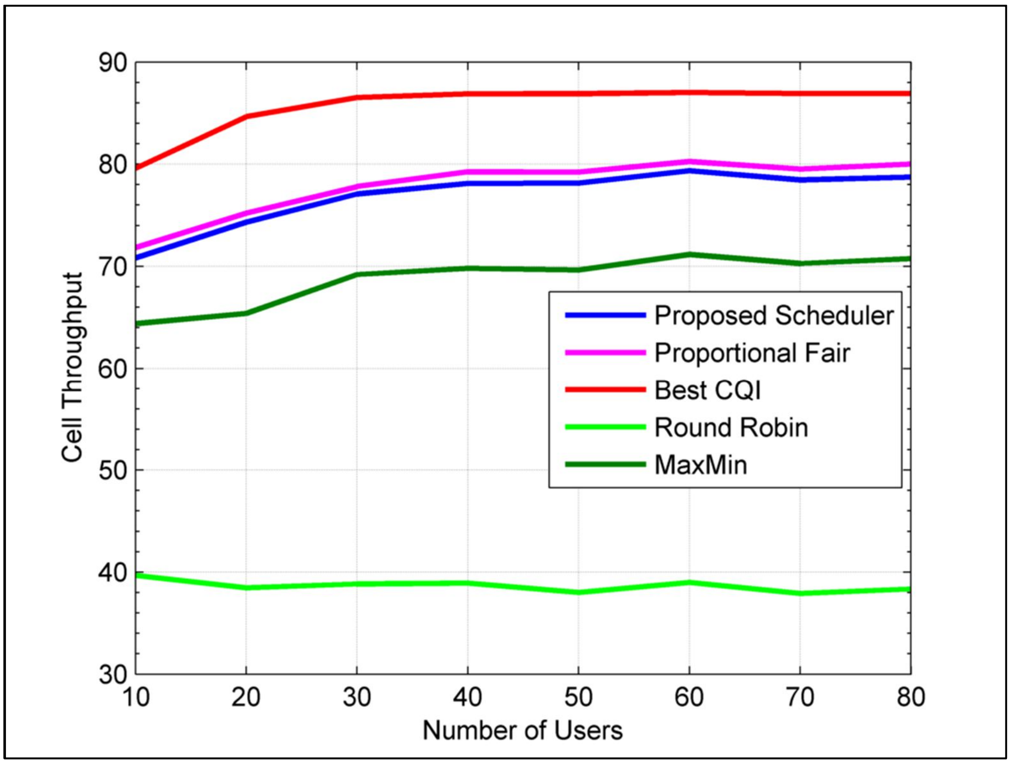
In this scenario, the performance of a single-cell network is investigated for the different number of users. The simulation parameters have been set according to the Table 6.2. Simulation run for 10, 20, 30, …, 80 users to find the behavior of the scheduling algorithms under the light and heavy load.

[1] SC: Single-Cell
[2] D: Directional Antenna
[3] MC: Multi-Cell
[4] N/S: Not specified
[5] O: Omni-antenna

Table 6.2: Simulation Parameters for the single cell multiple

Number of eNodeBs	1
Number of sectors	3
Bandwidth	20Mhz
Carrier Frequency	2100Mhz
Channel Model	Winner Phase II
Antenna Configuration	SISO, Directional
Pathloss [dB]	TS 36.942, urban

Figure 6.1: Cell Throughput vs Number of Users



The cell throughput is an important parameter that shows how efficiently the network works. The cell throughput is theoretically 100 Mbps in downlink under the perfect channel conditions for SISO antenna configuration. The average cell throughput is directly related with the channel quality. Poor channel conditions cause degradation in the transport block size and the cell throughput. Therefore, the cell throughput is determined by the channel qualities of the users in the real wireless networks. For that reason, Best CQI algorithm performs at close to the theoretical cell throughput since it serves only the users having good channel conditions.

The second-highest cell throughput can be reached by using PF and PS algorithms. The proposed scheduler which is also a proportional fair algorithm shows slightly less performance in the cell throughput. Decrease in the cell throughput is between 0 to 2 percent relative to PF scheduler. MaxMin scheduler can only reach up to 70 Mbps. Consequently it can be said that MaxMin is not efficient from the perspective of the system throughput/system efficiency. There are almost 26 percent and 10 percent decreases in cell throughput relative to Best CQI and PF algorithms respectively.

The edge throughput results of the scheduling algorithms are depicted in Figure 6.2. Edge throughput term is referred to 5 percent of the UE throughput ecdf[6]. It can be interpreted as the performance of the UEs close to the cell border. All the algorithms show the same decline trend in throughput when the number of UE increases. The reason for such behavior is that the number of RB per UE is decreasing while number of UE is increasing.

As seen from Figure 6.2, MaxMin algorithm serves the highest rate to the edge users. Proposed Scheduler (PS) shows better performance than the PF algorithm and it serves data rates slightly less than MaxMin algorithm for the edge throughput. Best CQI provides almost zero data rate at the cell edge. Since Round Robin algorithm is a channel-unaware scheduler, it supports poor data rates to the edge users.

Figure 6.3 is given to look at the overall throughput analysis. The throughput statistics of the RR and Best CQI scheduler extracted from the analysis to see the sharp differences among the three schedulers. MaxMin scheduler provides better data rates around 15 percent of the all UEs and 85 percent of the users stay far behind the other proportional fair algorithms in terms of throughput.

[1] Empirical Cumulative Distribution Function

Figure 6.2: Edge Throughput vs Number of Users

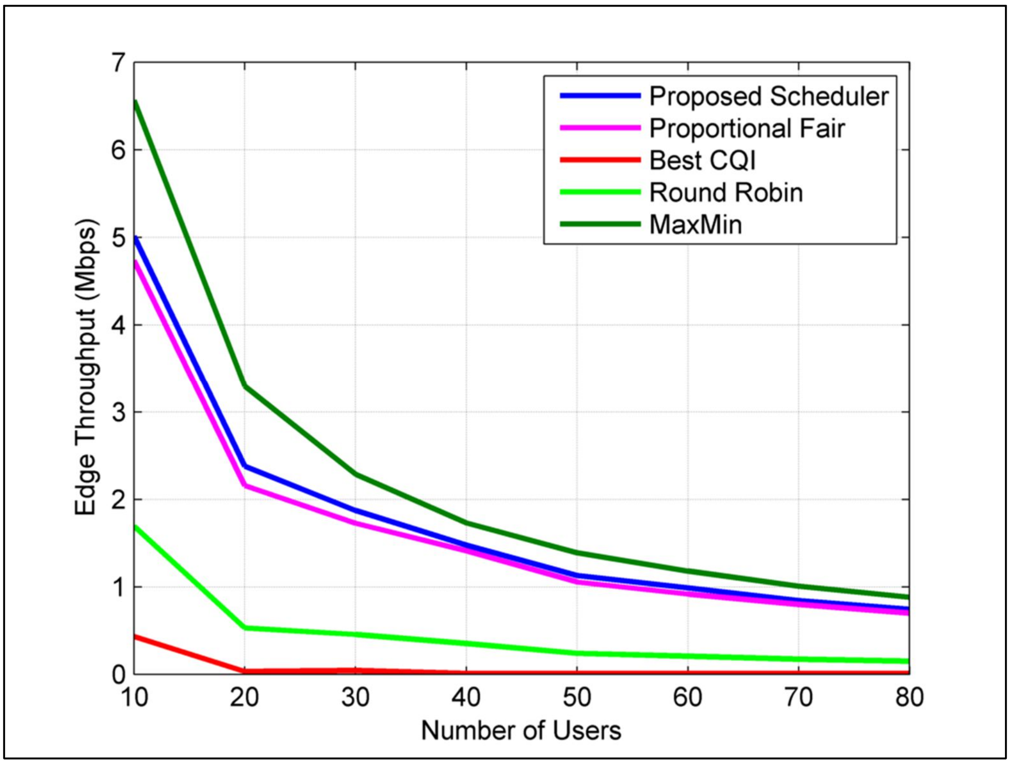
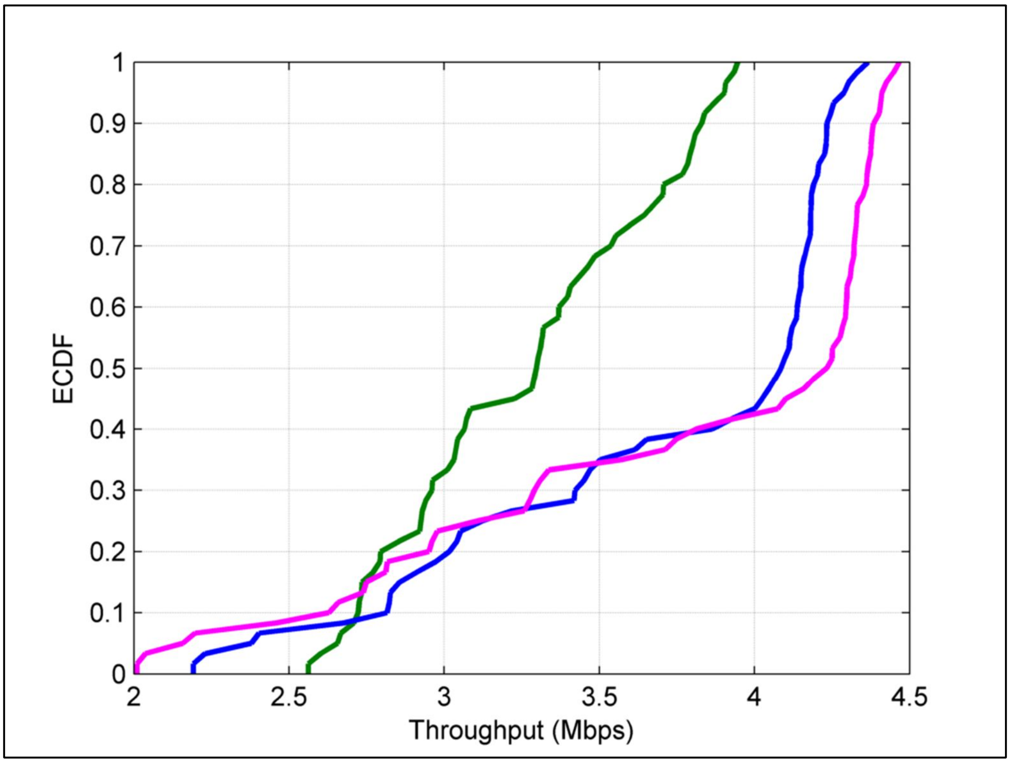
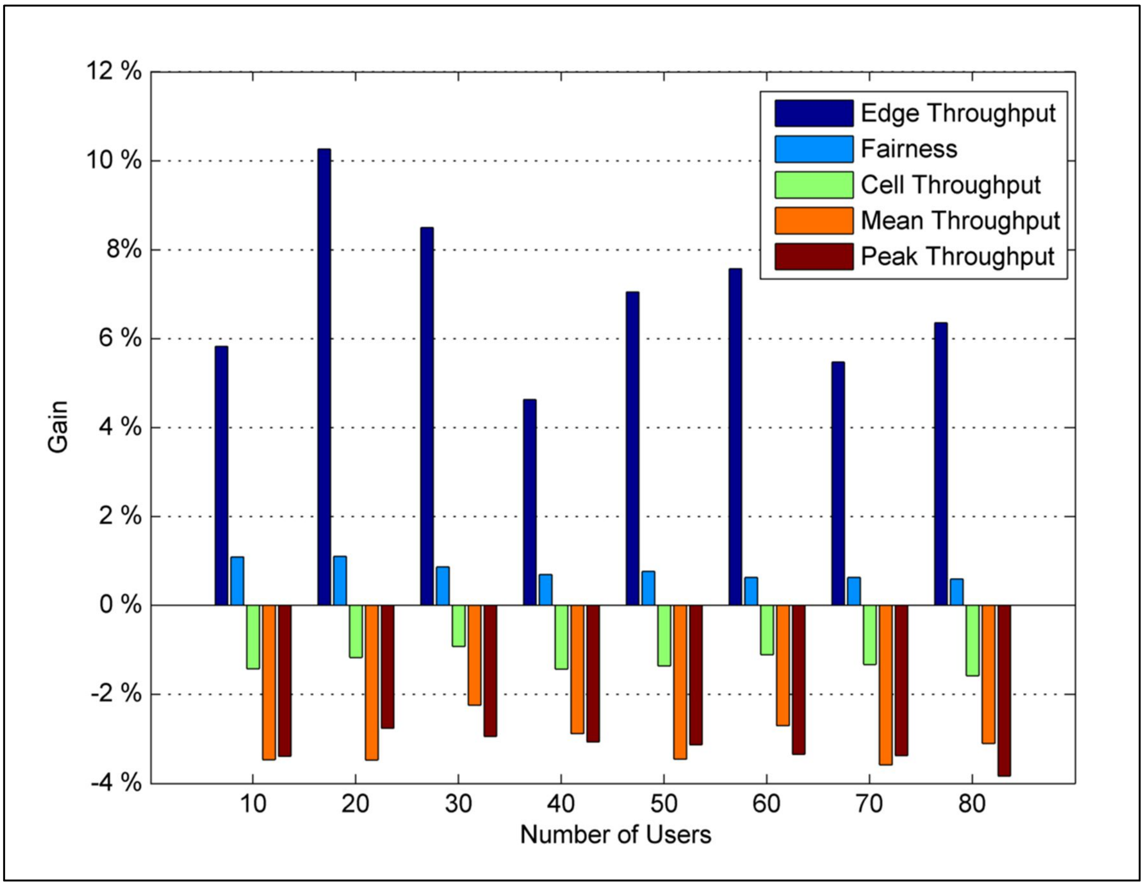


Figure 6.3: User Throughput Distribution



The proposed scheduler supports almost 30 percent of the users with better data rates with respect to the original proportional fair algorithm. And it performs worse for the rest of the user.

Figure 6.4: Gain Comparison of Proposed Scheduler and Proportional Fair



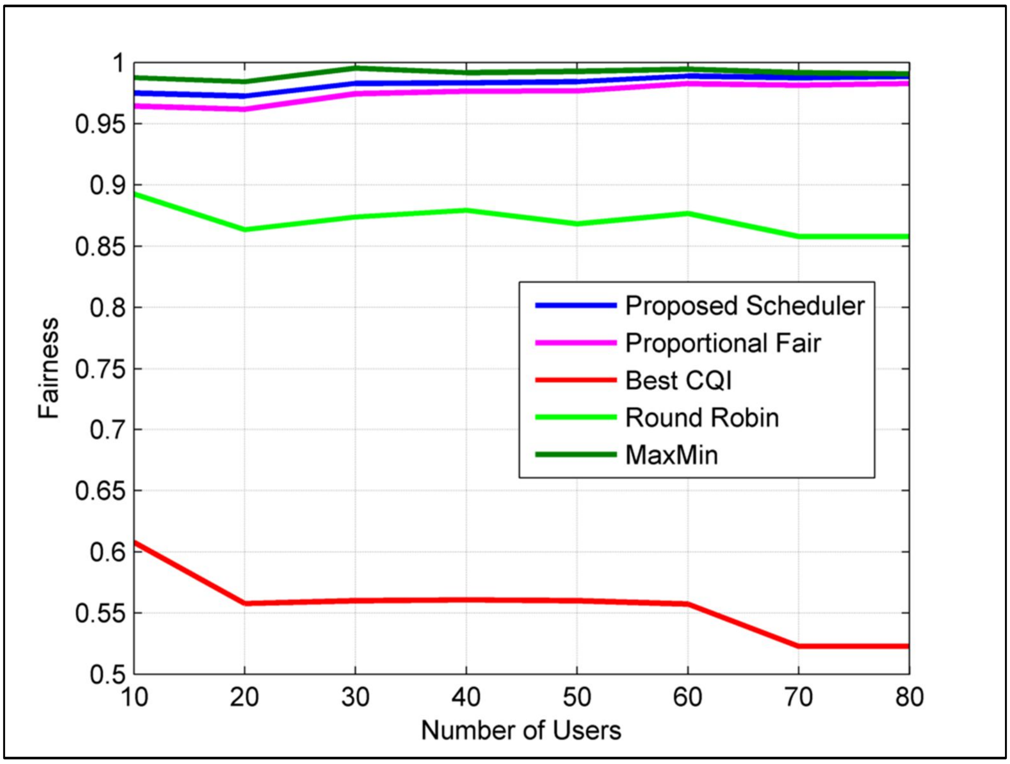
The gain in the edge, mean, peak and cell throughputs and fairness metrics comparing to the Proportional Fair can be seen from the Figure 6.4. The gain in the edge throughput reaches up to 10 percent depending on the number of users in the cell. Degradation in cell throughput stays under 2 percent. Decrease in the mean and peak throughputs is between 2 and 4 percent.

Fairness performances are shown in Figure 6.5. Fairness index is calculated by using Jain's fairness index (Jain, 1999). Jain's fairness index is formulated below.

$$J(x_1, x_2, \ldots, x_n) = \frac{\left(\sum_{i=1}^{n} x_i\right)^2}{n \cdot \sum_{i=1}^{n} {x_i}^2} \qquad (6.1)$$

where n is the number of users and x_i is the avera data rate of the i_{th} user. As seen from Figure 6.5, the highest fairness performance is achieved by the MaxMin scheduler. The proposed scheduler shows better performance than the Proportional Fair scheduler in terms of fairness. Round Robin shows also high fairness index and Best CQI provides almost no fairness with an index of around 0.6.

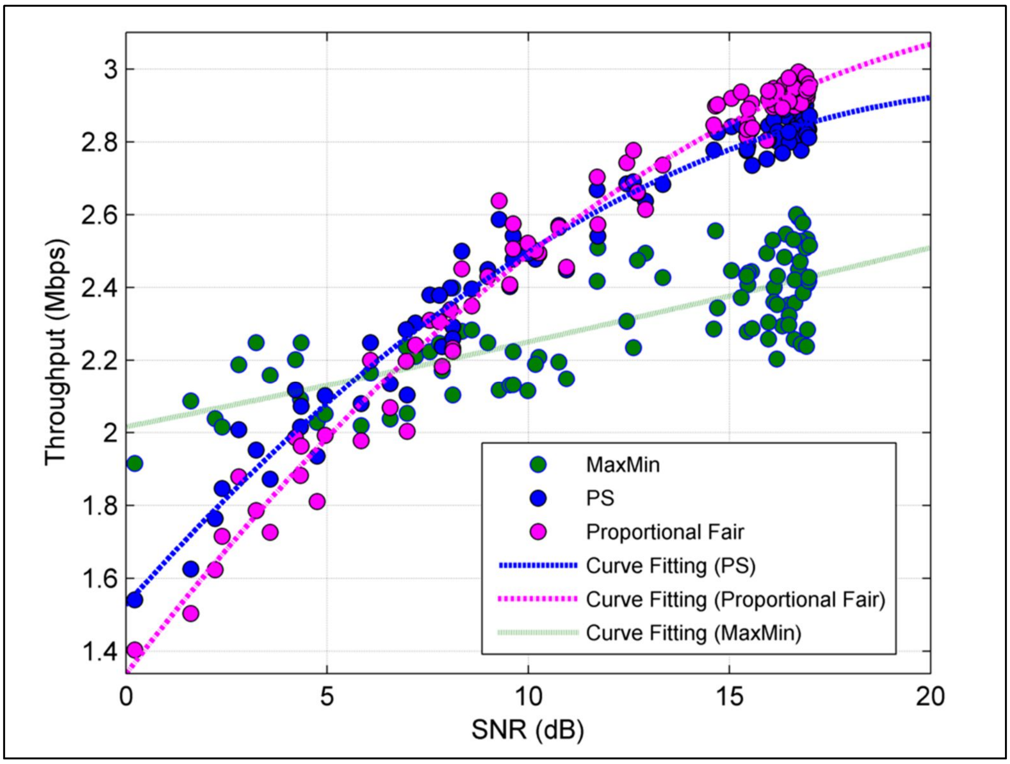
Figure 6.5: Fairness Analysis



Throughput-SNR results of the three scheduling algorithms are shown Figure 6.6 for 30 users. Proportional Fair supports high throughput for the users with high SNR, MaxMin serves almost same data rates for all users with different SNR. The proposed scheduler increases data rates of the users having SNR lower than 10 dB relative to Proportional fair. Proportional Fair schedulers show better performance than the proposed scheduler after 10 dB.

The priority of the proposed scheduler and MaxMin are to improve the throughput of the users at low SNR. Although MaxMin scheduler provides the highest throughput to the users at below 6 dB, it causes significant decreases in the throughput of the users with higher SNR. However, PS keeps the decreases as much as small in the peak throughputs.

Figure 6.6. SNR vs User Throughput, 30 users



6.2 SCENARIO 2

In scenario 2, the mobility performance of the schedulers is investigated. In terms of mobility, E-UTRAN is optimized to support low speeds (< 15 km/h); it shows high performance up to 120 km/h and maintains link for speeds up to 350 km/h. (up 500 km/h depending on the frequency band.). To compare the throughput performance of the schedulers, three different user velocities has been set in the simulator.

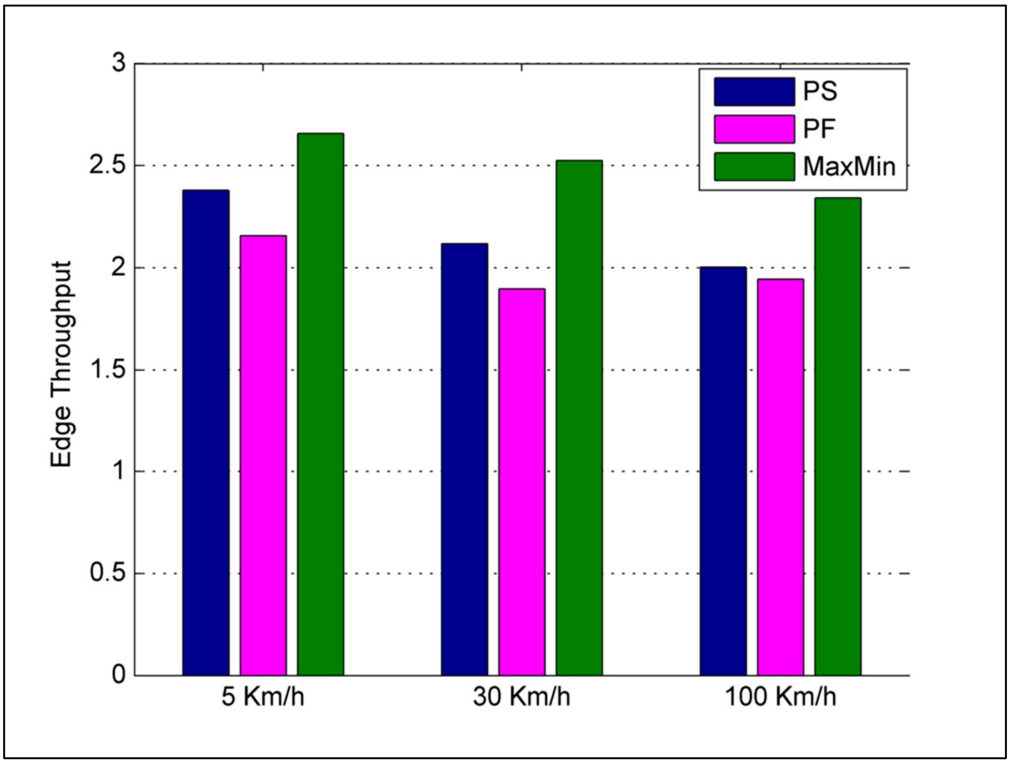
Transmission channel is modeled with channel convolution and additive noise, which gives in Fourier discrete domain (Pelcat et al. 2012):

$$Y(k) = H(k)X(k) + W(k) \tag{6.2}$$

where k is the discrete frequency X(k) and Y(k) are the transmitted and received signals respectively and H(k) is the channel impulse response and W(k) is the noise. User mobility affects the channel impulse response due to the Doppler shift. The Doppler shift is calculated from the wave length on carrier frequency λ_0, angle of arrival (downlink) $\varphi_{n,m}$, user speed v and direction of travel θ_v (Kyösti et al. 2008):

$$\vartheta = \frac{\|v\|\cos(\varphi_{n,m} - \theta_v)}{\lambda_0} \tag{6.3}$$

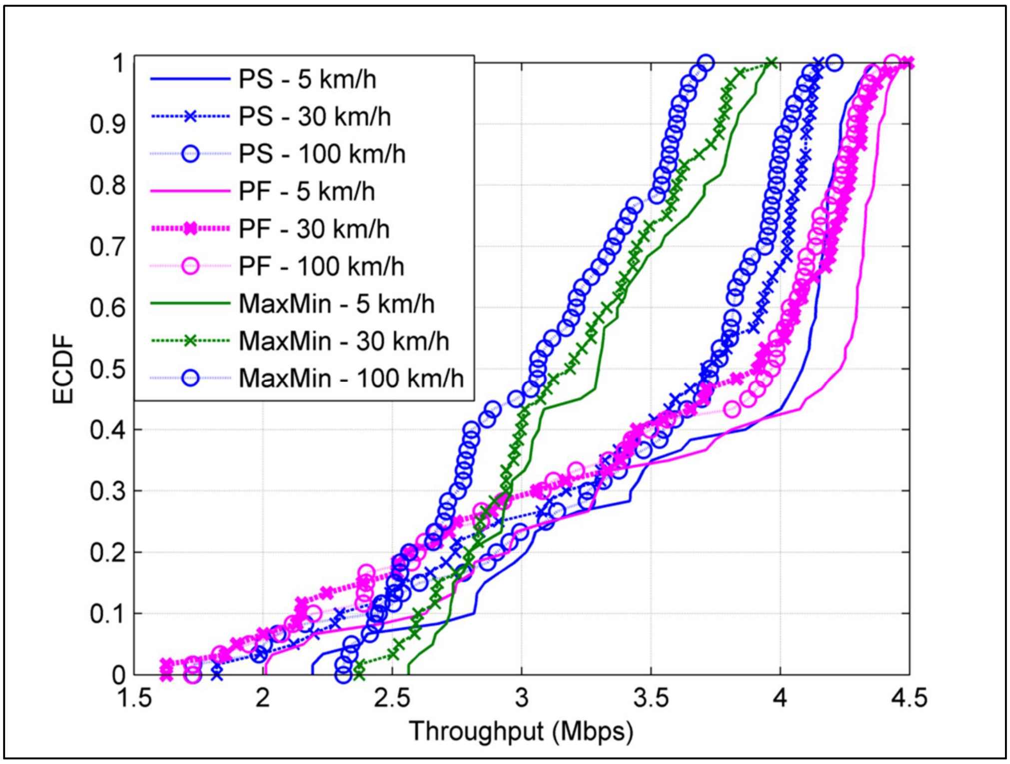
Figure 6.7: Mobility vs. Edge Throughput



The edge throughput results for different mobility scenarios are shown in Figure 6.7. When the user velocity increases, the gain between PS and PF decreases. Proposed scheduler shows almost no improvement in edge throughput under the high mobility scenario. Figure 6.8 helps to find out the effects of mobility on the throughput performance of the users.

Emprical cumulative distribution functions of throughput of different mobility scenarios are shown in Figure 6.8. Mobility has a negative effect of the throughput for all users regardless of scheduling algorithm.. Besides that, the peak throughputs are getting worse in the proposed scheduler relative to the other algorithms. PS is the most fragile scheduler against the mobility among the other schedulers.

Figure 6.8: Mobility vs Throughput CDF

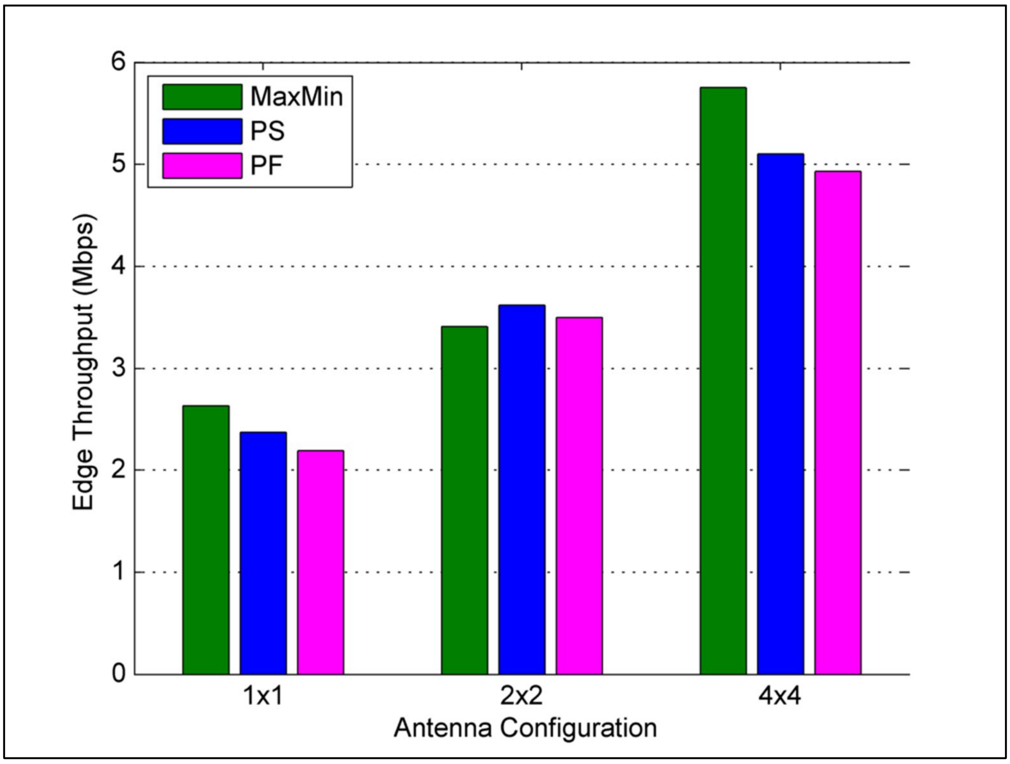


6.3 SCENARIO 3

To investigate behaviour of schedulers under the different MIMO scenarios, three different antenna configuration has been set up; 1x1, 2x2, 4x4. MIMO performances are shown in three figures for edge throughput, mean throughput and peak throughput. The number of the users is set as 20 for this simulation. In Figure 6.9, edge throughput of the schedulers for three antenna configuration is shown.

In 1x1 or SISO configuration, as we seen before, MaxMin provides highest throughput. In 2x2 antenna configiuration, all three schedulers performs almost the same for edge throughput. MaxMin again outperforms PS and PF in 4x4 and reaches the highest throughput, while PS shows a performance between MaxMin and PF.

Figure 6.9: Edge Throughput vs. Antenna Configuration



In SISO antenna configuration, PS cannot reach PF in terms of mean throughput. All three schedulers behaves similar to SISO in 2x2 case. However, PS catches PF for 4x4 antenna configuration.(Figure 6.10). It can be seen from Figure 6.11, for all antenna configuration, MaxMin performs worst in terms of peak throughput. PF scheduler achieves higher peak throughputs than PS in 1x1 and 2x2 antenna configuration. However, PS can obtain the same peak throughput in 4x4 antenna configuration as well as mean throughput.

Figure 6.10: Mean Throughput vs. Antenna Configuration

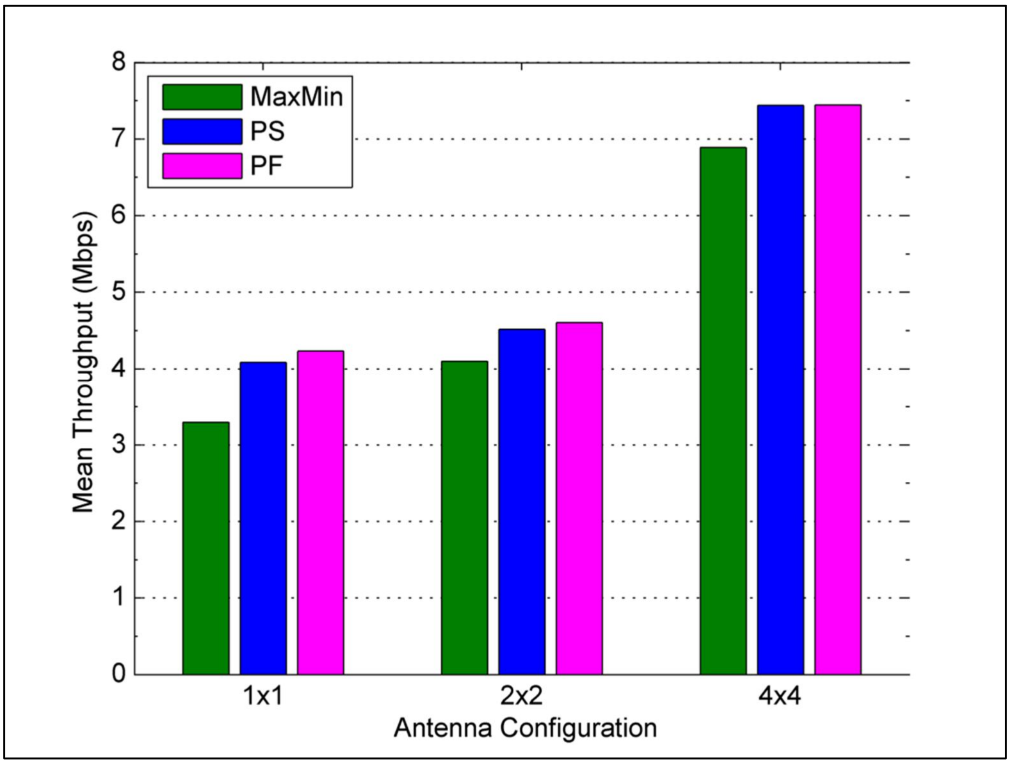
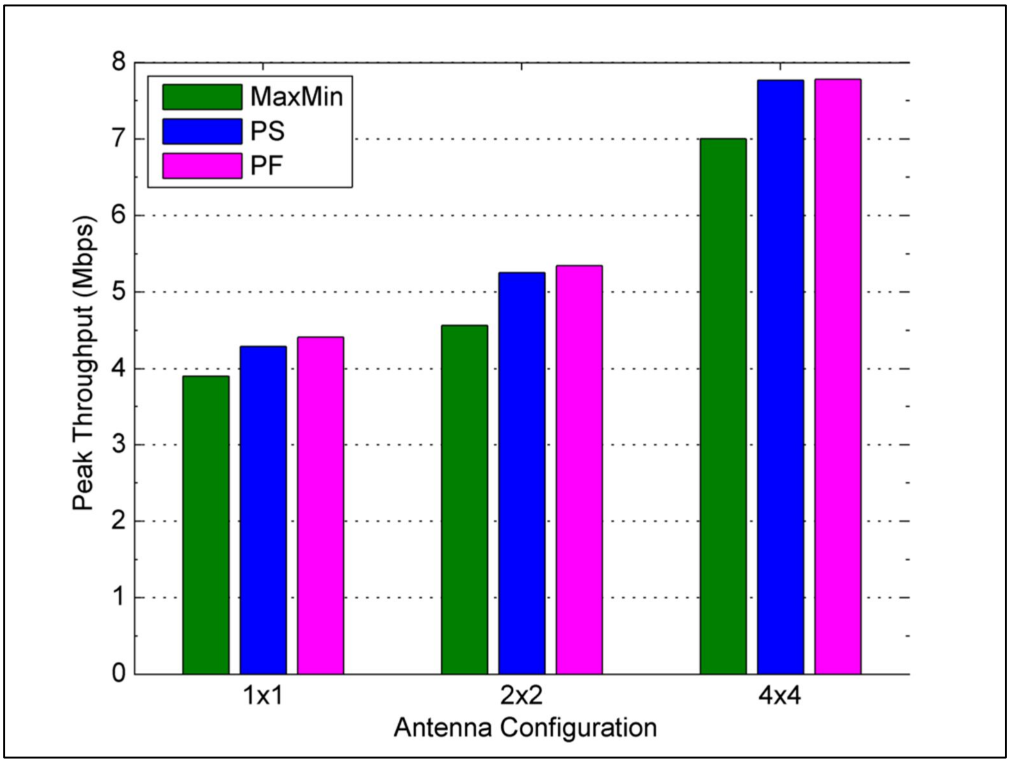


Figure 6.11: Peak Throughput vs. Antenna Configuration



6.4 SCENARIO 4

Carrier frequencies have different effect on the channel quality regarding of signal strength. Five carrier frequencies are selected to investigate in this work. These frequencies are; 800Mhz, 900 MHz, 1800 MHz, 2100 MHz and 2600 MHz. The number of users in this simulation is 10 and cell range is 1 km and pathloss model is selected as suburban.

The edge, mean and peak throughput analysis are shown in Figure 6.12, 13, 14. In terms of edge throughput, MaxMin serves better at 800 MHz, while PF and PS serves better at 900 MHz among the other frequency. For mean throughput, 900 MHz is the frequency that the all schedulers reach their highest throughput. After 900 MHz, PS outperforms the other schedulers in terms of mean throughput. In terms of peak throughput, all schedulers provides highest throughput at 900 MHz. For the all types of throughput, the when the carrier frequency gets higher, the performances are decreasing.

Figure 6.12: Edge Throughput vs. Carrier Frequency

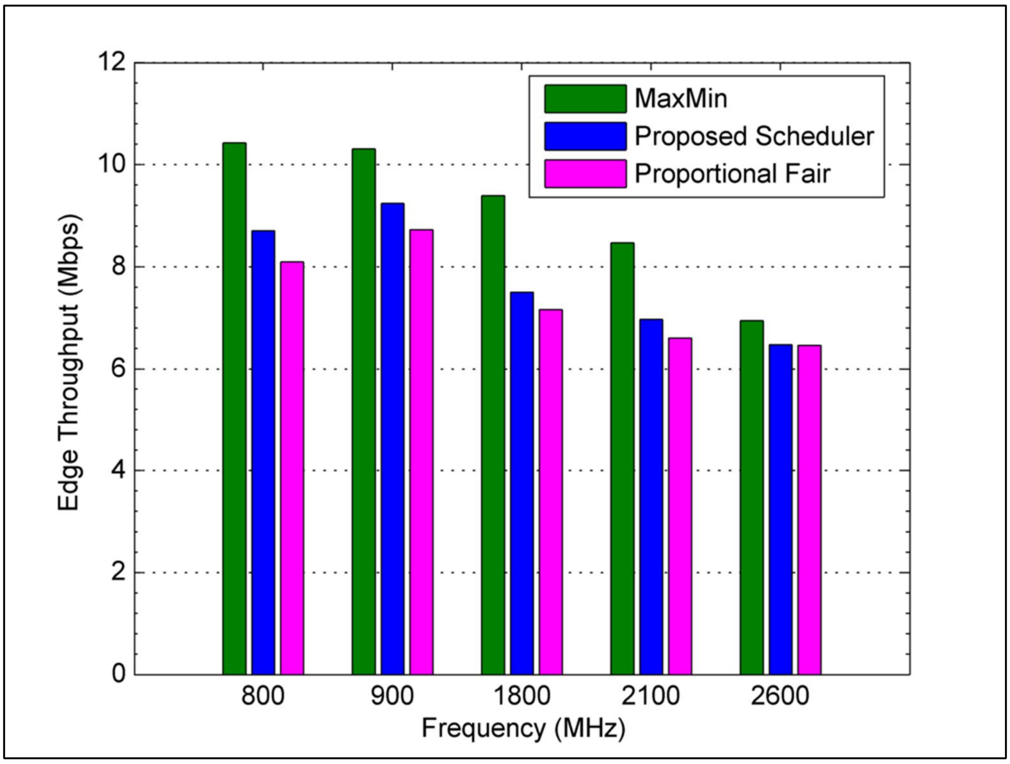


Figure 6.13: Mean Throughput vs. Carrier Frequency

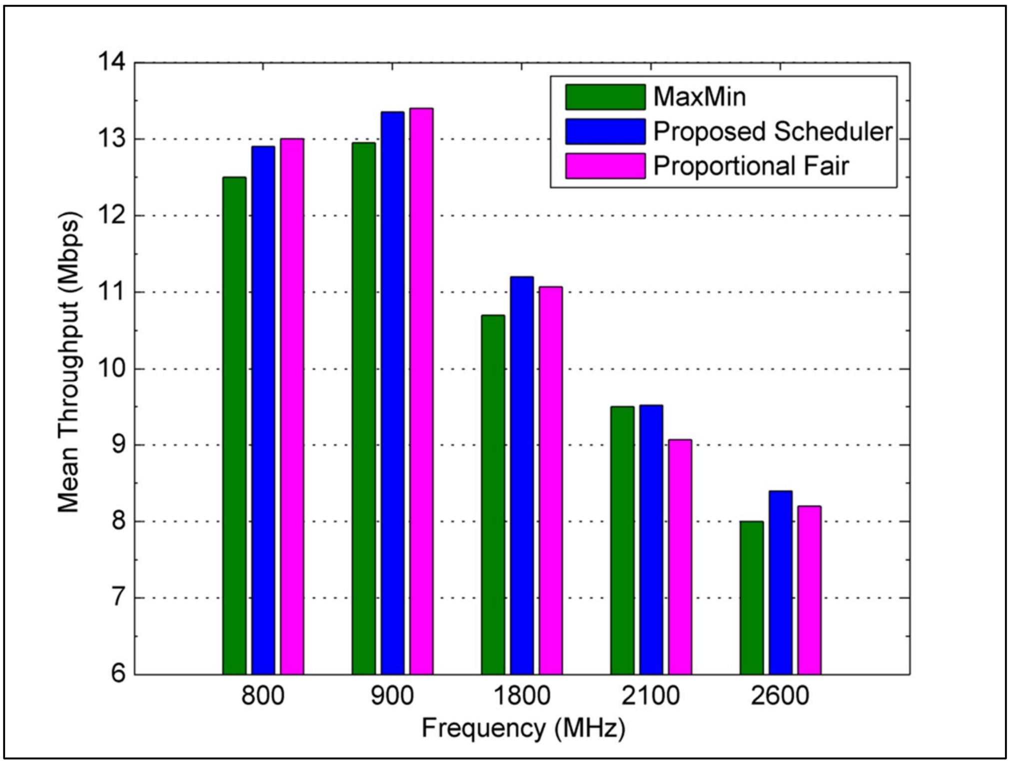
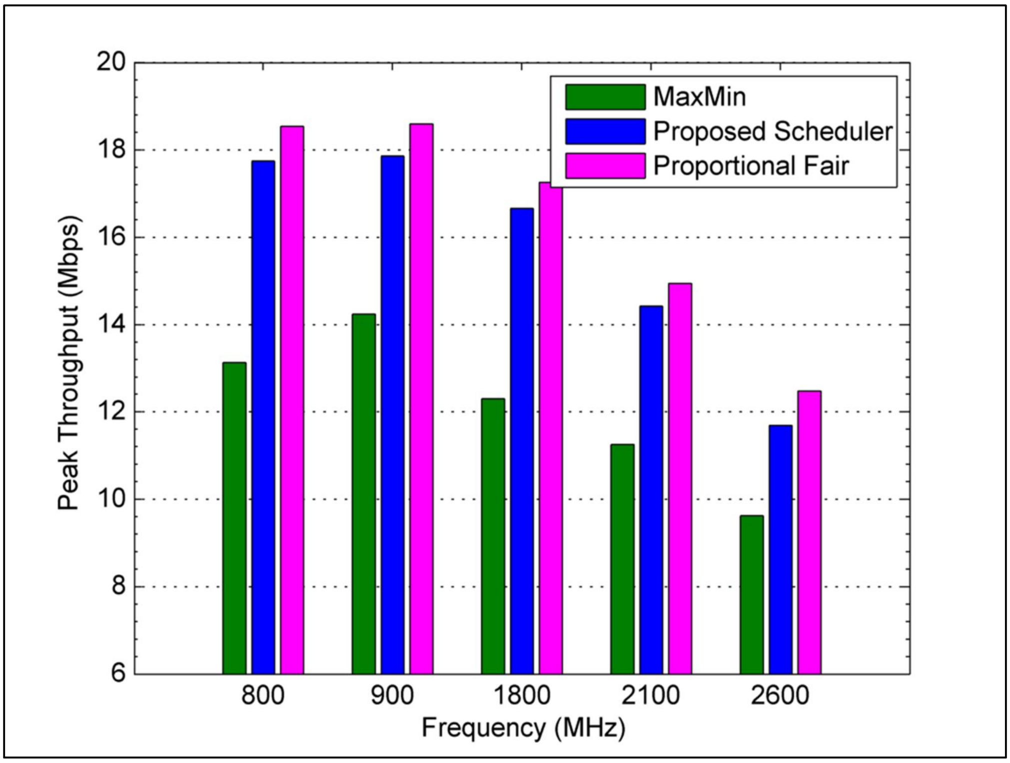


Figure 6.14: Peak Throughput vs. Carrier Frequency

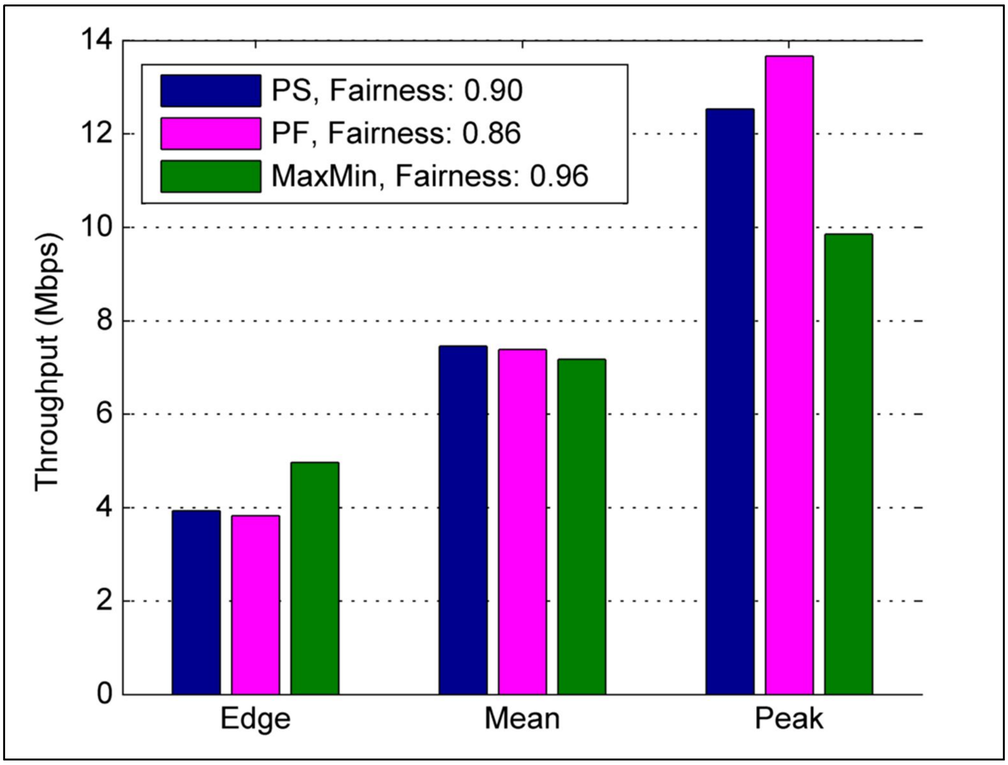


In terms of peak throughput, all schedulers provides highest throughput at 900 MHz. For the all types of throughput, the when the carrier frequency gets higher, the performances are decreasing.

6.5 SCENARIO 5

In the previous subsections, all simulations have been done by using single site and three-cell network topology. In this subsection, the network topology consists of 7 site, 21 cells and 210 users. The antenna configuration is 4x4 MIMO. From the single cell topology, the proposed scheduler brings gain at the edge throughput and there is throughput degradation in average cell throughput relative to PF scheduler. As seen from Figure 6.15, gain at the edge throughput still exists with degradation. The gap between edge throughput results of PS and PF schedulers became narrower. Besides that, PS achieves higher than PF in terms of mean throughput. In terms of peak throughput, PF performs best among these three schedulers in multi-cell network topology.

Figure 6.15: Edge, Mean and Peak Throughputs for Multi-cell topology



6.6 SCENARIO 6

Directional antenna or sector antenna has been used in the previous simulation configuration. The simulation has been done to make comparison performance of different scheduler when omnidirectional antenna is used. The cell range is 500 meters, antenna gain is 5W and the number of users is 30.

Figure 6.16: Edge, Mean, Peak Throughputs for omnidirectional antenna

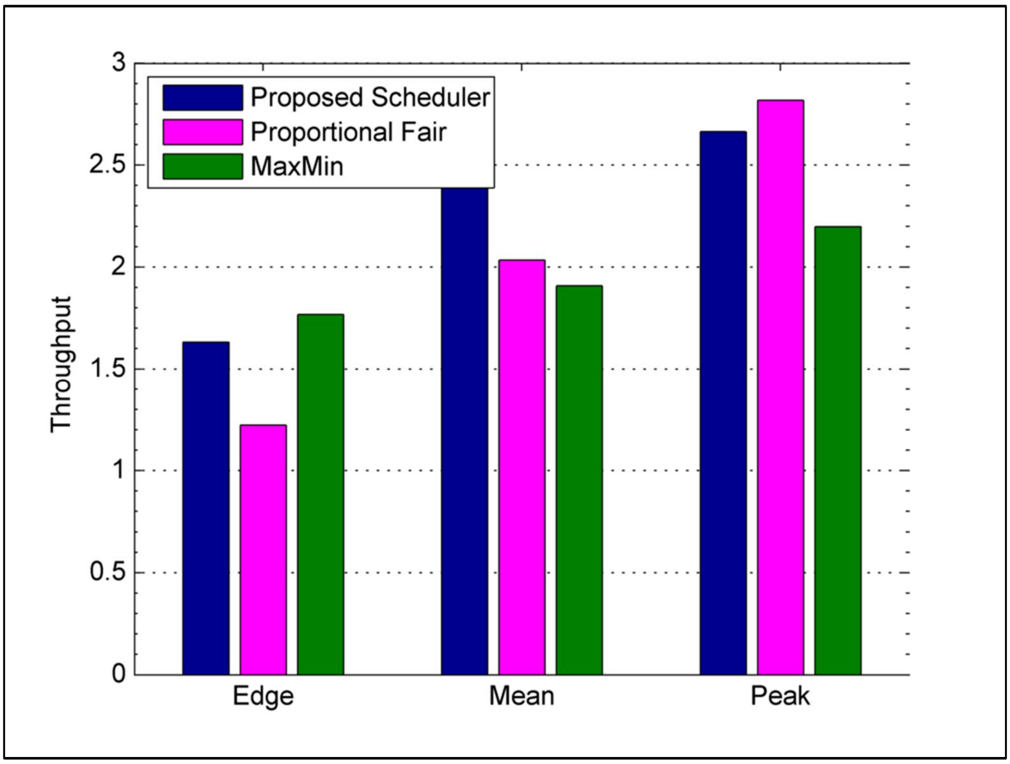
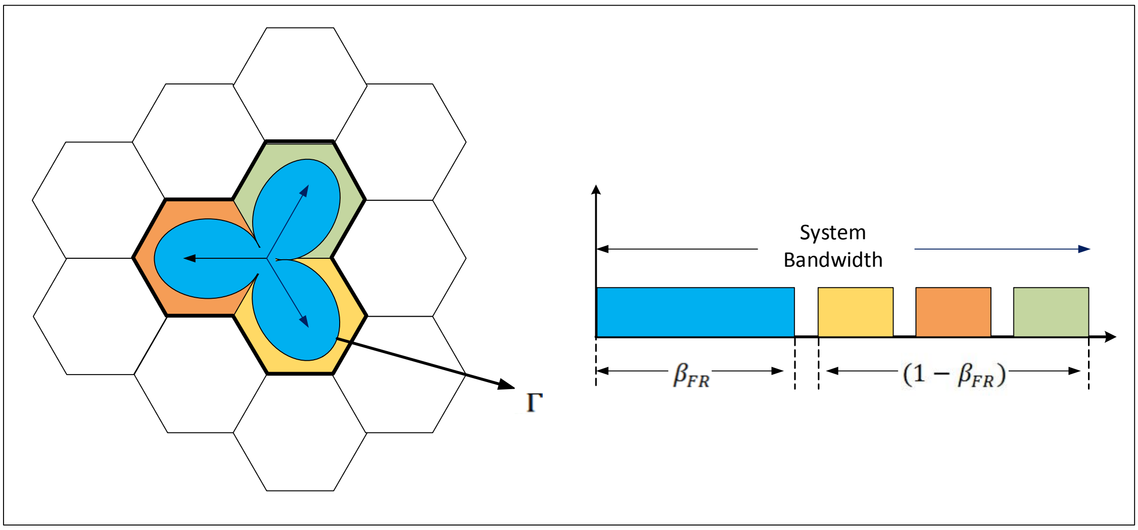


Figure 6.16 depicts the edge, mean and peak throughput results of the scheduling algorithms. It indicates that schedulers show different behavior in terms of mean throughput for the omnidirectional antenna and directional antenna cases. In the mean throughput, PS serves highest data rate to the users relative to the other schedulers. The peak and the edge throughput performances of the schedulers are the same for omnidirectional and directional antenna cases.

6.7 SCENARIO 7

Fractional Frequency Reuse is based on splitting cell area in into two and the system bandwidth into a number sub-bands according to a reuse scheme. Cell area is divided into a center part called Full Reuse (FR) zone and outer part called Partial Reuse (PR) zone. In FR zone, interference is lower and a single reuse factor is used. In PR zone, interference is higher therefore higher reuse scheme is employed in that zone to minimize the interference. Figure 6.17 depicts the case of a PR reuse factor of 3.

Figure 6.17: Frequency partitioning of the cells



A fraction β_{FR} of the total system bandwidth is assigned to the FR zones and remaining part of the bandwidth $(1-\beta_{FR})$ employs a reuse-n factor. The boundary of FR zone is determined by using Γ, which denotes SINR at a position. In the previous work (Ikuno et al. 2013), round robin and proportional fair algorithms has been used to investigate FFR performance. In another work (Gok & Koca 2014), Gok and Koca evaluated the performance of FFR schemes using round robin, proportional fair and Best CQI schedulers. In this subsection, we evaluate FFR performance by using proposed scheduling and proportional fair algorithm. For each scheduling algorithm, values in the Table 6.3 have been simulated.

Table 6.3: Simulation Parameters for FFR

Number of eNodeBs	57
Number of users	570
User speed	5 km/h
β_{FR}	[0.3 0.5 0.75]
Γ (dB)	[-5 0 5 10 15 20]
Bandwidth	20Mhz
Carrier frequency	2100Mhz
Inter-cell distance	500 m
Antenna configuration	4x4, Directional
Pathloss [dB]	$L = 128.1 + 37.6log_{10}(R)$, urban area
Minimum coupling loss	70 dB
Channel Model	Winner Phase II
Simulation length	50 TTI

Figures 6.18, 19 and 20 depict the edge, mean and peak throughput results of the scheduling algorithms for different β_{FR} values. Γ is fixed at 10 dB to observe the effect of β_{FR} on the performance. The proposed scheduler performs better in terms of the edge throughput with low β_{FR} . On the contrary, mean and peak throughput performances of the proposed scheduler are getting higher when β_{FR} gets higher. In terms of fairness, both of the scheduling algorithms perform almost the same for all β_{FR} values and they both decline with β_{FR}. Figure 6.21 shows the fairness results of the scheduling algorithms.

Figure 6.18: Edge Throughput vs β_{FR}

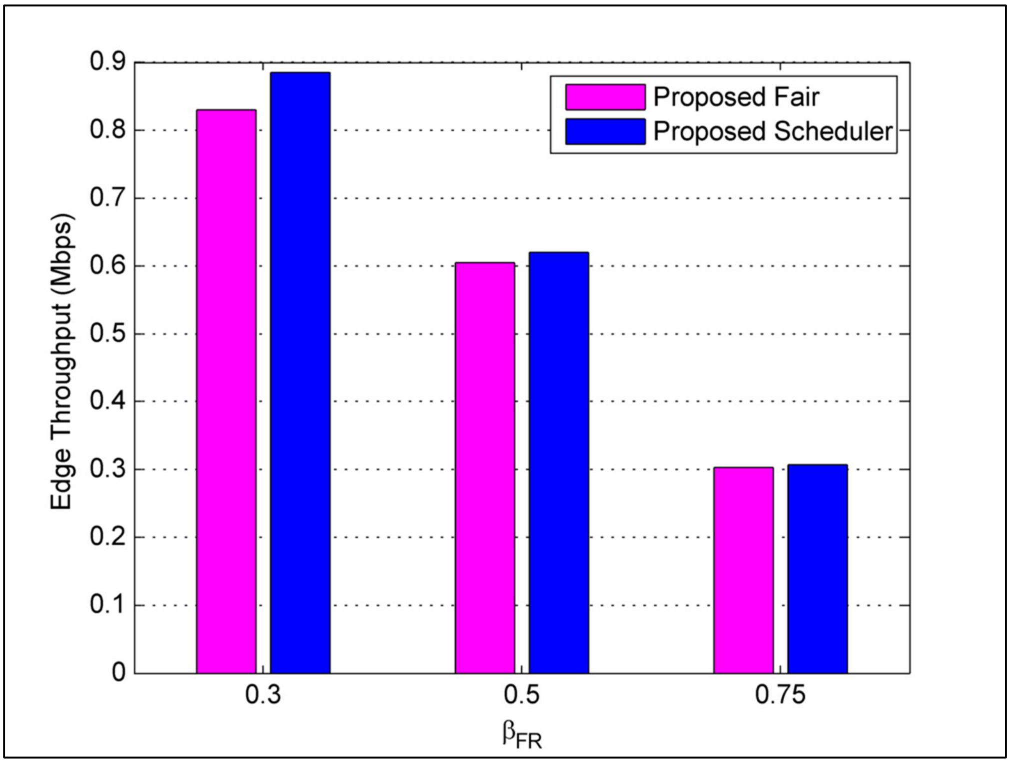


Figure 6.19: Mean Throughput vs β_{FR}

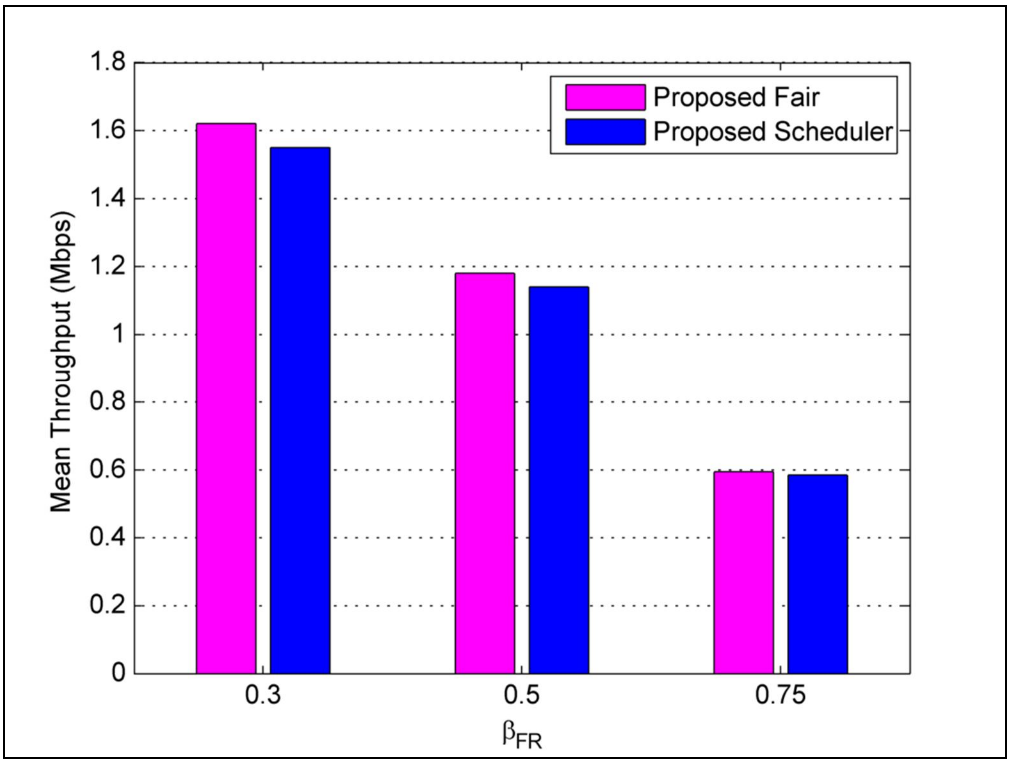


Figure 6.20: Peak Throughput vs $\boldsymbol{\beta_{FR}}$

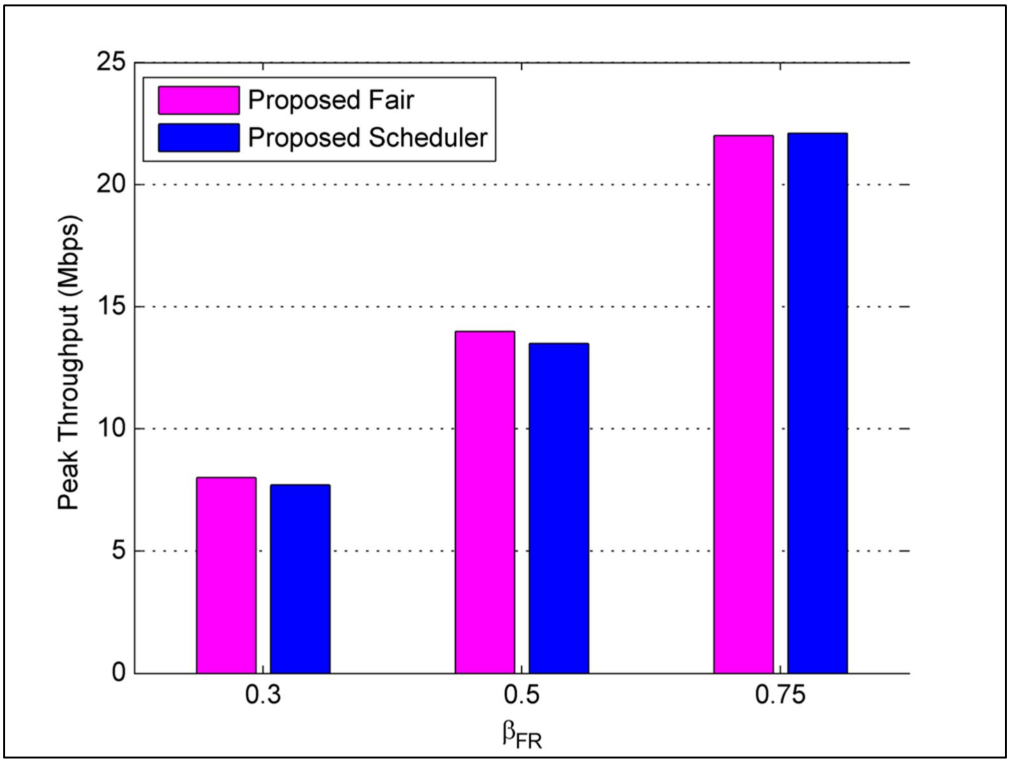


Figure 6.21: Fairness vs $\boldsymbol{\beta_{FR}}$

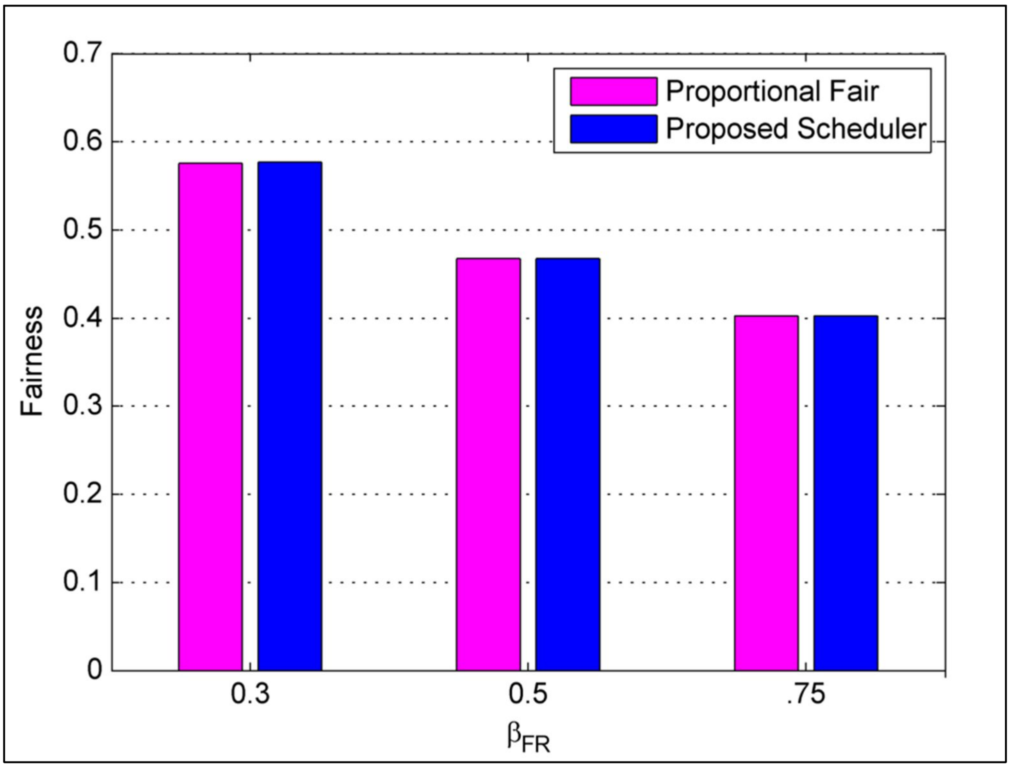


Figure 6.18, 19, 20 and 21 depict the edge, mean, peak throughput and fairness results for six different Γ values. β_{FR} is fixed at 0.3 for these results. As seen from the figures, the proposed scheduler shows better performance for edge and mean throughput and fairness when Γ is less than 15 dB. On the contrary, Proportional fair scheduler shows better performance when Γ is greater than 15 dB. It can be said that optimum Γ value is 5 and 15 dB for proposed scheduler and proportional fair algorithm respectively. For maximum peak throughput performance, Γ should be set to 20 dB for both scheduler.

Figure 6.22: Edge Throughput vs Γ

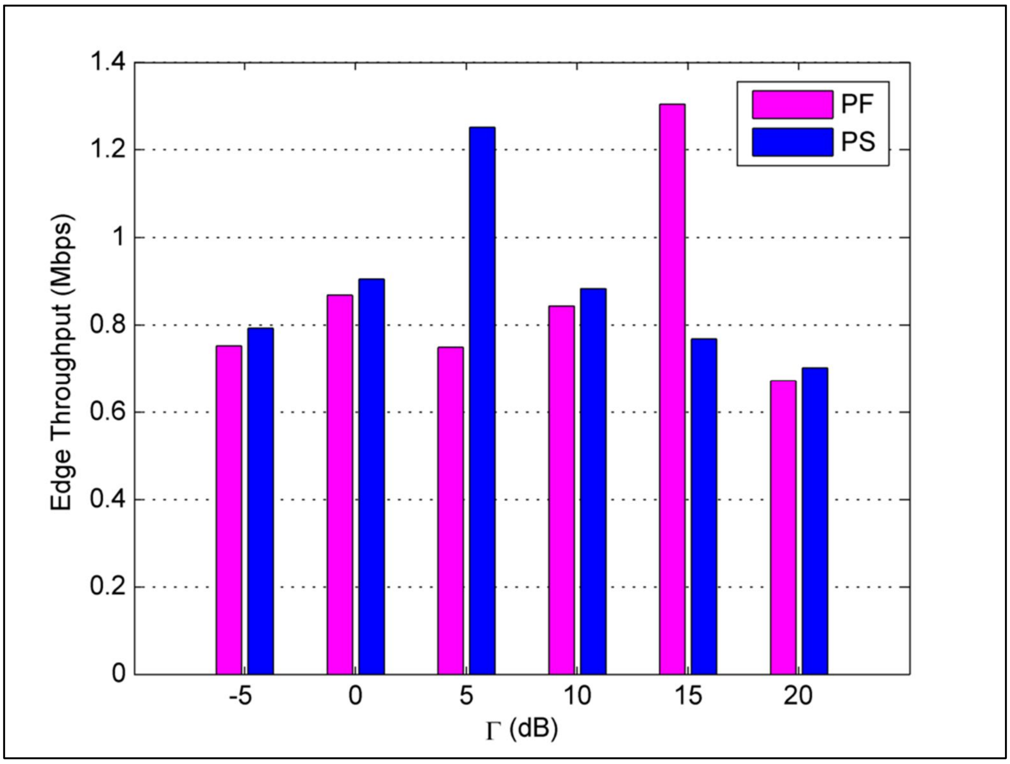


Figure 6.23: Mean Throughput vs Γ

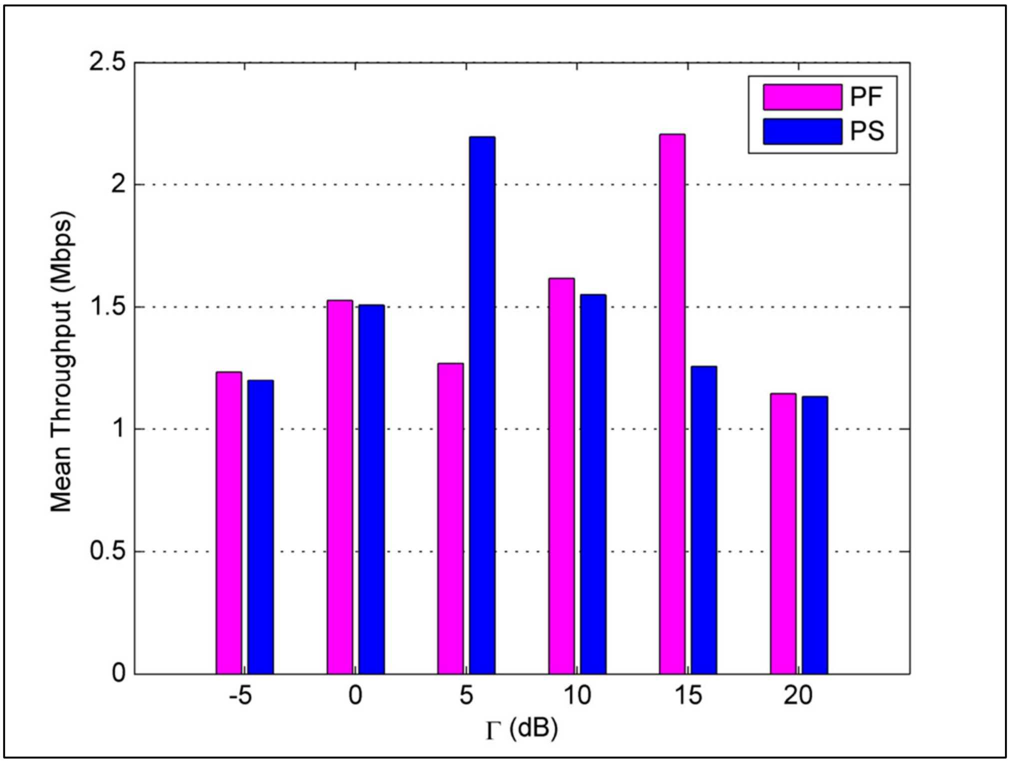


Figure 6.24: Peak Throughput vs Γ

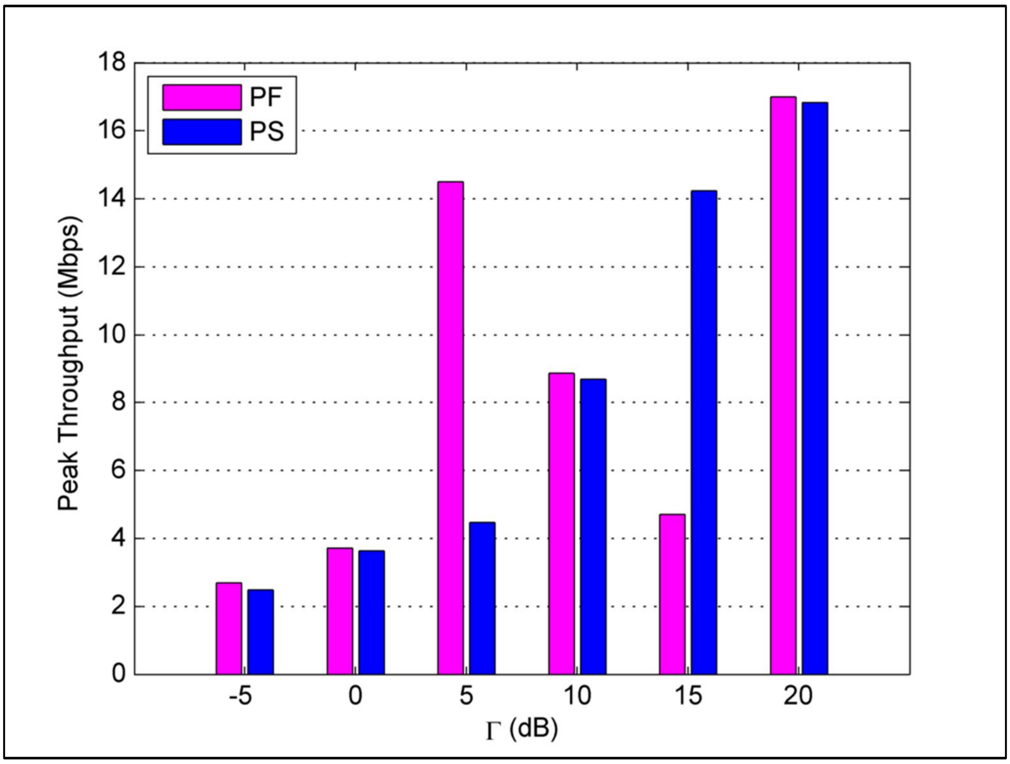
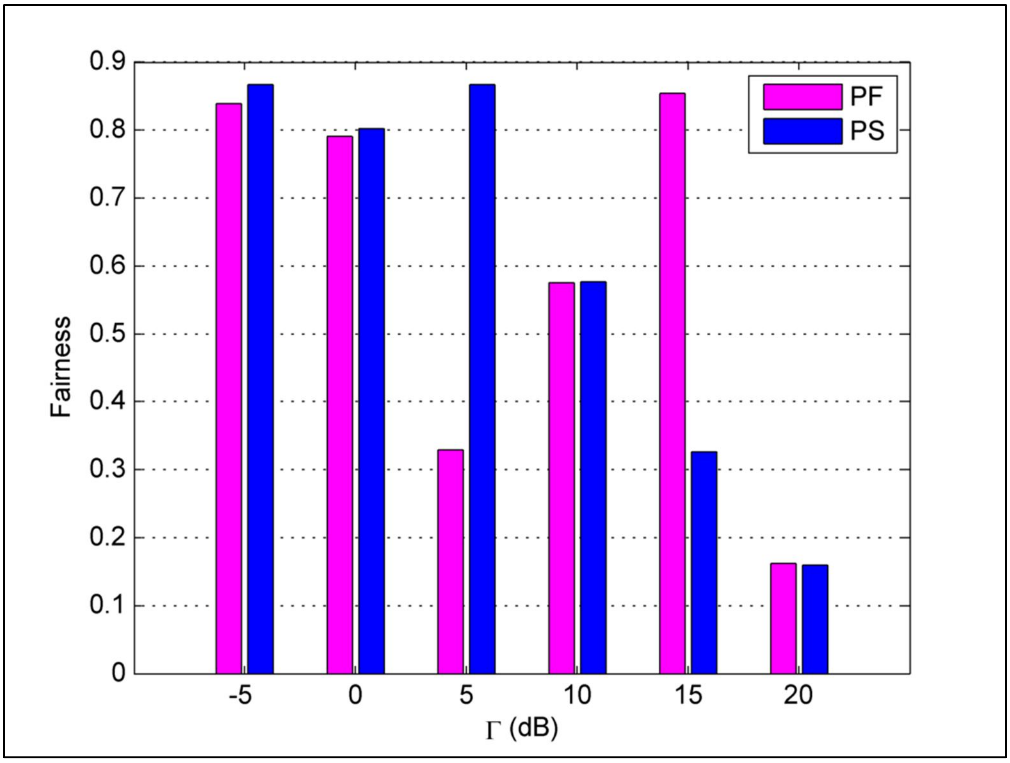


Figure 6.25: Fairness vs Γ



6.8 SUMMARY OF RESULTS

In this section, we have simulated different scenarios and show performances of scheduling algorithms under several parameters. In the first scenario, we examined the scheduling algorithms under different user loads. For a single cell with SISO antenna configuration, the proposed scheduler causes degradation up to 2 percent in the mean throughput which can be interpreted as an indicator of system throughput. In terms of edge throughput, the proposed scheduler increases the performance relative to proportional fair regardless of how many users exist in the network. Since there is a big performance gap between Round Robin and Best CQI algorithms relative to the other schedulers, these algorithms have been removed from the results after these subsections.

Table 6.4: Overview of performance evaluations of scheduling algorithms

	Round Robin	Best CQI	MaxMin	Proportional Fair	Proposed Scheduler
Edge Throughput	Moderate	Bad	Good	Good	Good
Mean Throughput	Bad	Good	Moderate	Good	Good
Peak Throughput	Moderate	Good	Bad	Moderate	Moderate
Fairness	Moderate	Bad	Good	Good	Good

Good: ✓ Bad: ✗ Moderate: !

Table 6.5: Proposed Scheduler vs. Proportional Fair

Advantages	**Disadvantages**
Gain in the edge throughput up to 10 percent	System throughput degradation between 0-2 percent
Small fairness gain between 0.5-1 percent	Peak Throughput degradation up to 10 percent

In the second subsection, user speeds were set to 5, 30, 100 km/h in three different simulation. Performance of the proposed scheduler has been decreased for all metrics more than other schedulers.

Impacts of the antenna configurations on the performance metrics have been investigated in the Scenario 3. Proposed scheduler provides an edge throughput between Proportion Fair and MaxMin algorithms for all antenna configurations. It should be underlined that proposed scheduler achieves the same amount of mean and peak throughput by using 4x4 antenna configuration. Additionally it is seen that there is no decrease in system throughput for both 2x2 and 4x4.

Effects of different carrier frequencies on the performance metrics were investigated in the subsection 5.4. Cell range has been set to 1 km to observe the changes more clearly. It is shown that edge throughput increases when the carrier frequency decreases. It is important that the proposed scheduler achieves highest system throughput and mean throughput for the higher frequencies, i.e. 1800, 2100 and 2600 MHz.

In subsection 5.5, we set up a network which consists of 7 sites, 21 cells and 210 users. Proposed scheduler performs better than both MaxMin and Proportional Fair algorithms in terms of the mean throughput. There are no differences between single and multi-cell scenarios for the edge and peak throughput results.

In Scenario 6, bi-directional antenna is replaced with an omnidirectional antenna to see the impact of antenna type on the throughput performances. For bi-directional with SISO antenna configuration, proposed scheduler causes decrease in the mean throughput. On the contrary, proposed scheduler increases the mean throughput relative to other scheduling algorithms.

The performance of FFR when combined with Proportional Fair (PF) and Proposed Scheduler (PS) is analyzed in the last subsection. We set up simulations with three different β_{FR} and six different Γ values. Edge and mean throughputs decrease when β_{FR} increases for both schedulers. We show that proposed scheduler and Proportional Fair algorithm has different behavior for the same Γ value. Optimum Γ is 5 and 15 dB for the proposed scheduler and Proportional Fair algorithm respectively. To obtain maximum peak throughput performance, Γ should be set to 20 dB for both schedulers.

7. CONCLUSION

In this thesis, we proposed a new LTE downlink scheduling algorithm and we investigated throughput and fairness performances of the proposed algorithm and four different existing scheduling algorithms, i.e. Round Robin, Proportional Fair, MaxMin and Best CQI.

Simulations have been performed for multiple scenarios to observe the impact of the parameters on the performance metrics of the scheduling algorithms. In each scenario, we focused on the one of the following parameters: the number of users, the number of cells, the carrier frequency, the antenna type and configuration, FFR and the mobility. The simulation results were evaluated in terms of the edge, mean, peak and cell throughputs and fairness.

As a result, it was found out that in terms of edge throughput, the proposed scheduler always showed better performance than Proportional Fair algorithm. Although MaxMin algorithm was developed to maximize the edge throughput without any constraint on system throughput, the proposed scheduler mostly showed significantly close results with MaxMin. Besides that, the proposed scheduler kept the system throughput much higher than MaxMin algorithm.

The proposed scheduler achieved much higher data rates than other scheduling algorithms except the Proportional Fair in terms of the mean throughput. The proposed scheduler caused degradation in the mean and cell throughput however the decrease in the mean and peak throughput stayed between 0 and 2 percent. In addition to that, the proposed scheduler showed better mean throughput than the Proportional Fair in some scenarios, i.e. 4x4 MIMO, carrier frequencies higher than 1800 MHz. We can say that the proposed scheduling algorithm showed an acceptable tradeoff between overall system throughput and edge throughput when the gain in the edge throughput is taken into account. In terms of the peak throughput, the proposed scheduler stayed behind of the Proportional Fair in all scenarios. The reason for that is the proposed scheduler is not designed to increase the peak throughputs of the users. Finally we should note that fairness performance of the proposed scheduler was higher than the Proportional Fair and less than MaxMin.

As a work to be done in the future, we believe that there are good chances for the proposed scheduler to be adapted to handle QoS, real-time traffic, femtocell scenarios and LTE-A features such as carrier aggregation, Multi-User MIMO, Coordinated Multipoint (CoMP) and Relay nodes.

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