Performance Analysis of a Resource Allocation Scheme for LTE

Sepideh Golshani

Submitted to the
Institute of Graduate Studies and Research
in partial fulfillment of the requirements for the degree of

Master of Science
in
Computer Engineering

Eastern Mediterranean University
September 2016
Gazimağusa, North Cyprus

Approval of the Institute of Graduate Studies and Research

Prof. Dr. Mustafa Tümer
Acting Director

I certify that this thesis satisfies the requirements as a thesis for the degree Master of Science in Computer Engineering.

Prof. Dr. Işık Aybay
Chair, Department of Computer Engineering

We certify that we have read this thesis and that in our opinion it is fully adequate in scope and quality as a thesis for the degree of Master of Science in Computer Engineering.

Assoc. Prof. Dr. Muhammed Salamah
Supervisor

Examining Committee

1. Assoc. Prof. Dr. Muhammed Salamah
2. Asst. Prof. Dr. Yıltan Bitirim
3. Asst. Prof. Dr. Gürcü Öz

ABSTRACT

In this thesis, we proposed an Intelligent Proportional Fair (IPF) scheduling algorithm for the Long Term Evolution (LTE) downlink system with multimedia traffic. The IPF algorithm is designed with aims to improve fairness, and providing acceptable system throughput. It is split into two parts, a Fuzzy-based Priority Determination (FPD) scheme and a Proportional Fair (PF) scheme. Considering Channel State Information (CSI), Quality of Service (QoS) Fulfillment Information (QFI), and service type, the FPD intelligently determines a priority value for each mobile user. The PF algorithm has been extended to compute the priority levels of active users and assigns the radio resources (Time and Frequency) based on the FPD priority value to guarantee the fairness as well as system's throughput while allocating sufficient radio resource to the high priority users.

The obtained results illustrate that compared to basic PF, the proposed IPF algorithm shows improvement in fairness as well as acceptable progress in system's throughput.

Keywords: LTE, Downlink, Resource Allocation, Scheduling, Proportional Fair, Fuzzy-based Priority Determination, Intelligent Proportional Fair.

ÖZ

Bu tezde, Uzun Süreli Evrim (LTE) downlink sistemi için, multimedya trafiği ile bir Akıllı Orantılı Adaletli (IPF) zamanlama algoritması önerilmiştir. IPF algoritması, kabul edilebilir sistem verimi sağlayarak, adaleti iyileştirmek amacı için tasarlanmıştır. IPF algoritması Bulanık- tabanlı Öncelik Belirleme (FPD) şeması ve Orantılı Adaletli (PF) düzeni olarak iki parçadan oluşmaktadır. Kanal Durum Bilgisi (CSI), Yerine-getirilmesi gereken Hizmet Kalitesi Bilgileri (QFI) ve servis tipi göz önüne alındığında, FPD akıllıca her mobil kullanıcısı için bir öncelik değerini belirler. PF algoritması aktif kullanıcıların öncelik düzeylerini hesaplamak için genişletilmiş olup, yüksek öncelikli kullanıcılar için ise yeterli radyo kaynaklarını (Zaman ve Frekans), FPD öncelik değerlerine göre adil bir şekilde tahsis ederken sistemin verimliliğini de garanti etmiş olur.

Elde edilen sonuçlar, geleneksel PF ile karşılaştırıldığında, öneriler IPF algoritması ile sistemin adaletinin iyileşmesinin yanı sıra, sistemin verimliliğinde de kabul edilebilir yükselme görülmektedir.

Anahtar Kelimeler: Uzun Süreli Evrim (LTE), Aşağı bağlantı, Kaynak Tahsisi, Planlama, Orantılı Adaletli, Bulanık merkezli Öncelik Belirleme, Akıllı Orantılı Adaletli.

DEDICATION

This thesis work is dedicated to my husband, Shahram who has been a constant source of support and encouragement during the challenges of graduate school and life. I am truly thankful for having you in my life. This work is also dedicated to my parents and my brother, Ali who have always loved me unconditionally and whose good examples have taught me to work hard for the things that I aspire to achieve.

ACKNOWLEDGMENT

Firstly, I would like to express my sincere gratitude to my advisor Assoc. Prof. Dr.Muhammed Salamah for the continuous support of my master study and related research, for his patience, motivation, and immense knowledge. His guidance helped me in all the time of research and writing of this thesis.

Besides my advisor, I would like to thank the rest of my thesis committee: Prof … for their insightful comments and encouragement, but also for the hard question which incented me to widen my research from various perspectives. At last, I would like to thank my family for supporting me spiritually throughout writing this thesis and my life in general.

TABLE OF CONTENTS

ABSTRACT iii

ÖZ iv

DEDICATION v

ACKNOWLEDGMENT vi

LIST OF TABLES ix

LIST OF FIGURES x

LIST OF ABBREVIATIONS xi

1 INTRODUCTION 1

  1.1 Thesis Objectives and Goals 2

  1.2 Organization of the Thesis 3

2 BACKGROUND AND THEORETICAL INFORMATION 5

  2.1 General Overview of LTE Network 5

  2.2 LTE System Architecture 6

  2.3 LTE Radio Resource Structure 7

    2.3.1 LTE Spectrum Bandwidth 9

    2.3.2 LTE Frame Structure 10

  2.4 LTE Radio Bearer 11

  2.5 Scheduling in LTE System 12

  2.6 Scheduling Objectives 14

    2.6.1 Service Classes with their QoS Requirements 14

    2.6.2 Throughput 15

    2.6.3 Fairness 16

  2.7 Overview on LTE Resource Allocation Strategies 17

2.7.1 Round Robin (RR) 18

2.7.2 Best CQI (BCQI) 18

2.7.3 Blind Equal Throughput (BET) 19

2.7.4 Proportional Fair (PF) 19

3 MODEL METHODOLOGY 26

3.1 The Proposed Intelligent Proportional Fair Scheme 26

3.1.1 Fuzzy-Based Priority Determination (FPD) 26

3.1.2 Intelligent Proportional Fair (IPF) 32

4 SIMULATION SCENARIOS AND RESULTS 35

4.1 Simulation of LTE System 35

4.1.1 Vienna LTE Simulator 35

4.2 Simulation Parameters and Environments 37

4.2.1 Close Loop Spatial Multiplexing (CLSM) 39

4.2.2 Service Classes 40

4.3 Implementation of Fuzzy Inference System 41

4.4 Simulation Results and Performance Metrics 43

4.4.1 Fairness 44

4.4.2 Average User and Cell Throughput 46

5 CONCLUSIONS 50

REFERENCES 52

APPENDICES 58

Appendix A: Running a Simulation 59

Appendix B: Simulation Parameters 60

Appendix C: Scheduler Settings 61

LIST OF TABLES

Table 2.1: Operation bandwidths and their specification [10] 10

Table 2.2: TDD frame-structure format [9] 10

Table 2.3: QCI and its specification [13] 11

Table 2.4: CQI and Modulation [15] 13

Table 2.5: Service classes QoS requirements 15

Table 2.6: Alpha value computation 20

Table 2.7: RR, MT, and PF Fairness and Throughput 20

Table 3.1: Gama value for different class of services 27

Table 3.2: UIK value for different class of services [5] 29

Table 3.3: Fuzzy term set and membership function [5] 30

Table 3.4: The fuzzy logic rules [5] 31

Table 4.1: Simulation parameters 38

Table 4.2: Traffic category [15] 40

Table 4.3: The system requirements for each traffic type [30] 41

LIST OF FIGURES

Figure 2.1: Simplified Model of LTE System Architecture [6] 6

Figure 2.2: Radio Resources Grid with Related RBs and REs [6, 9] 8

Figure 2.3: Time and Frequency Structure of LTE Downlink Sub-frame [6] 9

Figure 2.4: SNR to CQI Mapping [14] 12

Figure 2.5: Design of eNB Scheduler [6] 14

Figure 3.1: The Membership Functions (a) CIK, (b) UIK, and (c) TIK [5] 31

Figure 3.2: Intelligent Proportional Fair 33

Figure 3.3: Flow chart for IPF algorithm 34

Figure 4.1: Block Diagram of LTE Downlink System Level Simulator [31] 36

Figure 4.2: Throughput Comparison among CLSM with Diffrent Antenna Setup [34] 39

Figure 4.3: The Fuzzy Logic Toolbox 41

Figure 4.4: The Fuzzy Membership Function for CIK, UIK and TIK 42

Figure 4.5: Fuzzy Interface for CIK, UIK and TIK 43

Figure 4.6: The Position of UEs and eNBs 44

Figure 4.7: Fairness in time ranging from 10 to 100 ms 45

Figure 4.8: Average UE Throughput in Time Ranging from 10 to 100 ms 47

Figure 4.9: Average Cell Throughput in Time Ranging from 10 to 100 ms 47

Figure 4.10: Fairness for UEs Ranging from 5 to 20 in TTI=50 ms 48

Figure 4.11: Average Throughput for UEs Ranging from 5 to 20 in TTI=50 ms 48

LIST OF ABBREVIATIONS

3GPP	Third-Generation Partnership Project group
4G	Fourth-Generation
AMC	Adaptive Modulation and Coding
BCQI	Best Channel Quality Indicator
BE	Best Effort
BER	Bit Error Rate
BET	Blind Equal Throughput
BLER	Block Error Rate
BS	Base Station
CDF	Cumulative Distribution Function
CLSM	Close Loop Spatial Multiplexing
CoA	Center of Area
CQI	Chanel Quality Indicator
CSI	Channel State Information
DL	Downlink
DS	Delay Sensitive
ECDF	Empirical Cumulative Distribution Function
ENB	Evolved-Node B
EPC	Evolved Packet Core
E-UTRAN	Evolved-Universal Terrestrial Radio Access Network
FDD	Frequency-Division Duplex
FIS	Fuzzy Inference System
FPD	Fuzzy-based Priority Determination

FTP	File Transfer Protocol
GBR	Guaranteed Bit rate
HOL	Head of Line
HSPA	High Speed Packet Access
HTTP	Hypertext Transfer Protocol
IPF	Intelligent Proportional Fair
IPRA	Intelligent Priority-Based Resource allocation
ISI	Inter-Symbol Interference
JFI	Jain Fairness Index
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MME	Mobility Management Entity
MS	Mobile Station
Non-GBR	Non-Guaranteed Bit rate
Non-RT	Non-Real Time
OFDMA	Orthogonal Frequency-Division Multiple Access
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PF	Proportional Fair
PFS	Proportional Fair Sun
PGW	Packet data network Gateway
PLR	Packet Loss Rate
PMI	Precoding Matrix Indicator
QCI	Quality of Service Class Identifier
QFI	QoS Fulfilment Information

QoS	Quality of Service
RA	Resource Allocation
RAN	Radio Access Network
RB	Resource Block
RE	Resource Elements
RI	Rank Indicator
RR	Round Robin
RRA	Radio Resource Allocation
RRM	Radio Resource Management
RS	Rate Sensitive
RS	Reference Signal
RT	Real Time
SGW	Serving-Gateway
SINR	Signal Interference plus Noise Ratio
SNR	Signal to Noise Ratio
TDD	Time-Division Duplex
TDMA	Time-Division Multiple Access
TTI	Time Transmission Interval
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System
VoIP	Voice over IP

Chapter 1

INTRODUCTION

As the number of mobile users is developing rapidly, next generation wireless cellular networks are anticipated to provide worldwide bandwidth access to satisfy end-users' needs. The growing requests for various communication services (real-time, non-real-time or best-effort) with existing delay and bandwidth constraints cause many problems in the current generation wireless cellular networks.

LTE, Long Term Evolution phenomenon is a significant approach in stepping toward Fourth-Generation (4G) wireless communication, which was standardized by the Third-Generation Partnership Project group (3GPP) with the aim to increase data transmission rate up to 100(50) Mbps for Downlink (Uplink) direction transmission and it is capable of operating on different bands of a spectrum ranging from 1.4 MHz to 20 MHz, for both paired and unpaired bands. It boosts the system performance 50 times better and enhances the speed 10 times faster than the 3G cellular network.

Traditional radio resource allocation designs are built on either CSI (Channel Status Information) for increasing throughput [1], or QFI (QoS (Quality of Service) Fulfilment Information) for guaranteeing QoS [2], [3]. The CSI value is computed by each Mobile Station (MS) and it is fed back to the Base Station (BS) through a feedback channel. The QFI value informs about QoS requirements of each kind of communication service. Utility-Based scheduling strategies try to exploit both CSI and

QFI in order to enhance the whole system utility function [4], [5]. However, it is a total challenge to strike a balance between CSI and QFI for a user with various service needs. To satisfy QoS requirements, the QFI (CSI) must overcome the CSI (QFI) if the user is an urgent (non-urgent) user. On the other side, differentiating the weight between throughput, fairness and QoS is a difficult design consideration in LTE cellular network so that increasing one of these factors may sacrifice and violate the other one.

Several LTE scheduling strategies have been introduced in literature and each scheduler follows a different discipline for Resource Allocation (RA). Proportional Fair (PF) algorithm is a well-known scheduling strategy that allots radio resources in a fair manner with respect to user's data rate and past average throughput. However, this strategy can just approximate the channel quality condition since it isn't aware of user QoS requirements and it does not consider some scheduling input parameters such as buffer state, maximum packet delay, maximum Packet Loss Rate (PLR) and service type [6].

1.1 Thesis Objectives and Goals

In this thesis, we fine-tune PF algorithm and make it capable of targeting user's prioritization to improve LTE Downlink (DL) scheduling performance in terms of throughput and fairness. We proposed an Intelligent Proportional Fair (IPF) strategy for active users with five different types of traffic like VoIP (Voice over IP), video, gaming, HTTP (Hypertext Transfer Protocol), and FTP (File Transfer Protocol). The IPF intelligently calculates the precedence of end-users by applying Fuzzy Inference System (FIS) [7]. The IPF is a Fuzzy Logic Based Scheduler (FLBS) which dedicated radio resources to active users according to the channel information and the user information.

Although it is hard to keep the balance between CSI and QFI by mathematical functions, the FIS makes it much easier to deal with these kinds of scenarios. The IPF scheme with FIS can smartly specifies priority of each user depending on its CSI and QFI values. The objectives of a newly designed scheduler are to boost system's fairness as well as satisfying the users' QoS requirements and maintaining the throughput delivered by PF scheduler as high as possible.

1.2 Organization of the Thesis

The thesis outline is organized around five sections as follows;

- In Chapter 2, the background related to LTE system architecture and radio resources is introduced followed by an explanation of the radio bearer, spectrum bandwidth, and frame structure. This chapter also gives information about service classification and at last discuses about some well-known resource allocation strategies applied in LTE wireless network.
- In Chapter 3, the details of model methodology related to resource allocation and scheduling are presented. Then Vienna LTE simulator structure is explained. The configuration details of IPRA are introduced followed by fuzzy-based priority determination and the Intelligent Proportional Fair that will be used for users' prioritization is presented at the end of this chapter.
- In Chapter 4, the simulation parameters are defined and the results are presented. The implementation of two algorithms i.e. the PF scheduling algorithm and the Intelligent PF algorithm is shown and at the end part the analysis of Intelligent PF algorithm is followed with its comparison to the conventional PF scheduler.

- In Chapter 5, the main simulation conclusions of the thesis are summarized and topic for future work has been proposed.

Chapter 2

BACKGROUND AND THEORETICAL INFORMATION

2.1 General Overview of LTE Network

LTE suggests several important achievements over last technologies like UMTS (Universal Mobile Telecommunications System) and HSPA (High Speed Packet Access) by modifying physical layer and core network in order to provide higher spectrum efficiency, lower latency (delay), energy consumption reduction, flexible bandwidth deployments and high speed data transmission with seamless mobility for mobile users [8].

Simultaneous optimization of the throughput, fairness and QoS is one of the challenging issues in an LTE cellular network so that each scheduling algorithm makes a different trade-off among these objectives. For example, scheduling algorithms aiming to have an improved throughput are not fair enough to the users who are far away from the base station or have unfavorable channel conditions (such as cell-edge users). Plus, scheduling strategies that try to keep fairness among UEs are not efficient enough in terms of system throughput.

The scheduler located at the base station (known as Evolved node B) follows particular scheduling policies to broadcast radio resources (time, frequency) among attached users who apply for transmission in the cell area. Each scheduler tries to strike a balance between throughput maximization and the fairness guarantee while each end-user`s Quality of Service (QoS) needs is satisfied.

2.2 LTE System Architecture

LTE system architecture is developed with goal to support packet switched traffic flow with seamless mobility and better QoS. LTE system has a flat network architecture which is composed of two parts: a core network known as the Evolved Packet Core (EPC) and a Radio Access Network (RAN) known as the Evolved-Universal Terrestrial Radio Access Network (E-UTRAN); Figure 2.1 presents the LTE system architecture and its main components [6].

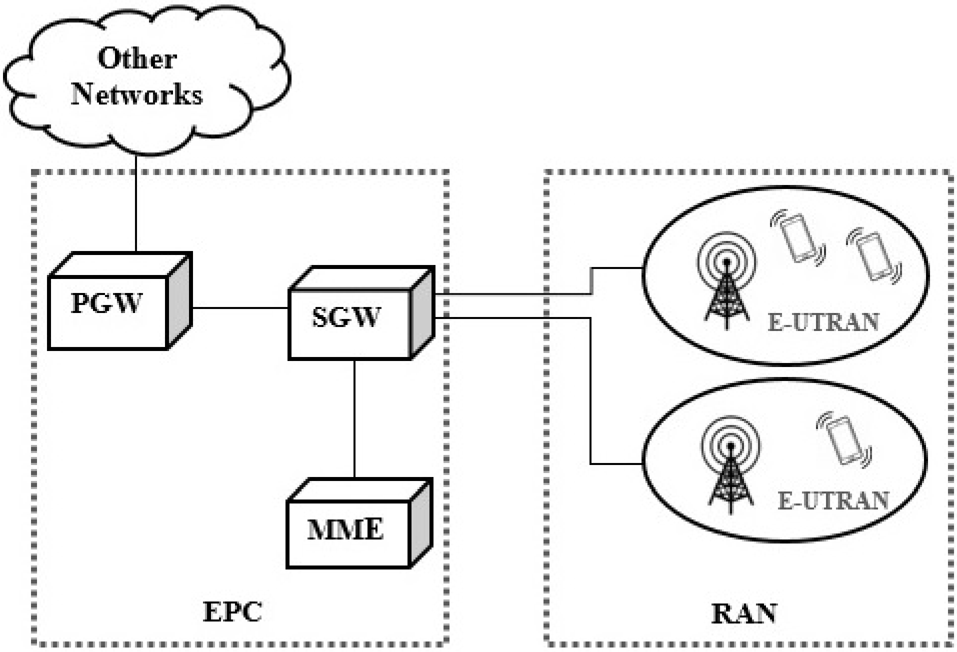


Figure 2.1: Simplified Model of LTE System Architecture [6]

The EPC has three essential components, namely the MME (Mobility Management Entity), the SGW (Serving-Gateway) and the PGW (Packet data network Gateway). The main functionalities of MME are user mobility, hand-off, and recording and paging process of users. SGW is mainly responsible for routing and forwarding user data packets and hand-over management. The major role of PGW is providing connection between LTE core network and other external networks.

The LTE radio access network can support two types of nodes: a Base Station (BS) known as eNB (Evolved-Node B) which is the only entity in charge of performing Radio Resource Management (RRM) processes and a Mobile station (MS) known as UE (User Equipment) that is end-user serviced by eNB.

2.3 LTE Radio Resource Structure

The radio access technology applied to LTE downlink system is built on Orthogonal Frequency-Division Multiple Access (OFDMA) which enables multiuser diversity and tries to prevent Inter-Symbol Interference (ISI) for broadband wireless cellular networks.

In particular, OFDMA is based on basic OFDM, which consolidates TDMA (Time-Division Multiple Access) and FDMA techniques. Differently from OFDM, that just one UE can transmit on total bandwidths at any given time interval, OFDMA technique permits several UEs to transmit simultaneously which results in better spectrum efficiency. In each time interval, OFDMA allots a fraction of system bandwidth to each UE, so several mobile users are authorized for data transmission at the same time and it is expected to support several multimedia applications and web services even in high mobility scenarios [9].

Radio Resource Allocation (RRA) mechanism is the process of distributing appropriate time and frequency by following some specific disciplines and policies among the UEs with various traffic streams. The radio resources are allotted into time and frequency region and distributed among UEs with different class of service (see Figure 2.2).

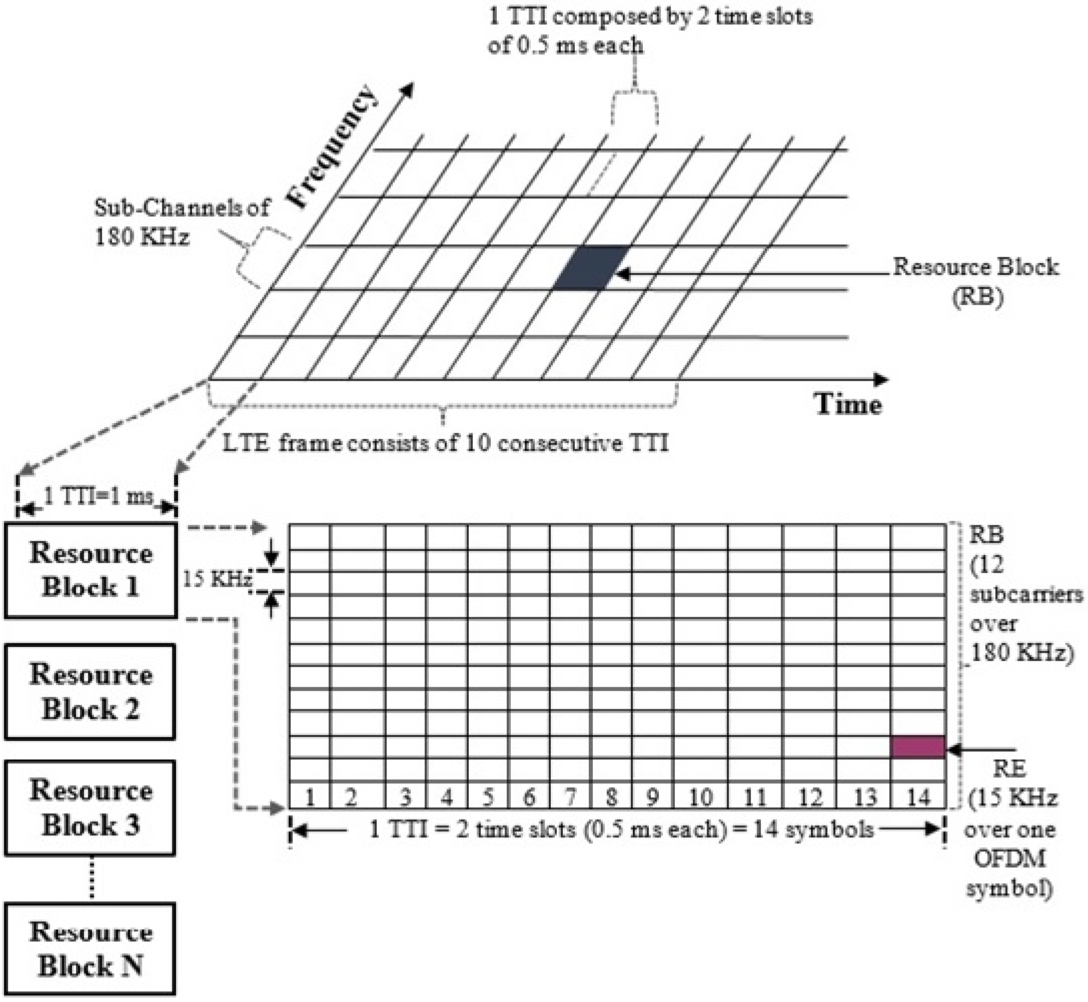


Figure 2.2: Radio Resources Grid with Related RBs and REs [6, 9]

In time region, the time is separated into frames of 10ms, each with 10 sub-frames known as TTI (Time Transmission Interval) which last for a period of 1 ms and each TTI is split into two slots of 0.5 ms ,each with 7 (6) OFDM symbols.

On the other side, in the frequency region, the whole bandwidth spectrum is composed of sub-channels of 180 KHz, each with 12 consecutive same size subcarriers of 15 KHz (12×15 = 180). The smallest entity of LTE radio resources is RB (Resource

Block) which spans over two time slots (1 ms) in time area and one sub-channel (180 KHz) in the frequency area. The RB is the smallest amount of radio resource that can be allotted to a UE for data transmission and each RB comprises 168 (144) Resource Elements (RE) for 7(6) OFDM symbols.

Note that, in each TTI, control message employs some specific OFDM symbols for exchanging control message, for example, as it is pictured in Figure 2.3, in the 3 MHz bandwidth case, in each TTI, 3 OFDM symbols are assigned for control message transmission and 11 OFDM symbols are assigned for data transmission.

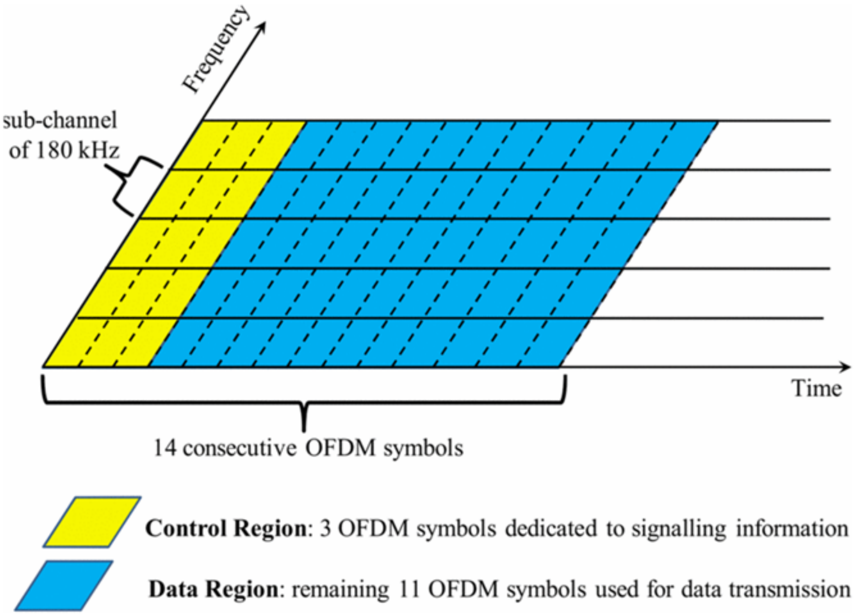
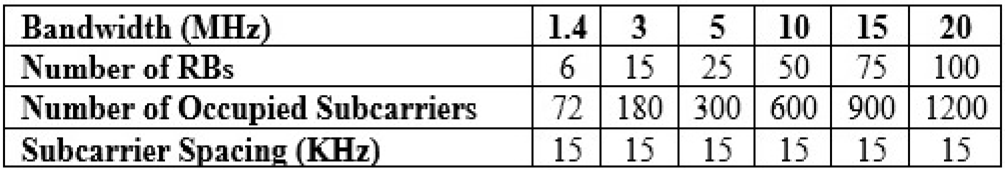


Figure 2.3: Time and Frequency Structure of LTE Downlink Sub-frame [6]

2.3.1 LTE Spectrum Bandwidth

LTE is enabled of provisioning different spectrum bandwidth ranging from 1.4 to 20 MHz; each comprises a different number of Resource Blocks ranging from 6 to 100 respectively. Table 2.1 reveals to us the operation bandwidths and their specification and as we can see, since the sub-channel size is stable the number of RBs just depending on the system total bandwidth.

Table 2.1: Operation bandwidths and their specification [10]

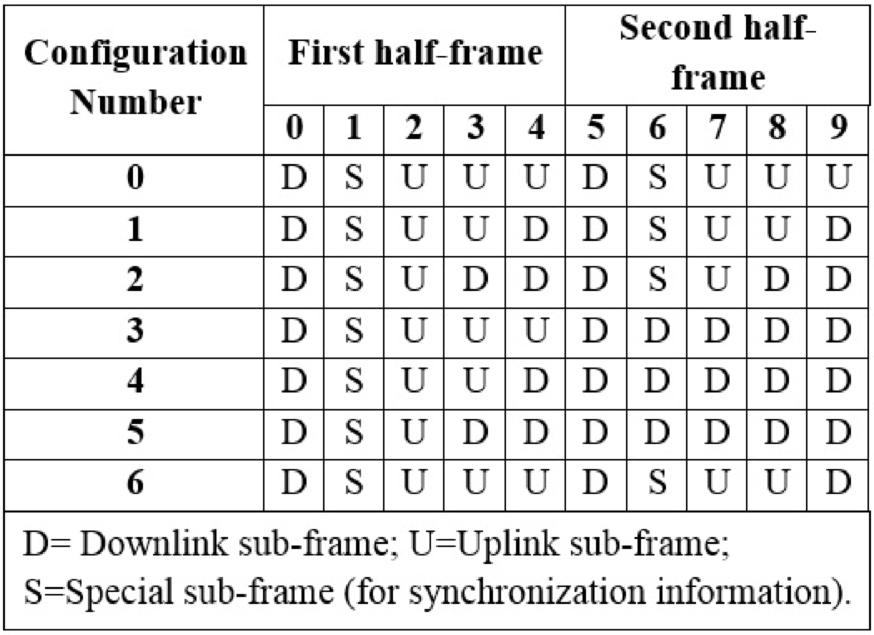


Bandwidth (MHz)	**1.4**	**3**	**5**	**10**	**15**	**20**
Number of RBs	6	15	25	50	75	100
Number of Occupied Subcarriers	72	180	300	600	900	1200
Subcarrier Spacing (KHz)	15	15	15	15	15	15

2.3.2 LTE Frame Structure

The LTE system employs two kinds of frame structure, known as Frequency-Division Duplex (FDD) and Time-Division Duplex (TDD) mode. In particular, in FDD mode, the entire bandwidth is separated into two parts which permit for synchronous Downlink (DL) and Uplink (UL) data transmission. Under TDD mode, the frame (10 ms) is split into two parts (two half-frames) which last for a period of 0.5 ms and the unbalanced amount of radio resources are assigned by RRM for DL and UL data transmission (see Table 2.2) [11].

Table 2.2: TDD frame-structure format [9]



Configuration Number	**First half-frame**					**Second half-frame**				
	0	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**
0	D	S	U	U	U	D	S	U	U	U
1	D	S	U	U	D	D	S	U	U	D
2	D	S	U	D	D	D	S	U	D	D
3	D	S	U	U	U	D	D	D	D	D
4	D	S	U	U	D	D	D	D	D	D
5	D	S	U	D	D	D	D	D	D	D
6	D	S	U	U	U	D	S	U	U	D

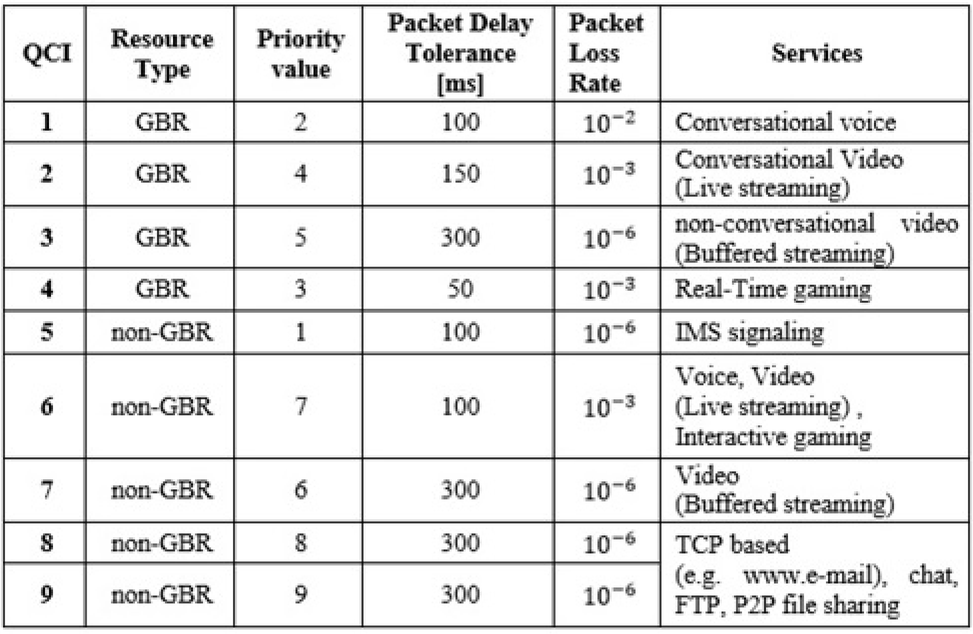
D= Downlink sub-frame; U=Uplink sub-frame;
S=Special sub-frame (for synchronization information).

2.4 LTE Radio Bearer

A radio bearer is a logical channel between two end-points (UE and eNB) and it has two kinds, namely default bearer and dedicated bearer. When a UE connects to the wireless network for the first time, a default bearer is assigned to it in order to exchange control message and connection establishment and remains until the end of connection duration. On the other side, dedicated bearers are allotted to UE for transmitting traffic messages and depending on QoS needs, are classified into two types known as GBR (Guaranteed Bit rate) bearers and non-GBR (non-Guaranteed Bit rate) bearers [12].

Based on service types, a class of QoS is assigned for both GBR and non-GBR, so it makes it possible to distinguish between traffic flows. The 3GPP group has standardized QoS features into 9 QCI (QoS Class Identifier) classes and each is defined by its resource type, a priority value, packet delay tolerance and packet loss rate (see Table 2.3).

Table 2.3: QCI and its specification [13]



QCI	Resource Type	Priority value	Packet Delay Tolerance [ms]	Packet Loss Rate	Services
1	GBR	2	100	10^{-2}	Conversational voice
2	GBR	4	150	10^{-3}	Conversational Video (Live streaming)
3	GBR	5	300	10^{-6}	non-conversational video (Buffered streaming)
4	GBR	3	50	10^{-3}	Real-Time gaming
5	non-GBR	1	100	10^{-6}	IMS signaling
6	non-GBR	7	100	10^{-3}	Voice, Video (Live streaming) , Interactive gaming
7	non-GBR	6	300	10^{-6}	Video (Buffered streaming)
8	non-GBR	8	300	10^{-6}	TCP based (e.g. www.e-mail), chat, FTP, P2P file sharing
9	non-GBR	9	300	10^{-6}	

2.5 Scheduling in LTE System

Scheduling is one of the important procedures of LTE system that allots available resources (Time, Frequency) to the active UEs due to satisfy their objectives. In each TTI, the eNB transmits the RS (Reference Signal) to all UEs in the cell region and then it is decoded by active UEs. Afterward, each UE measures the SNR (Signal to Noise Ratio) value of received RS and maps it onto CQI (Chanel Quality Indicator) values.

Figure 2.4 indicates a clear representation of the SNR to CQI mapping; depending on SNR values, CQI values can be determined (ranging from 0 to 15). Note that SNR and CQI change in the same manner; as the SNR value increases, the CQI value increases.

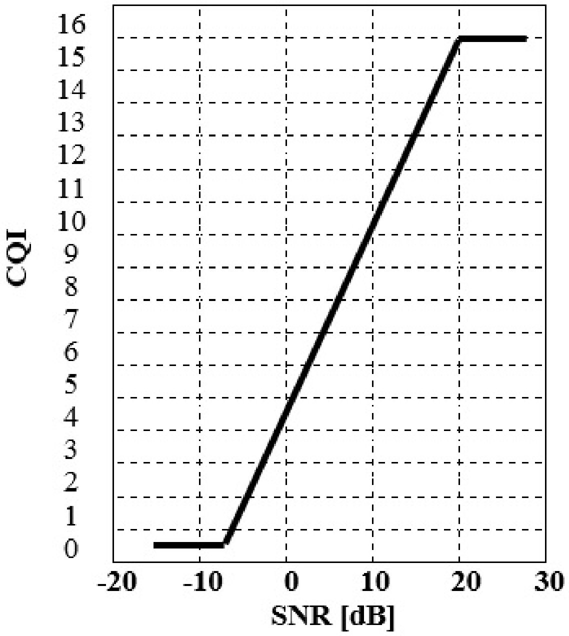
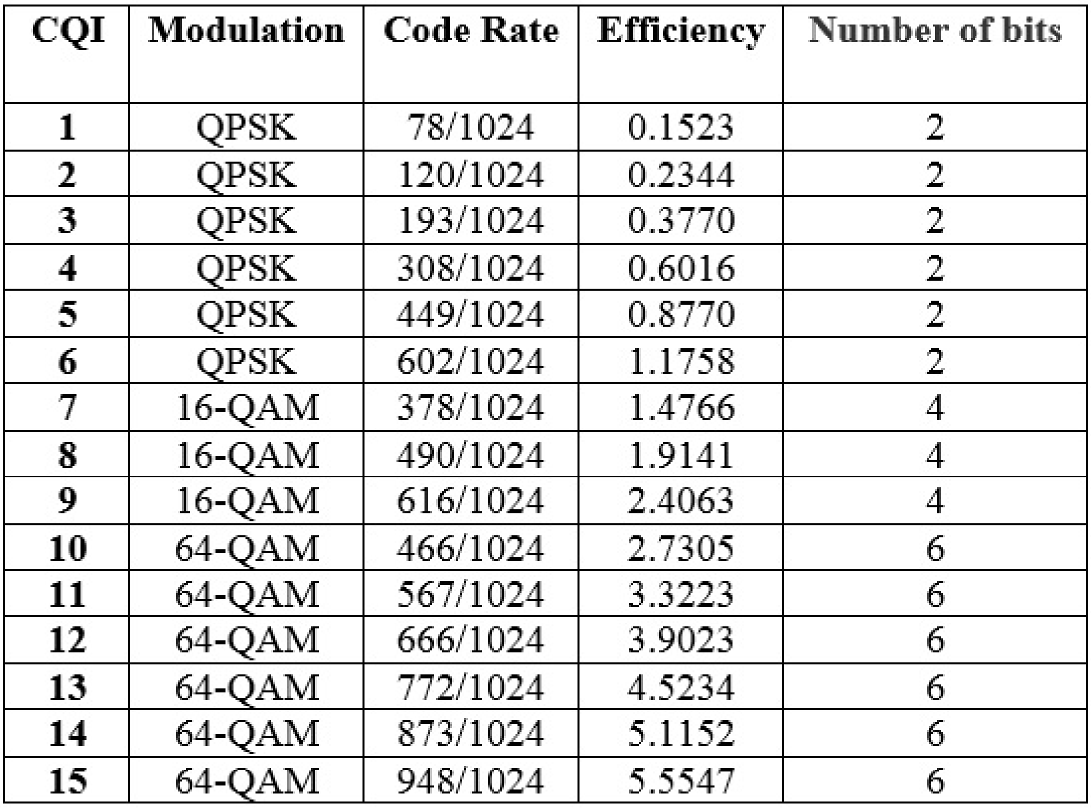


Figure 2.4: SNR to CQI Mapping [14]

Table 2.4: CQI and Modulation [15]



CQI	Modulation	Code Rate	Efficiency	Number of bits
1	QPSK	78/1024	0.1523	2
2	QPSK	120/1024	0.2344	2
3	QPSK	193/1024	0.3770	2
4	QPSK	308/1024	0.6016	2
5	QPSK	449/1024	0.8770	2
6	QPSK	602/1024	1.1758	2
7	16-QAM	378/1024	1.4766	4
8	16-QAM	490/1024	1.9141	4
9	16-QAM	616/1024	2.4063	4
10	64-QAM	466/1024	2.7305	6
11	64-QAM	567/1024	3.3223	6
12	64-QAM	666/1024	3.9023	6
13	64-QAM	772/1024	4.5234	6
14	64-QAM	873/1024	5.1152	6
15	64-QAM	948/1024	5.5547	6

As you can observe in Table 2.4, each CQI value is defined by its modulation (QPSK or 16 QAM or 64 QAM), code rate, and efficiency. The CQI reporting permits making an estimation of channel quality condition at the eNB. As it is depicted in Figure (2.5), the eNB scheduler utilizes the CQI value and allots RBs to the active UE in the related cell. On the other side, Adaptive Modulation and Coding (AMC) chooses the proper Modulation and Coding Scheme (MCS) for data stream transmission trying to boost the throughput with the given Block Error Rate (BLER). Finally, this information is transmitted to the UEs via Physical Downlink Control Channel (PDCCH), and then each UE receives selected MCS and allocated RBs and connects to Physical Downlink Shared Channel (PDSCH) for communication. Resource Allocation (RA) scenario is repeated every 1 ms, thus LTE scheduler follow some specific policies and rules to schedule all active mobile users in the cell area every TTI.

Note that in OFDM systems, each UE can apply various MCS in such a way that all RBs dedicated to one UE must have the same MCS in any given TTI.

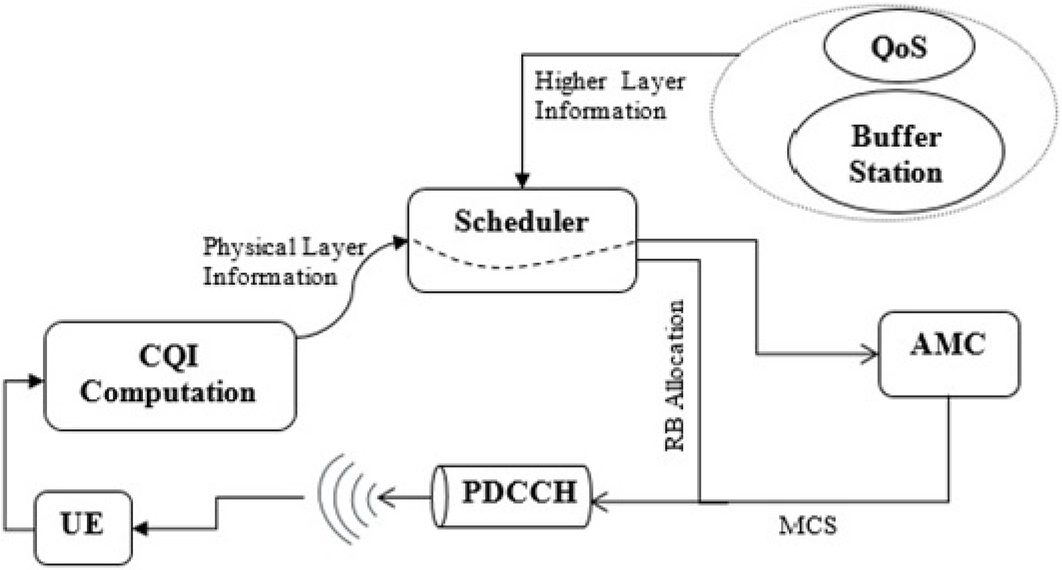


Figure 2.5: Design of eNB Scheduler [6]

2.6 Scheduling Objectives

Scheduling mechanism is the process of distributing and allocating available radio resources (Time, Frequency) to the attached UEs to boost their objectives in terms of QoS, throughput and fairness.

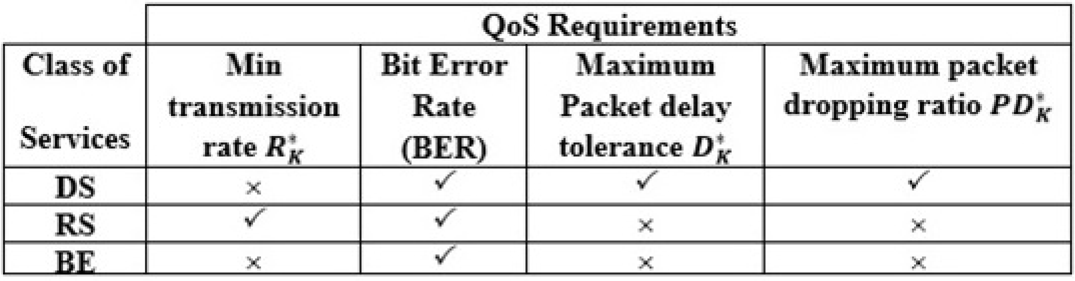
2.6.1 Service Classes with their QoS Requirements

Three types of communication services are served in LTE-A system: Real Time (RT) or Delay Sensitive (DS) such as voice, video and gaming, Non-Real Time (Non-RT) or Rate Sensitive (RS) such as HTTP, and Best Effort (BE) such as FTP which are distinguished with their QoS requirements [16].

Each UE belongs to one kind of service class and each has a different and specific QoS requirements such as the Min transmission rate (R_K^*), Bit Error Rate (BER), Maximum

Packet delay tolerance (D_K^*), and Maximum packet dropping ratio (PD_K^*) which have listed in below Table 2.5.

Table 2.5: Service classes QoS requirements



Class of Services	**QoS Requirements**			
	Min transmission rate R_K^*	**Bit Error Rate (BER)**	**Maximum Packet delay tolerance D_K^***	**Maximum packet dropping ratio PD_K^***
DS	×	✓	✓	✓
RS	✓	✓	×	×
BE	×	✓	×	×

The RT services such as VoIP, video, and online gaming is declined when the packet delay goes beyond a threshold while non-RT services such as ftp, http, and e-mail can endure more delays. Briefly note that RT packets will be discarded if packet delay is more than maximum packet delay tolerance, whereas NRT packets or BE packets are let to be in queue without being discarded if buffer capacity is not finished.

2.6.2 Throughput

In order to calculate the user overall throughput, Signal to Noise Ratio (SNR) and data rate must be defined. The received SNR of user k on the RB n at time slot t can be expressed by

$$SNR_{k,n}(t) = \frac{P_{k,n}(t) * |g_{k,n}(t)|}{N_0 * B/l} \quad (2.1)$$

Where $P_{k,n}(t)$ is the allocated power, $g_{k,n}(t)$ is the channel gain and N_0 is the total noise. The frequency bandwidth B is divided into l subcarrier, each with a bandwidth of $\Delta f = B/M$. Then the instant data rate of the user k on RB n at slot t can represented by following

$$r_{k,n}(t) = log_2\left(1 + \frac{SNR_{k,n}(t)}{\tau}\right) \quad (2.2)$$

Where $\tau = \ln(5\ BER)\ /1.5$, usually called SNR gap. Afterward the overall throughput of user *k* at slot *t* can be expressed as follow

$$R_k(t) = \sum_{n=1}^{N} x_{k,n}(t) * r_{k,n}(t) \tag{2.3}$$

Where $x_{k,n}(t)$ is the assignment indicator variable for the *k* user and the subcarrier *n*. That is $x_{k,n}(t) = 1$ when the RB is assigned to the user *k*, while $x_{k,n}(t) = 0$ otherwise. Note that the throughput reduces as the number of UEs goes up since the same amount of radio resources are shared between more numbers of UEs in the same geographic area.

2.6.3 Fairness

Fairness means to distribute resources fairly among all UEs in the cell and assure user minimum performance, especially cell edge users that experience bad channel conditions. Providing and improving fairness may give up the system throughput and/or contaminate the QoS requirements, so one of the important system design considerations of radio resource allocation strategy is trade-off between throughput enhancement, fairness improvement with quality of service guarantee that is a challenging and interesting issue and a blind maximization of one of them can have negative effects on the other one. The system fairness can be expressed as follow

$$JFI = \frac{\left(\sum_{k=1}^{K} R_k\right)^2}{K\ \sum_{k=1}^{K} (R_k)^2} \tag{2.4}$$

Where R_k denotes the k-th user throughput, K is total number of UE and JFI is Jain Fairness Index [17]. Note that one approach to indicate the fairness performance is to consider the Cumulative Distribution Function (CDF) of an average data rate of the UEs in the system.

2.7 Overview on LTE Resource Allocation Strategies

Resource sharing methods are mostly built on the trade-off between computational intricacy and optimal decision making. However using complicated and non-linear optimization problem can encounter us to a complicated and exhaustive search which causes high computational complexity and time wasting. Radio resources must be dedicated to the UEs according to their requirements and priority in such a way that improves the system performance.

According to [6] Resource allocation strategy is generally based on RB metrics for each active UE, so that the n-th RB is allotted to k-th UE if it's metric $m_{k,n}$ is the largest one ($m_{k,n} = max_i \{m_{k,n}\}$). The $m_{k,n}$ value indicates the precedence of each attached UE on a particular RB which is computed based on status of transmission queues, channel quality, resource allocation history, buffer state and QoS needs. Plus there is linear problem between the number of active UEs (K) and number of available RBs (N) that is computed by scheduler in every TTI; it is expressed as follow

$$M = K \cdot N \qquad (2.5)$$

By using metric (M), system complexity reduces since each RB is independent of other RBs and also ensures scalability because of linear dependent of the number of UEs and RBs.

Providing high data rate in spite of a limited bandwidth with a low delay is a challenging problem especially in multiuser and high mobility scheduling scenarios. A practical scheduler must try to strike a balance between throughput maximization and fairness while satisfying QoS needs for all the attached UEs in the cell area. There are three well-known and basic RA strategies in the LTE downlink cellular network, known as Round Robin (RR), Best CQI (BCQI) and Proportional Fair (PF) that is introduced in the following sections [6].

2.7.1 Round Robin (RR)

Round Robin (RR) is a channel-unaware RA strategy which assigns the RBs in equal TTI and sequential manner in turns (cyclically). Plus, RR doesn`t take channel state condition into account and completely ignores the UE feedback; its metric can be calculated from the following formula as

$$M_{k,n}^{RR} = t - t_k \tag{2.6}$$

Where t value refers to the current time and t_k is the last time when k-th UE was serviced. Although the RR scheduler approach achieves a very high fairness performance (~100%) since dedicates the same amount of resources to each UE, results in poor and unequal throughput in order to not consider CQI feedback.

2.7.2 Best CQI (BCQI)

Best CQI (BCQI) or Maximum Throughput (MT) is a channel-aware and QoS-unaware RA strategy that gives RBs to the UEs with the best channel conditions in order to maximize the throughput; its metric can be shown as

$$M_{k,n}^{BCQI} = r_{k.n}(t) \tag{2.7}$$

Where $r_{k.n}(t)$ refers to the instance data-rate for the k-th UE in the time t on the n-th RB. In this scenario, the UE with higher data rate will be served sooner and has a higher priority compare with a UE with lower data rate due to poor channel condition such as cell edge users. Hence under BCQI scheme, UEs on the boundary of hexagonal cell or having a bad channel quality conditions may not be served. In fact, in this approach, cell edge users may suffer from lack of service and starvation. The BCQI scheduler completely sacrifices fairness in order to boost system throughput. However, in this scenario, one UE may get the chance of completely using the total bandwidth during certain TTI if its data transmission rate is comparatively higher than the others and the other UEs starve [10].

2.7.3 Blind Equal Throughput (BET)

Blind Equal Throughput (BET) is a channel-unaware RA approach which just considered the past average throughput of each UE ($T_{k,n}(t)$) and utilizes it as a metric; its metric can be presented as

$$M_{k.n}^{BET} = \frac{1}{T_{k,n}(t)} \tag{2.8}$$

In fact, the UEs with the lower past average throughput (such as cell edge users) have higher priority and will be served sooner. Thus, BET allocation strategy keeps fairness but the throughput will decrease.

2.7.4 Proportional Fair (PF)

The PF scheduler aims to strike the balance between fairness and system throughput by combining BCQI and BET metrics [16]; it can be expressed as

$$M_{k,n}^{PF} = M_{k,n}^{BCQI} \cdot M_{k,n}^{BET} = \frac{r_{k,n}(t)}{T_{k,n}(t)} \tag{2.9}$$

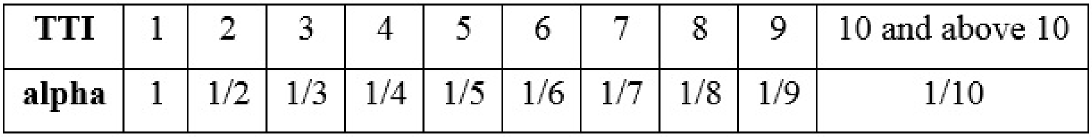
Where $r_{k,n}(t)$ is instance data-rate and as in [18], $T_{k,n}(t)$ is the past average throughput achieved by UE_k on *n*-th RB until time slot *t*; the $r_{k,n}(t)$ and $T_{k,n}(t)$ are presented as follow

$$r_{k,n}(t) = log\left[1 + SINR_{k,n}(t)\right] \tag{2.10}$$

$$T_{k,n}(t) = (1 - alpha) * T_{k,n}(t-1) + alpha * r_{k,n}(t) \tag{2.11}$$

Furthermore the alpha value from TTI=1 until TTI=10 is calculated as 1/TTI and for all TTI above 10 is equal to 0.1 [17] (see Table 2.6).

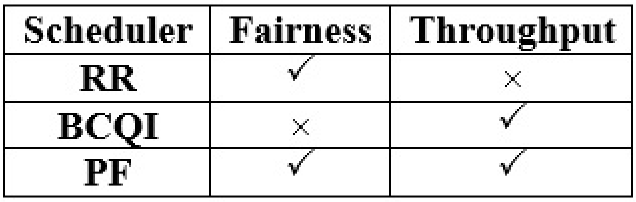
Table 2.6: Alpha value computation



TTI	1	2	3	4	5	6	7	8	9	10 and above 10
alpha	1	1/2	1/3	1/4	1/5	1/6	1/7	1/8	1/9	1/10

Briefly, the PF is a good candidate which takes both the fairness and throughput into accounts and achieves high system throughput while maintaining fairness among all UEs in the cell. Table 2.7 summarize all mentioned information for RR, BCQI and PF in terms of system fairness and throughput.

Table 2.7: RR, MT, and PF Fairness and Throughput



Scheduler	**Fairness**	**Throughput**
RR	✓	×
BCQI	×	✓
PF	✓	✓

Many RA strategies have been proposed in literature to deploy RR, BCQI, and PF algorithms. However these three schedulers don’t take QoS and traffic type into consideration.

Paper [11] introduces a reduced-complexity PF scheduling algorithm known as PFS (Proportional Fair Sun) which can be implemented almost as well as the PF scheduling algorithm while it suggests an important computational benefit; its metric expressed as follow

$$m_{k,n}^{PFS} = arg\,\underset{\text{k,n}}{max}\left[\frac{r_{k,n}}{(t_c-1)\,T_k+\sum_{n=1}^{N} x_{k,n} r_{k,n}}\right] \tag{2.12}$$

Where T_k is the user past average throughput, $r_{k,n}$ is the instant data rate of user k on RB n, t_c is average window size and $x_{k,n}$ is assignment indicator variable. That is $x_{k,n} = 0$, if RB n is not allotted to the UE_k , and $x_{k,n} = 1$ if RB n is allocated to the UE_k. This scheme prepares near optimal solutions with lower computational complexity compared with PF scheduler and they have similar performance.

Paper [20] introduces a new scheduling algorithm which considers requested data rate as feedback without mapping this value to CQI value. The requested data rate is computed in UEs and transmit as feedback value to eNB every TTI, then eNB receives as a matrix with dimension of the number of UEs multiply by RB grid size (N-UE * RB-S). This novel algorithm finds the highest requested data rate in matrix and allocates RB to the user with the highest $\frac{r_{k,n}(t)}{T_{k,n}(t)}$ value. However, this scheme enhances system complexity, it increases throughput with a little decrease in system fairness compared to the PF scheduler.

The traditional scheduling schemes which are only based on the queue`s priority without considering other criteria would not be efficient enough over resource apportion process [21]. In response to this challenging problem, many resource allocation strategies proposed to prioritize users based on their characteristics.

In [22], the UEs are grouped into two classes, namely priority UEs and non-priority UEs. In this scenario, the RBs are assigned to the priority UEs first and afterward the remaining RBs are allotted to the non-priority (or without priority) UEs. In addition, this scheme considers the minimum data rate requirement of each UE such that it prevents wastage on any UEs by preparing very high transmission rate than their needs. High data rate UEs are serviced first and they are satisfied with less number of RBs since they just need RB with high CQIs; so RBs aren`t wasted in a way to satisfy many UEs especially the high-priority ones.

Paper [19] adds a priority level to proportional fair scheduler, by considering QCI value; new PF metric is changed as follow

$$M_{k,n}^{PF} = M_{k,n}^{MT} \cdot M_{k,n}^{BET} = \alpha_{QCI} * \frac{r_{k,n}(t)}{T_{k,n}(t)} \tag{2.13}$$

In this scheme, users are classified into two groups with two QCI value, $QCI_1$and QCI_2; the user with QCI_1 have higher priority (higher α_{QCI} value) compared with the user with QCI_2. Although it promotes proportional fair algorithm by providing priority access, it doesn't take into account user feedback and channel quality conditions. Also, this scheme doesn't provide a smart way to differentiate high-priority UEs from low-priority UEs.

There are many schedulers that protect diversified communication services at the same time [16]. But most of these schedulers assign higher precedence to RT services unconditionally, so when the RT traffic flow is heavy, non-RT services will not be served for a long period of time. To satisfy non-RT users' QoS needs, the scheduler introduced in [3] assigns higher transmission priority to RT and non-RT services under the indispensable condition and BE users always have lower precedence. It determines urgent-factor for both RT and non-RT users and afterwards dedicates higher priority to the users whose factor are greater than the threshold. The scheduler first allots resources to high priority UEs in a way that minimizes the radio usage and then the residual resource is assigned to low-priority UEs such that the throughput is improved. However, this scenario cannot give clear separation of the RT service from non-RT service and RT users may be serviced after the non-RT users in heavy load traffic.

The scheduling algorithm is [23] dedicates high priority value to the RT service if its waiting time is near to the maximum delay tolerance , then for the non-RT service and not urgent RT service, give higher priority to the one who has a better channel quality condition and at last it schedules BE service. However, this scheduling strategy is not efficient enough, especially for the system that has different kinds of service and it also doesn’t take into account the specifications of different traffics.

Paper [24] proposed a cross-layer scheme of user scheduling which assigns radio resources based on traffic flow types and estimated CSI of UEs. This scheme applies different scheduling disciplines for different service classes; it first schedules RT service and if there are still RB has not been allotted, it schedules non-RT service according to the transmission priority factor which is calculated from below equation (lambda is a positive constant).

$$k^* = lambda \cdot SNR_k(t) \ \cdot WaitingTime_k(t) \qquad (2.14)$$

At last, BE traffic will be scheduled according to the same procedures as non-RT service. But, it schedules UEs according to the fixed precedence of service and it maybe not satisfy rate requirement for non-RT service since most resources may be utilized by RT service.

Paper [25] proposed an algorithm which computes the average channel gain for each UE and estimates the number of RBs needed by k-th UE on n-th RB, based on the ratio of minimum transmission rate ($R_{k,n}^*$) to average channel gain ($\bar{g}_k$).The average channel gain and the number of RBs required by each UE can be calculated in equations (2.15) and (2.16), respectively.

$$\bar{g}_k = \frac{1}{N} \sum_{n=1}^{N} g_{k,n} \tag{2.15}$$

$$\text{Number of RBs needed by each UE} = \frac{r_{k,n}^{*}}{\bar{g}_k} \tag{2.16}$$

Where $g_{k,n}$ denotes the CQI of k-th UE in n-th RB, then this UE’s CQI can be presented as follow;

$$g_k = \left[g_{k,1}, g_{k,2}, \dots, g_{k,N-1}, g_{k,N}\right] \tag{2.17}$$

Afterward, the RBs are dedicated to the UEs according to their presences and UEs are sorted in decreasing order. The UE with higher average channel gain has higher priority compared to others and for the same average channel gain, the UE with a smaller transmission rate requirement has higher priority *(P*); it can be presented as follow

If $\bar{g}_k > \bar{g}_i$ then $P_k > P_i$;
If $\bar{g}_k = \bar{g}_i$ and $R_k < R_i$ then $P_k > P_i$;

On the other side, in this scenario, if one UE has been allotted the number of RBs estimated in equation 2.16, but its rate requirement cannot be guaranteed, then more RBs are dedicated to this UE until its rate need is guaranteed. Plus, if all UEs’ rate need have been guaranteed and there are RBs remaining, these RB are dedicated to the UE with the highest precedence value .This algorithm improves the throughput as well as advancement in satisfying UE’s QoS needs and considers channel sate information. However the differentiation between the types of traffic is not taken into account and it can`t still guarantee user’s QoS requirements.

Paper [26] introduced a prioritized dynamic resource allocation which is based on the number of service classes and QCI value. It first classifies the service types based on the QCI value and then it counts the number of RT and non-RT traffic flows. If the number of RT is more (less) than non-RT, it dedicates more (less) RB and bandwidth to the UE. Then it schedules the UEs by using well-known scheduler like RR, BCQI, and PF. In particular, it smartly chooses the priority of users in such a way that it dedicates more number of RBs to RT users as compared to non-RT users. Although this prioritized scheduler improves the throughput, it has a little reduction in the system fairness.

Conventional scheduling strategies are based on the user information and the channel information, but this information cannot be simultaneously used in a mathematical function to develop scheduling policies [27]. In Chapter 3 we introduced a fuzzy logic based scheduling algorithm which schedules active users based on the user information and the channel information.

Chapter 3

MODEL METHODOLOGY

3.1 The Proposed Intelligent Proportional Fair Scheme

In this section, we introduced an Intelligent Priority-Based Resource allocation (IPRA) namely Intelligent Proportional Fair (IPF) scheme for the LTE downlink system. The IPF algorithm is split into two major parts, a Fuzzy Priority Determination (FPD) scheme and a Proportional Fair (PF) scheme. The FPD is fuzzy logic based that takes Channel State Information (CSI) and QoS Fulfillment Information (QFI) into accounts in order to compute the user's precedence level [5]. The PF scheduler combines with FPD system to determine intelligently a suitable priority for each active users while considering each user's QoS requirements, traffic types, and channel condition; the details will be explained in the following parts.

3.1.1 Fuzzy-Based Priority Determination (FPD)

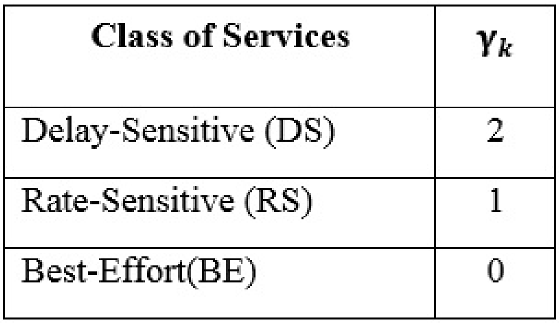
Conventionally, the user information and the channel information are applied to help the scheduler for resource allocation procedure. However, both of them cannot be simultaneously employed in a mathematical function to prepare obvious scheduling rules. By applying fuzzy logics, the scheduler can dedicate radio resource to the active users according to the user information and the channel information. The fuzzy logics is a mathematical way which imitates the thinking way of human by utilizing if-then principles.

The FPD algorithm calculates suitable transmission priority of UEs intelligently by applying Fuzzy Inference System (FIS) to boost the system performance in terms of fairness, throughput, and QoS [5], [27]. In particular, the FIS prioritizes each UE based on its CSI and QFI values. The priority of each UE can be computed as follow

$$\alpha_{k} = TI_k + \gamma_k \tag{3.1}$$

Where α_{k} denotes the UE_K priority and a UE with higher α_{k} has the higher priority value in the scheduling process. The γ_k is a constant value and it just depends on the service types (Delay Sensitive, Rate Sensitive, and Best Effort) which are presented in the Table 3.1.

Table 3.1: Gama value for different class of services



Class of Services	$\boldsymbol{\gamma_k}$
Delay-Sensitive (DS)	2
Rate-Sensitive (RS)	1
Best-Effort(BE)	0

As you can observe in Table 3.1, the DS and RS services have higher priority than BE service, hence delay-tolerance and rate-tolerance UEs can give their opportunity to the UEs who are more urgent.

By using FIS, TI_K which is the output parameter of fuzzy system can be calculated. The values CI_K and UI_K are input parameters of fuzzy system, where CI_K is the index of CSI and UI_K is the index of QFI for UE_K.

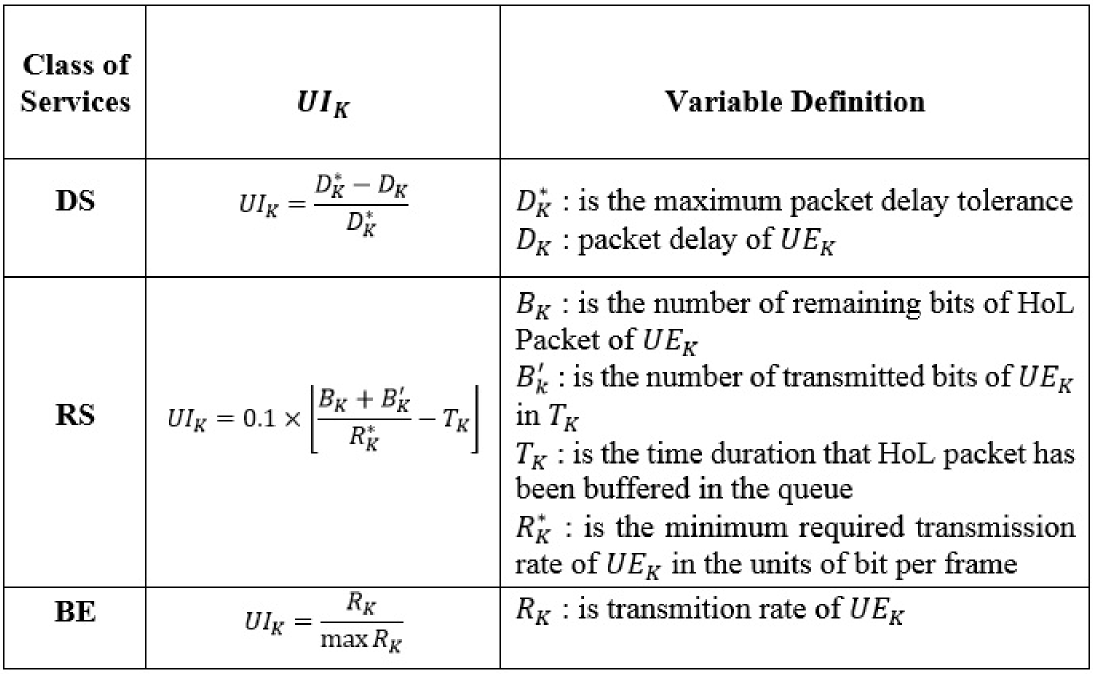
Each UE computes the channel gain ($g_{k,n}$) of each RB (from 1 to *N*) and sends it back to the eNB through a separate feedback channel. Note that, the channel gain denotes the CQI of k-th UE in n-th RB .The $\mathrm{CI_K}$ is the ratio of average channel gain ($\bar{g}$) over maximum channel gain [28] for every UE which can be calculated from formula (3.2) and the higher value of $\mathrm{CI_K}$ indicates $\mathrm{UE_K}$ has a larger throughput compare with other UEs, so higher priority value must be dedicated to it.

$$\mathrm{CI_K} = \frac{\bar{g}}{\max g} = \frac{\frac{1}{N}\sum_{n=1}^{N}\|g_{k,n}\|}{\max g} \tag{3.2}$$

On the other hand, as it is presented in following Table (3.2), $\mathrm{UI_K}$ is computed totally differently for various service classes, so you can distinguish between different traffic types. The $\mathrm{UI_K}$ shows the remaining life time of Head of Line (HoL) packet of $\mathrm{UE_K}$ in such a way that it doesn’t violate QoS needs [29] and the smaller $\mathrm{UI_K}$ indicates the higher degree of urgency of UE.

For DS service, $\mathrm{UI_K}$ is determined with respect to user’s delay requirement. For RS service $\mathrm{UI_K}$ is defined according to user’s rate requirements and user’s HOL packet must accomplish its transmission until expiration time, otherwise the rate requirement of the UE is not guaranteed. Finally for BE service, $\mathrm{UI_K}$ is determined with respect to user average data transmission rate.

Table 3.2: UIK value for different class of services [5]

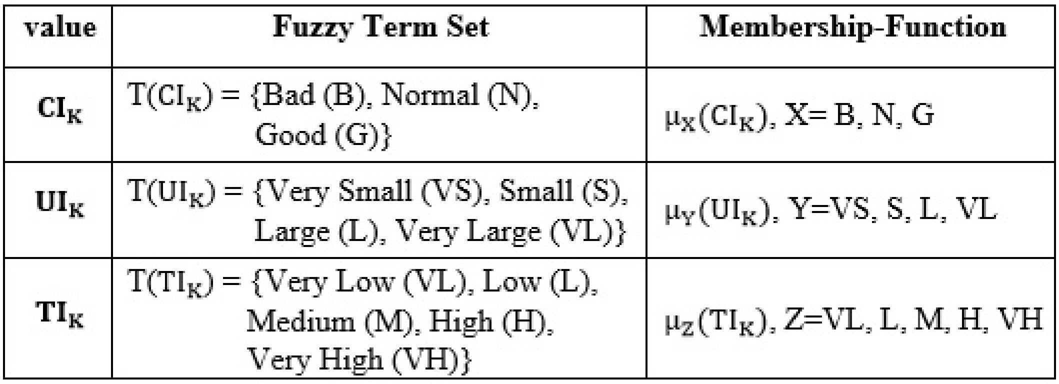


Class of Services	UI_K	**Variable Definition**
DS	$UI_K = \frac{D_K^* - D_K}{D_K^*}$	D_K^* : is the maximum packet delay tolerance D_K : packet delay of UE_K
RS	$UI_K = 0.1 \times \left\lceil \frac{B_K + B_K'}{R_K^*} - T_K \right\rceil$	B_K : is the number of remaining bits of HoL Packet of UE_K B_K' : is the number of transmitted bits of UE_K in T_K T_K : is the time duration that HoL packet has been buffered in the queue R_K^* : is the minimum required transmission rate of UE_K in the units of bit per frame
BE	$UI_K = \frac{R_K}{\max R_K}$	R_K : is transmition rate of UE_K

As mentioned, the CI_K, UI_K are the fuzzy input parameters and by defining some rules, the TI_K can be generated as fuzzy output parameter. Each parameter in fuzzy logic system has a term set which contains linguistic variables, the fuzzy term set is expressed as $T(CI_K)$, $T(UI_K)$ and $T(TI_K)$ for CI_K, UI_K, and TI_K ,respectively and they are presented with their related membership functions in Table 3.3. The fuzzy term set $T(TI)_k$ shows the priority degree of the UE_k deriving from the channel information and user information.

The CI_K ,UI_K and TI_K intervals and their related membership functions (ranging from 0 to 1) are represented in Figure 3.1. Not to mention that fuzzy partitions are selected by cut and try procedure and membership functions are determined by trial and error approach in [5],[30].

Table 3.3: Fuzzy term set and membership function [5]



value	Fuzzy Term Set	Membership-Function
CI_K	$T(CI_K)$ = {Bad (B), Normal (N), Good (G)}	$\mu_X(CI_K)$, X= B, N, G
UI_K	$T(UI_K)$ = {Very Small (VS), Small (S), Large (L), Very Large (VL)}	$\mu_Y(UI_K)$, Y=VS, S, L, VL
TI_K	$T(TI_K)$ = {Very Low (VL), Low (L), Medium (M), High (H), Very High (VH)}	$\mu_Z(TI_K)$, Z=VL, L, M, H, VH

Moreover to calculate TI_K, fuzzy rules must be defined between CI_K and UI_K variables. The k-th UE with larger CI_K has the better channel condition so higher MCS must be assigned to it in order to achieve higher throughput.

On the other hand the UE which has lower UI_K is more urgent and its priority value must be higher compared to other UEs in order to guarantee the QoS requirements. Plus for the UEs with the same UI_K, higher priority value must be given to the one with the larger CI_K (better channel condition) and also for the UEs with the same CI_K , higher priority value must be given to the one with the lower UI_K (urgent user). Therefore with respect to this information, 10 rules have defined as fuzzy logic rules and to clarify what we have said before Table 3.4 includes the fuzzy logic rules and let us see their relationship.

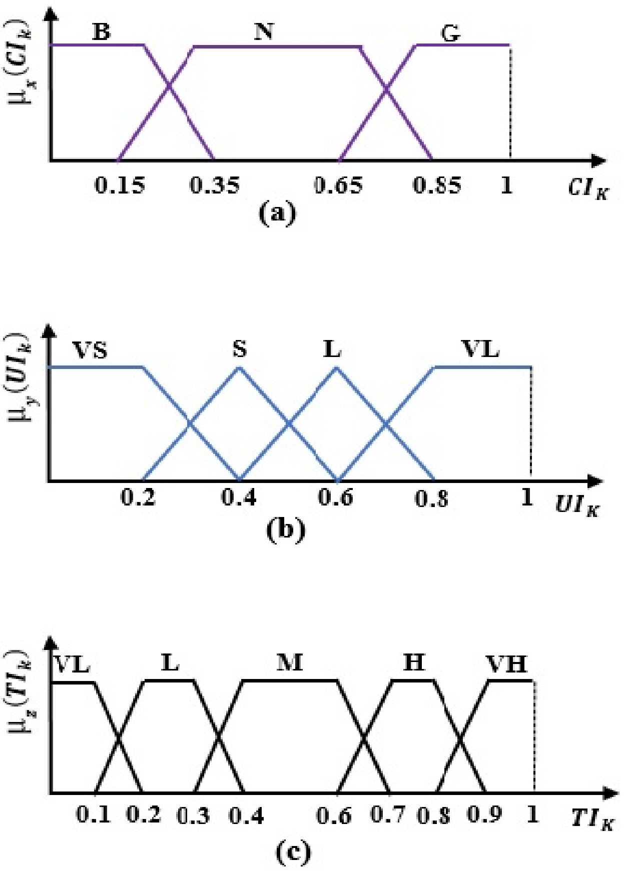


Figure 3.1: The Membership Functions (a) CI_K, (b) UI_K, and (c) TI_K [5]

Table 3.4: The fuzzy logic rules [5]

RULE	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**
CI_K	_	B	B	B	N	N	N	G	G	G
UI_K	VS	S	L	VL	S	L	VL	S	L	VL
TI_K	VH	M	L	VL	H	M	L	VH	H	M

Finally, by selecting max and min method in FIS and COA (center of area) strategy for defuzzification, the suitable priority value will be determined. Note that, in this scenario, a UE with a small priority value can be served by eNB if its channel condition is good and if other UEs with greater priority value have already been serviced, thereby improving the throughput.

3.1.2 Intelligent Proportional Fair (IPF)

So far we described in section 2.7.4, how the PF scheduler is implemented without considering many scheduling parameters such as Users' QoS requirements, types of services, and buffer state [6]. We use α_K value as an extension for PF scheduler to add priority access and considering users 'QoS requirements. The larger value of α_K indicates, the higher priority and the more degree of urgency of UE_k such that UE_k must accomplish its transmission during the time transmission interval. By combining PF and FPD, we introduce a new mechanism that is named Intelligent Proportional Fair (IPF) and new formula can be generated as follow

$$m_{k,n}^{IPF} = \alpha_K * (C \times 12 \times 7)/\, T_{k,n}(t) \tag{3.3}$$

Where α_K denotes fuzzy priority value; $C \times 12 \times 7$ represents the user instant data rate; C is the efficiency which is here in bits/channel use, 12 is the number of subcarriers in each RB and 7 is the number of symbols in each slot. The $T_{k,n}(t)$ is the past average throughput of user *k* in time slot *t*, on RB *n* which can be calculated using formula 2.11.We will use the IPF metric in log scale; it can be expressed as follow

$$metric_{k,n}^{IPF} = log_{10}\,(C \times 12 \times 7) - log_{10}(T_{k,n}(t)) + log_{10}(\alpha_k) \tag{3.4}$$

Figure 3.2 represents the design of the IPF scheduler and it shows how the scheduling algorithm works. Briefly, the FIS takes CI_K and UI_K values as fuzzy input variable and it generates TI_K as fuzzy output variable, then it is added to γ_k in order to differentiate between traffic types. Afterward, it generates the most suitable priority value α $_k$ and finally it is multiplied in the PF to produce IPF scheduler.

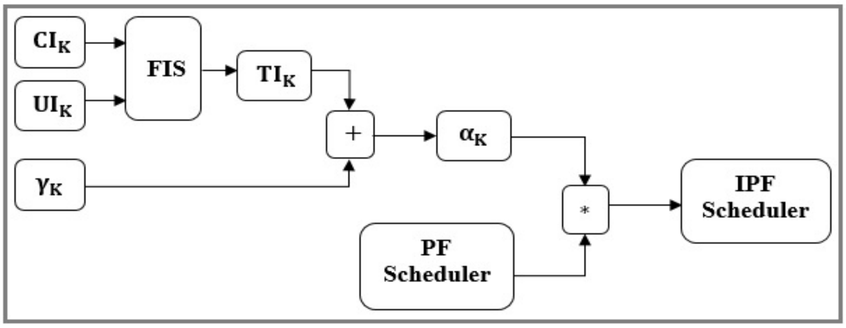


Figure 3.2: Intelligent Proportional Fair

Noticeably, Intelligent PF is designed to determine the priority value for each active UE such that the PF system fairness is boosted while each UE`s throughput is satisfied. This strategy can also maximize the system utility function, because it takes into account both CSI (channel information), and QFI (user information) for throughput improvement and QoS guaranteeing respectively.

Plus, there is linear problem between the number of active UEs (*N*) and number of available RBs (*R*) that is computed by scheduler in every TTI; it is expressed as follow:

$$M = N \cdot R \tag{3.5}$$

By using metric (*M*), system complexity reduces since each RB is independent of other RBs and also ensures scalability because of linear dependent of the number of UEs and RBs.

The intelligent PF scheduler simulation is provided in Appendix C and the following steps are taken into consideration:

Step 1: For each on allocated RB *n* and each user *k*, calculate the $\frac{\alpha_{K}*(C\times 12\times 7)}{T_{k,n}(t)}$

Step 2: Choose the pair $(k^{*}, n^{*}) = argmax_{k,n}\left(\frac{\alpha_{K}*(C\times 12\times 7)}{T_{k,n}(t)}\right)$ and allocate RB n^{*} to user k^{*}.

Step 3: Repeat step 1 and 2 until all RBs are allocated, then update $T_{k,n}(t)$ using equation 2.11.

The implementation of IPF algorithm is also depicted in figure 3.3. Where T is the simulation time in TTI and S is the number of sectors.

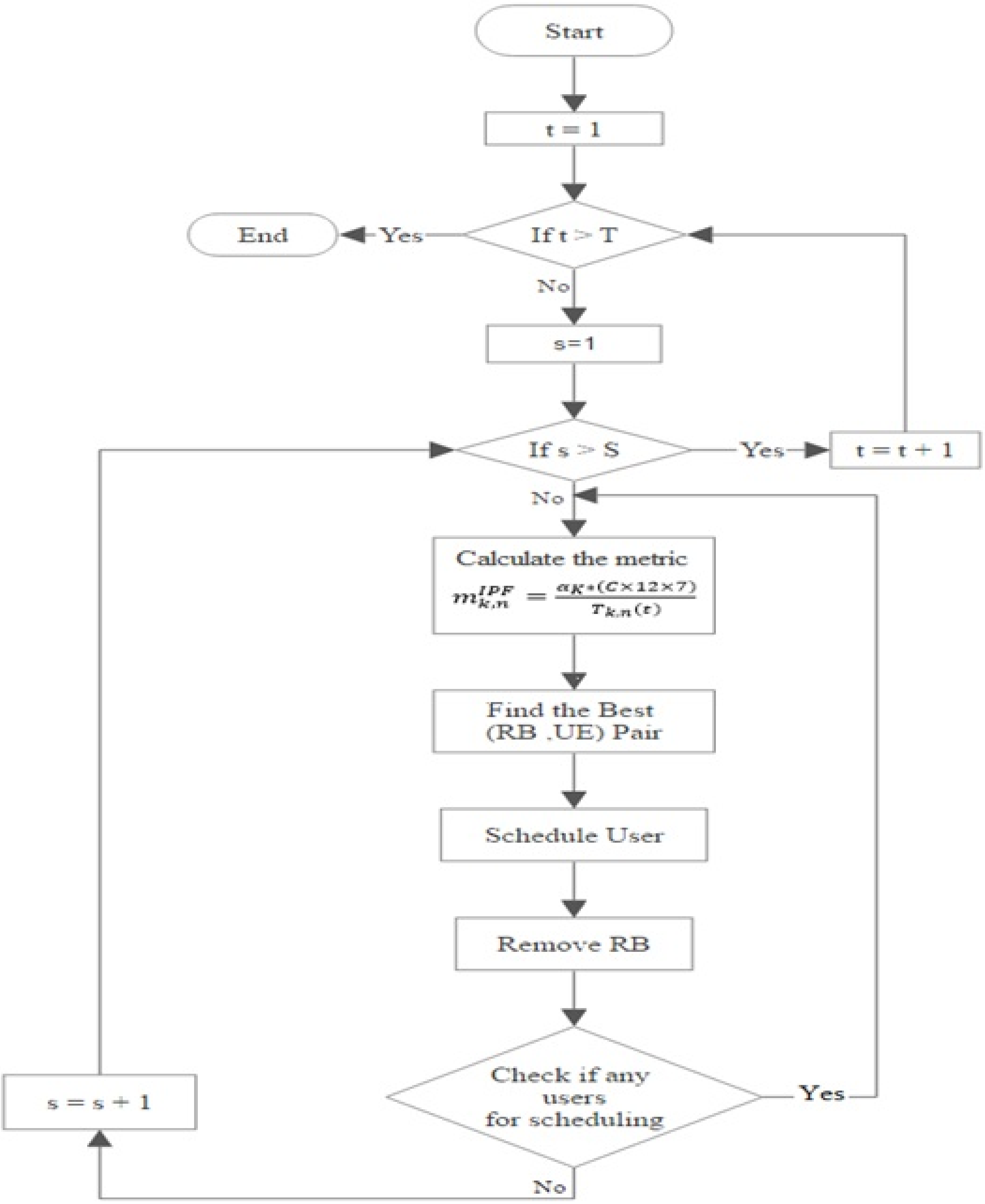


Figure 3.3: Flow chart for IPF algorithm

Chapter 4

SIMULATION SCENARIOS AND RESULTS

4.1 Simulation of LTE System

In this thesis, we employ Vienna LTE simulator [12] to design a new scheduler in the LTE downlink system environment. It is MATLAB-based simulator that enables reproducibility, evaluation of received data and the redevelopment of the LTE system architecture.

4.1.1 Vienna LTE Simulator

Vienna LTE simulator is split into two parts; LTE link-level simulation (mainly for MIMO gains, AMC feedback techniques and physical layer modeling for system-level simulation) and LTE system-level simulation (for resource allocation, cell planning, mobility management and inference handling) [14], [31].

Briefly, note that in order to decrease computational complexity, important and essential features of physical layer are abstracted in a system-level simulation. This case study is related to resource allocation and scheduling, so LTE system-level simulation is employed.

Figure 3.1 illustrates the schematic block diagram of LTE system-level simulator that includes two main parts: 1- a link-measurement model, 2- a link-performance model.

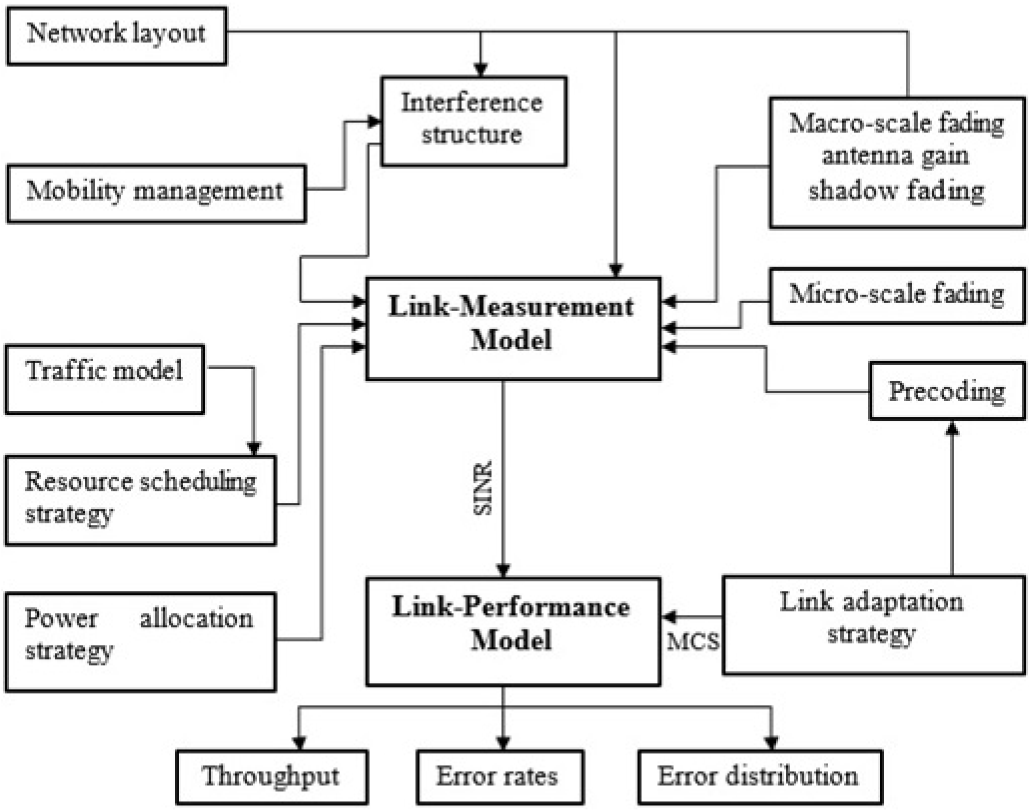


Figure 4.1: Block Diagram of LTE Downlink System Level Simulator [31]

The link-measurement model contains the link quality given by UE and it is employed for link adaptation and resource allocation strategy at eNB. The UE calculates the feedback values (PMI (Precoding Matrix Indicator), RI (Rank Indicator) and CQI based on SINR and sends it to eNB for link adaptation. Based on the feedback, the scheduler allots the radio resources to UEs to boost the efficiency of the system (in terms of throughput or fairness.

On the other side, the link-performance model specifies BLER (Block Error Rate) at receiver, based on SINR and transmission parameter such as MCS and finally, the simulator computes throughput, error rates, and error distribution as outputs.

The resource allocation strategy defined in Chapter 3 is now appraised in this Chapter through the simulation. In order to get the effect of prioritization capability on the PF scheduler, many snapshots are implemented and the obtained results are averaged. The proposed algorithm was developed in Vienna LTE system level simulator in MATLAB 2013 and the results are based on various simulation parameters presented in the following section. The comportments of two algorithms i.e. the PF scheduling algorithm and the IPF algorithm are analyzed and at the end part comparison is done between these two LTE scheduling strategies. The system fairness, average UE throughput, and average cell throughput are the metrics taken into account.

4.2 Simulation Parameters and Environments

This case study is implemented in an urban area according to standard [32]. The length of simulation time is ranging from 10 to 100 TTI and the total bandwidth is 20 MHz containing 100 RBs which is occupied 1200 subcarriers. The network layout is a regular hexagonal grid of 19 eNB located at equal distances of 500 meters [15] where each three cells are connected to one eNB, so each eNB has three equally sectors. The UEs are generated constantly over the Region of Interest (ROI). The simulation are performed for 20 UEs in each cell area that move with speed of 5 Km/h (or ~1.39 m/s). The power is distributed homogenously (equal power) and according to TS36.814, the eNB’s maximum transmit power is 46 dBm for 20 MHz bandwidth [33]. The Intelligent PF algorithm is selected as main scheduling algorithm for resource allocation in our work. The main simulation parameters with their related setting are tabulated in the Table (4.1).

Table 4.1: Simulation parameters

Parameter	**Setting**
Environment	Urban area
Network geometry	Regular hexagonal grid
Number of cells	57
Transmission mode	Close Loop Spatial Multiplexing (CLSM)
Number of transmit antennas	2
Number of receive antennas	2
Antenna pattern	$A(\theta) = -\min\left[12\left(\frac{\theta}{65^{\circ}}\right)^2, 20\ dB\right]$ $, -180 \leq \theta \leq 180$[26].
Number of eNBs	19
Distance between eNBs	500 m
Number of sectors per eNB	3
eNB's transmission power	46 dBm
System total bandwidth	20 MHz
Number of resource blocks	100
Simulation Time in TTI	10 to 100 TTI
Feedback delay	3 TTI
Number of UEs per eNB	20
UE distribution	Constant UE per cell
UE velocity	5 km/h (~1.39 m/s)
Type of scheduler	Intelligent Proportional Fair (IPF)
Average window size	25 TTI
OFDM symbols per slot	7
Block Error Rate (BLER)	10 %
Power allocation	Homogenous

4.2.1 Close Loop Spatial Multiplexing (CLSM)

Close Loop Spatial Multiplexing (CLSM) system is a MIMO (Multiple Input Multiple Output) transmission mode that requires CSI feedback at the transmitter. The relation between the CLSM input and output can be expressed as follow;

$$Y = HWS + Noise \tag{4.1}$$

Where Y is the received signal, H is a matrix of channel coefficients, W is precoding matrix, and S is transmitted signals. Figure 4.1 shows mapping between the throughput achieved by each UE and UE throughput Empirical Cumulative Distribution Function (ECDF) for Close Loop Spatial Multiplexing (CLSM) with different antenna setup.

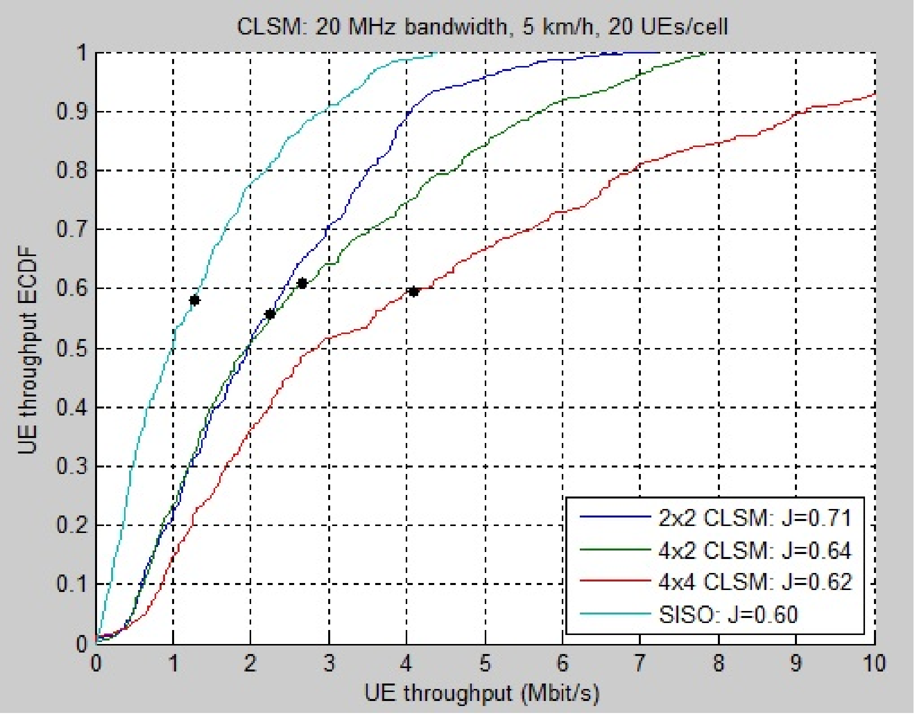


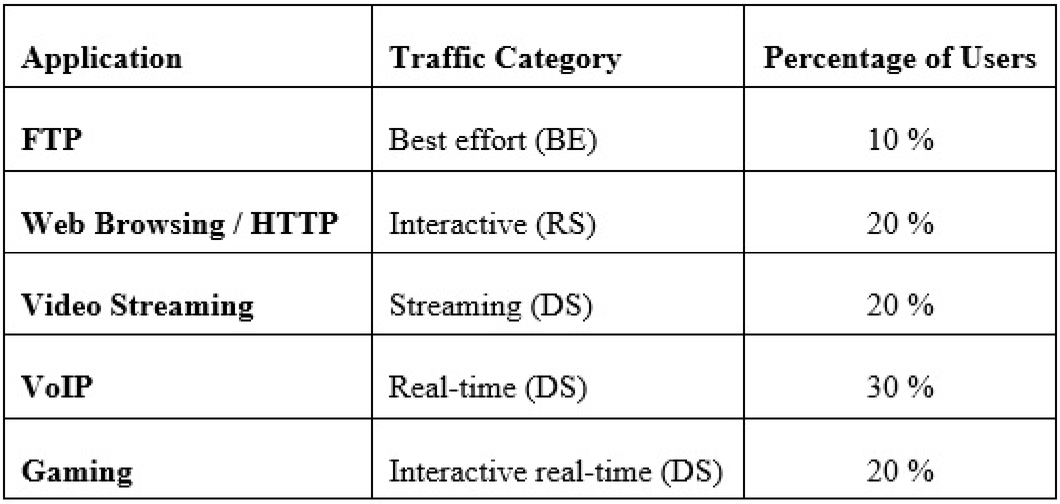
Figure 4.2: Throughput Comparison among CLSM with Diffrent Antenna Setup [34]

As you can see in Figure 4.2, the 2x2 CLSM has the highest Jain fairness index (0.71) as compared with others, so we choose 2 by 2 CLSM as our transmission mode.

4.2.2 Service Classes

In this case study, five traffic kinds are taken into consideration: video conferencing, VoIP (Voice over IP) and gaming traffic of RT service, HTTP (Hypertext Transfer Protocol) traffic of Non-Real-Time service, and FTP traffic of BE service. Traffic categories and the percentage of users of each service are presented in following Table 4.2.

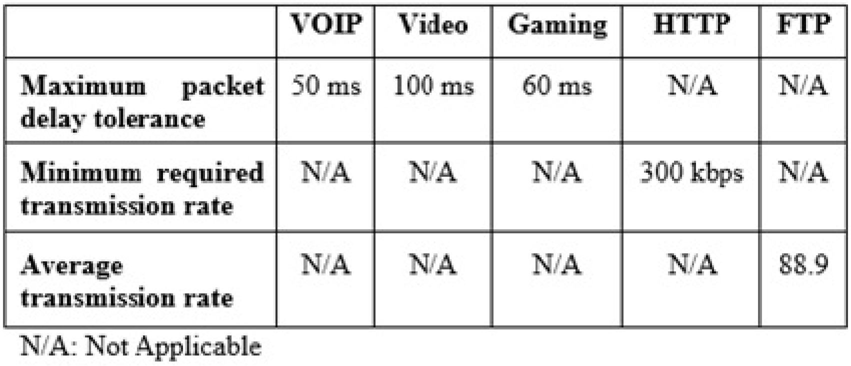
Table 4.2: Traffic category [15]



Application	**Traffic Category**	**Percentage of Users**
FTP	Best effort (BE)	10 %
Web Browsing / HTTP	Interactive (RS)	20 %
Video Streaming	Streaming (DS)	20 %
VoIP	Real-time (DS)	30 %
Gaming	Interactive real-time (DS)	20 %

The distribution probability of UEs in each traffic type is not equally likely to occur and selected according to the values suggested in RAN R1-070674 [15]. The probability distribution is 0.3, 0.2, 0.2, 0.2, and 0.1 for VOIP, video streaming, gaming, HTTP, and FTP respectively. Table 4.3 presents the simulation requirements of each traffic type which could be found in [27] and [33].

Table 4.3: The system requirements for each traffic type [30]

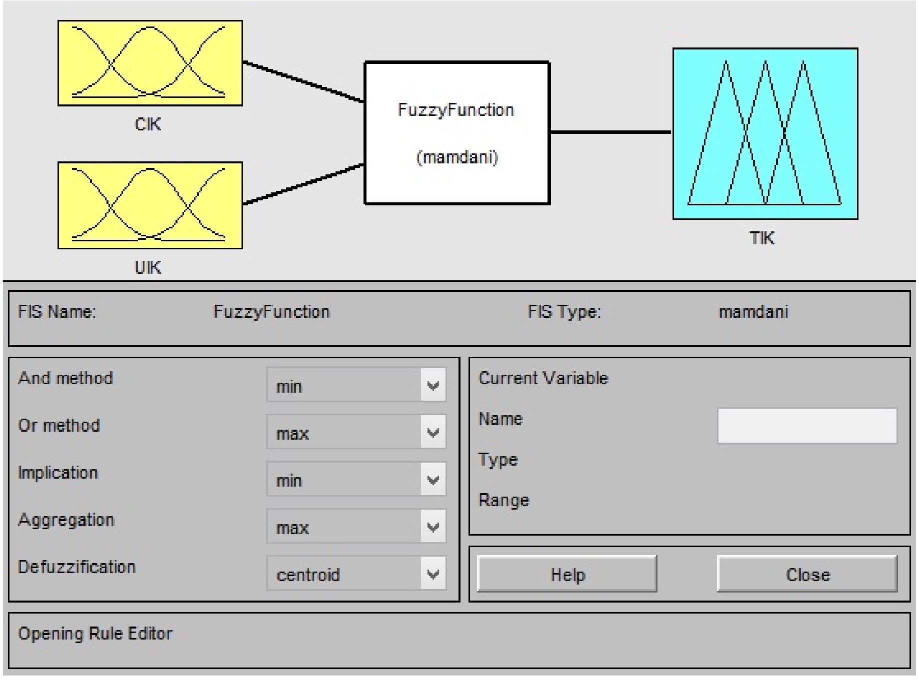


	VOIP	Video	Gaming	HTTP	FTP
Maximum packet delay tolerance	50 ms	100 ms	60 ms	N/A	N/A
Minimum required transmission rate	N/A	N/A	N/A	300 kbps	N/A
Average transmission rate	N/A	N/A	N/A	N/A	88.9

N/A: Not Applicable

4.3 Implementation of Fuzzy Inference System

Fuzzy Logic toolbox of MATLAB is employed for modeling, and simulating the system based on fuzzy logic. This toolbox can design complicated system behaviors by applying simple logic rules, and then carry out these rules in a FIS. As you can see in Figure 4.3, the fuzzy logic toolbox takes CI_K, and UI_K, as inputs and by applying some rules in fuzzy function, it generates TI_K. The membership function of CI_K, UI_K and TI_K, are also presented in Figure 4.4, respectively.



FIS Name: FuzzyFunction
FIS Type: mamdani

And method: min
Or method: max
Implication: min
Aggregation: max
Defuzzification: centroid

Opening Rule Editor

Figure 4.3: The Fuzzy Logic Toolbox

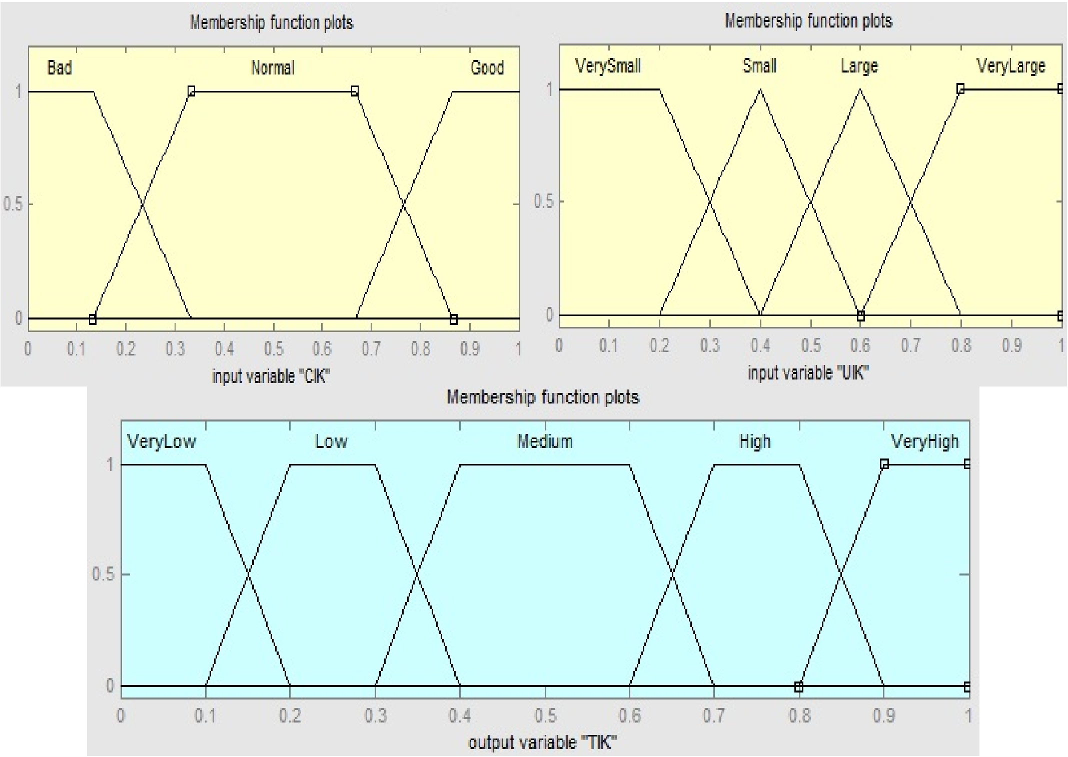


Figure 4.4: The Fuzzy Membership Function for CI_K, UI_K and TI_K

So far we explained that the user who has better channel quality condition (larger CI_K) must be assigned higher priority in order to boost the system throughput. On the other side, the user who is urgent such as cell edge users (lower UI_K) must be given higher priority for transmission in order to guarantee fairness. Plus, for users with same channel condition (same CI_K), the user who is more urgent (lower UI_K) has higher priority. For users who have same degree of urgency (same UI_K), the user who has better channel condition (larger CI_K) has higher priority for transmission. As depicted in Figure 4.5, following fuzzy surface indicates the relation between CI_K, UI_K and TI_K.

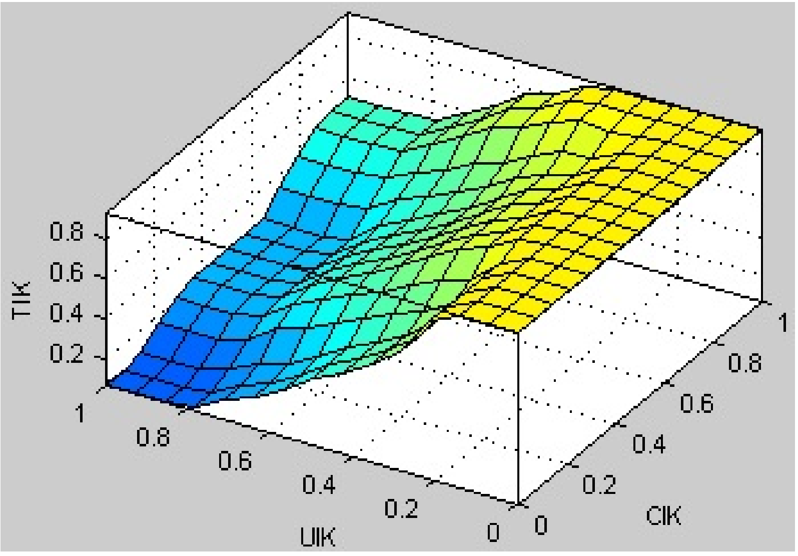


Figure 4.5: Fuzzy Interface for CI_K, UI_K and TI_K

4.4 Simulation Results and Performance Metrics

The PF scheduler was introduced in Section 2.7.4. The PF is implemented without enabling prioritization capability. The PF scheduler tries to strike a balance between the user instant data rate and past average throughput, however this algorithm doesn`t differentiate between user traffic types.

In proposed algorithm (IPF) with help of fuzzy inference system, both user prioritization and service types are taken into consideration. So the new mechanism changes the PF metric by adding an alpha to the users such that we can distinguish between users following their service types, channel condition, degree of urgency. Figure 4.6 illustrates the position of 1140 UEs (20 UEs per cell), 19 eNBs and 57 cells and UEs are distributed uniformly and constantly in all cells.

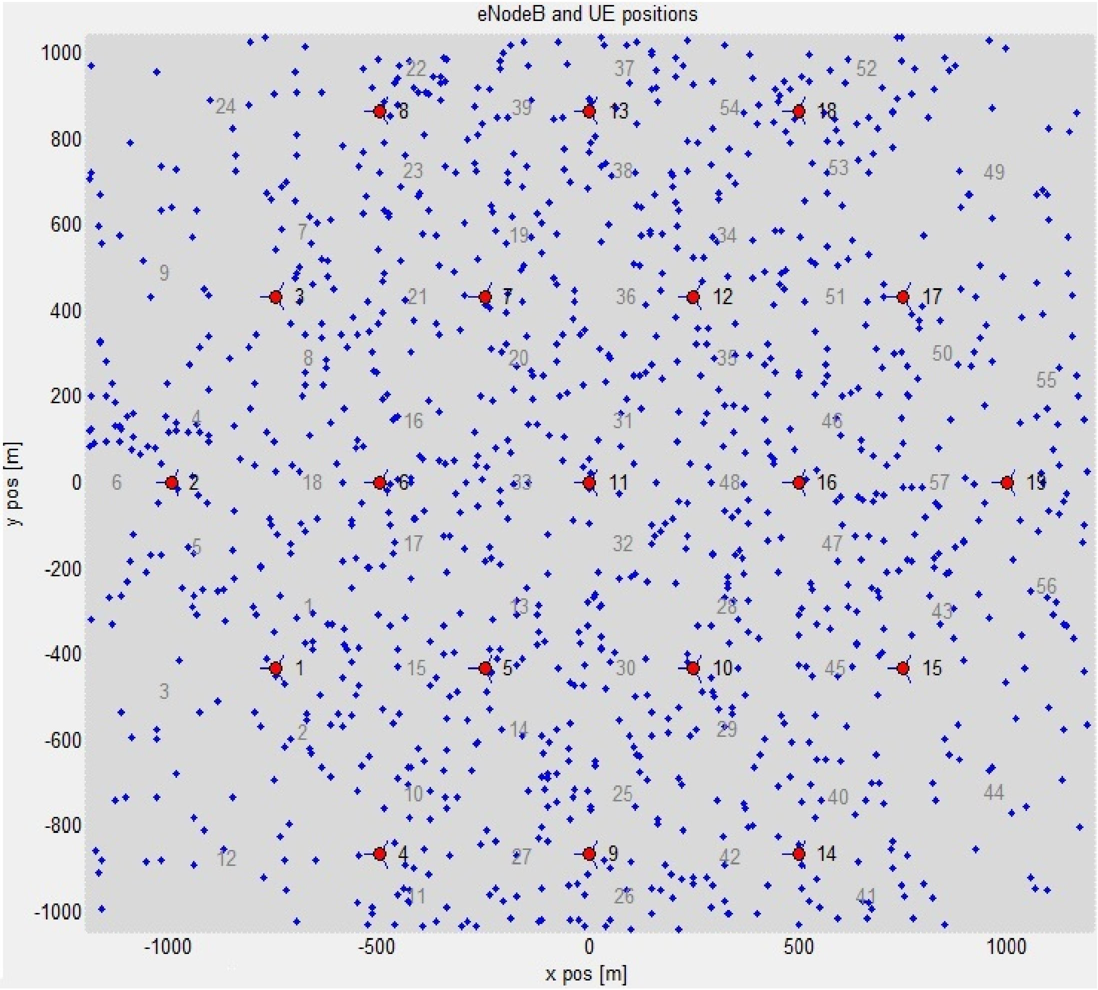


Figure 4.6: The Position of UEs and eNBs

In the following Section, in order to evaluate the system performance, obtained results of PF and Intelligent PF scheduling algorithms are analyzed. Afterward, the intelligent PF scheme is compared to the basic PF scheme. Note that results are average of 10 runs and the system performance is measured in terms of system fairness, average user and cell throughput.

4.4.1 Fairness

So far we explained how the Jain fairness index is computed in Section 2.6.3. The system fairness can be calculated as follow

$$JFI = \frac{\left(\sum_{k=1}^{K} R_k\right)^2}{K \sum_{k=1}^{K} (R_k)^2} \tag{4.1}$$

Where R_k denotes the *k*-th UE throughput, *K* is total number of UEs and JFI is Jain Fairness Index [17]. The system fairness for PF and IPF schedulers versus TTI ranging from 10 to 100 ms in fixed UE scenario is presented in Figure 4.7.

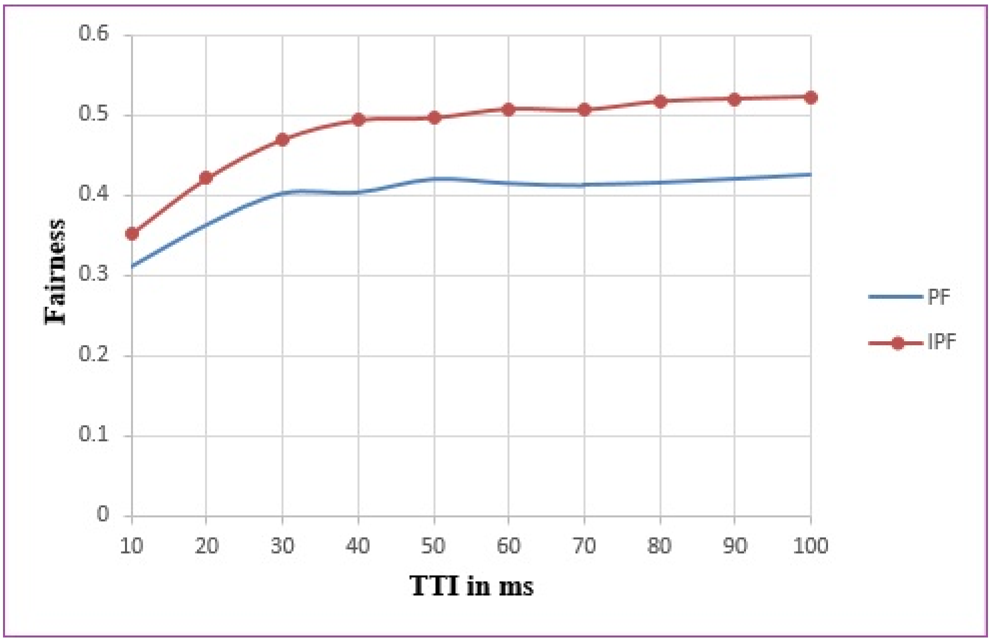


Figure 4.7: Fairness in TTI ranging from 10 to 100 ms

As you can see in Figure 4.7, the system fairness of both scheduler maintains constant after 50 TTI. From the obtained results, we can find out the IPF can delivers fairness to all attached UEs. The IPF achieves higher fairness by 21% than PF scheduler. This is because that it distinguishes UEs by their service types and gives a chance for transmission to urgent UEs who are delay sensitive and rate sensitive in such that UE's QoS requirement is satisfied. On the other side, it considers the UEs who have low past average throughput and channel quality such as cell edge users. So the IPF distributes resources fairly between all UEs in the cell area and assure user minimum performance, especially to DS and RS users.

4.4.2 Average User and Cell Throughput

So far we explained how the throughput is computed in Section 2.6.2. The instant data rate of the UE_k on RB *n* at slot *t* can calculated as follow

$$r_{k,n}(t) = log_2\left(1 + \frac{SNR_{k,n}(t)}{\tau}\right) \tag{4.2}$$

Where $SNR_{k,n}(t)$ is the Signal to Noise Ratio for the *k*-th UE on *n*-th RB and the value $\tau = \ln(5\ BER)\ /1.5$, usually called SNR gap. Then the overall throughput of user *k* at slot *t* can be represented as follow

$$R_k(t) = \sum_{n=1}^{N} x_{k,n}(t) * r_{k,n}(t) \tag{4.3}$$

Where $x_{k,n}(t)$ is the assignment indicator variable for the UE_k and the subcarrier *n*. That is $x_{k,n}(t) = 1$ when the RB is assigned to the UE_k, while $x_{k,n}(t) = 0$ otherwise. Afterward, the average UEs' throughput in time *t* can be expressed as follow

$$Average\ UEs'\ Throughput_t = \frac{\sum_{k=1}^{K} R_k(t)}{K} \tag{4.4}$$

Note that if you multiply the average UEs' throughput with the number of UEs per cell, you can calculate the average cell throughput. Figure 4.8 and Figure 4.9 illustrate the average UE throughput and average cell throughput versus TTI ranging from 10 to 100 ms, respectively for the 20 UEs environment. From the obtained results shown in following Figures, we can observe that average throughput achieved by the IPF is better by 5% than the basic PF. Throughput improvement is not as much as fairness progress, because there is a challenging issue to keep balance between throughput maximization and fairness guarantee; the enhancement in one of them may violate and sacrifice the other one. The IPF scheduler can achieve higher system fairness by 21% and better average throughput by 5% than basis PF scheme.

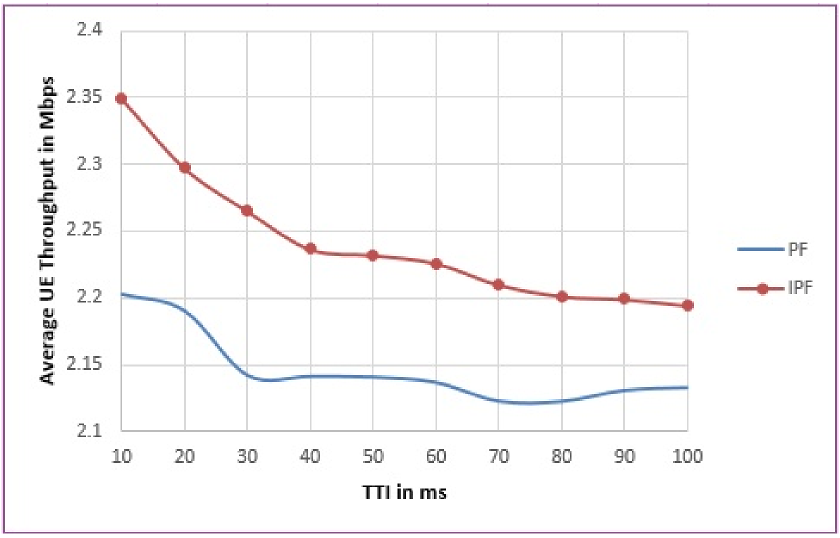


Figure 4.8: Average UE Throughput in TTI Ranging from 10 to 100 ms

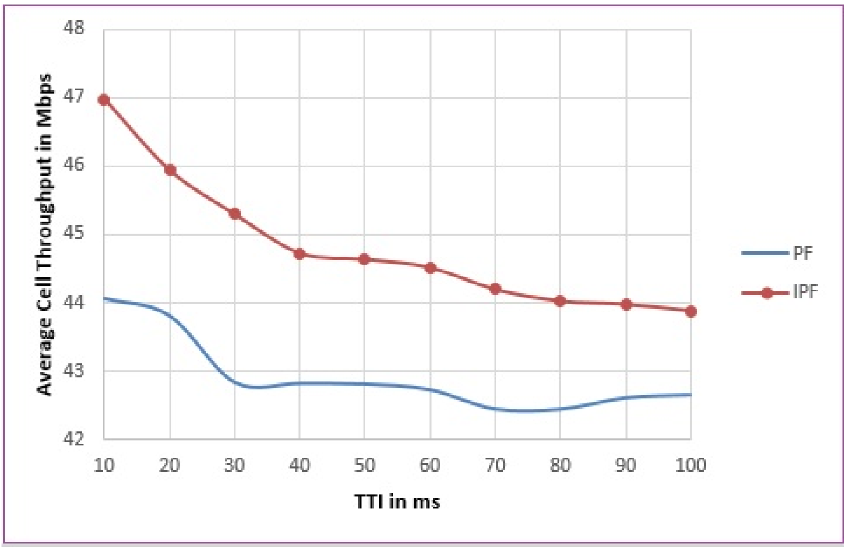


Figure 4.9: Average Cell Throughput in TTI Ranging from 10 to 100 ms

In proposed scheduling strategy, the user channel quality condition (CI_K), and the user instant data rate are considered in order to boost system throughput in such a way that the user who has better channel quality and higher data rate has higher precedence for data transmission. Average cell and UE throughput remain constant for both scheduling strategies after a short period of time, however IPF shows little progress in average system throughput.

In previous scenario, the number of UEs was constant and the TTI was changing between 10 to 100 ms. Now let us to change the number of UEs between 5 to 20 while the TTI is constant (50 ms). Figures 4.10 and 4.11 present the fairness and average UE throughput versus UEs ranging from 5 to 20, respectively.

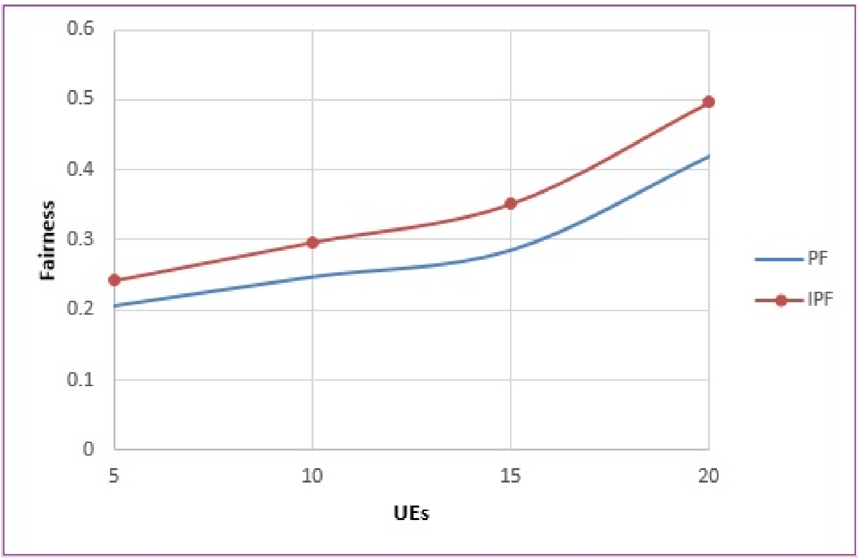


Figure 4.10: Fairness for UEs Ranging from 5 to 20 in TTI=50 ms

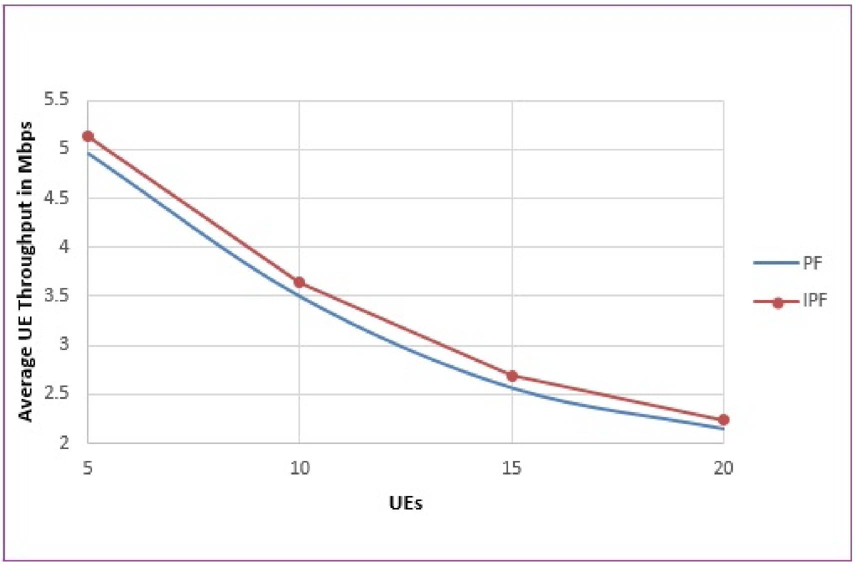


Figure 4.11: Average Throughput for UEs Ranging from 5 to 20 in TTI=50 ms

As you can see in both Figures, the IPF has improvement in fairness while the average throughput doesn`t change a lot and also it is clear that the system fairness increases as the number of UEs increases but average UE throughput decreases. This is because that same amount of radio resources are dedicated to more number of users, so less RBs are allotted to UEs and it causes lower throughput and data rate.

Finally, Intelligent PF by considering the UEs’ past average throughput and UEs’ QoS requirements can guarantee system fairness between UEs. It also takes channel quality condition into account while allots RBs to the UEs who have better channel quality and data rate in order to boost system throughput.

Generally, IPF dedicates radio resources to the UEs who are more urgent and have better channel quality condition. Thus IPF can intelligently strike a balance between fairness guarantee and throughput improvement. With the Intelligent PF scheduler, the system performance outperforms in terms fairness while each UE’s throughput is satisfied in comparison with the basic PF.

Chapter 5

CONCLUSIONS

This thesis has proposed an Intelligent Proportional Fair (IPF) scheme for LTE downlink direction with multimedia traffic such as VOIP, video, gaming, HTTP, and FTP. With help of fuzzy system, rules of Proportional fair (PF) is fine-tuned targeting to capable users prioritization in the system. Considering channel quality condition, users' QoS requirements, and service types, the fuzzy smartly chooses a priority value for each attached UE. The fuzzy takes both channel information and user information as input parameters to produce an output which determines the precedence level of each UE.

In this work, three classes of communication service are supported such as Delay Sensitive (DS), Rate Sensitive (RS) and Best Effort (BE). Users are prioritized in this order, first DS, second RS and Third BE. Thus delay and rate tolerance UEs can give their opportunity to DS and RS users. From the fuzzy point of view, it is always best to dedicated RBs to who is more urgent and better channel quality condition. Plus, other factors are considered such as user instant data rate and past average throughput. So cell edge users who may suffer from low channel quality have a chance for data transmission. To summarize, differently from basic PF scheduler, IPF differentiates between users by following their traffic kinds, channel quality condition, degree of urgency, and QoS requirements.

The simulation is done in Vienna system level simulator and the obtained results are compared with conventional PF. Fuzzy logic toolbox of MATLAB is also applied for designing of fuzzy logic based system. The system performance is evaluated in terms of some key metrics such as fairness, average user and cell throughput.

Obtained results illustrates that the intelligent PF implementation can boost system total fairness by 21% and better throughput by 5% than basic PF scheduler. Throughput improvement is not as much as fairness because balancing the weight between fairness and system throughput is a challenging issue such that increasing one of them may sacrifice and violate the other one.

Finally, there are a number of issues that can be addressed in future research. It is recommended to evaluate the system in more complex scenarios for example higher number of users with higher speed or more number of cells and eNBs. Furthermore, the growing requests for wireless communication services with existing energy consumption cause many difficulties in wireless cellular networks. As future work, it is also suggested to survey on heterogeneous power distribution, in order to decrease the power consumption. Undoubtedly, design of this scheduling strategy needs much more investigation, research and new methods.

REFERENCES

[1] Peng, Y., Armour, S., & McGeehan, J. P. (2007). An investigation of dynamic subcarrier allocation in mimo–ofdma systems. Vehicular Technology, IEEE Transactions on, 56(5), 2990-3005.

[2] Orange, C.M., KPN, N. and DoCoMo, S., T-Mobile, Vodafone, and Telecom Italia, “R1-070674: LTE Physical Layer Framework for Performance Verification; 3GPP TSG RAN WG1,” Tech. Rep. [Online]. Available: http://www. 3gpp. org/ftp/tsg ran/WG1 RL1/TSGR1 48/Docs/R1-070674. Zip.

[3] Xu, H., Tian, H., Feng, Y., Gao, Y., & Zhang, P. (2008). An efficient resource management scheme with Guaranteed QoS of heterogeneous services in MIMO-OFDM system. In Wireless Communications and Networking Conference, 2008. WCNC 2008. IEEE (pp. 1838-1843). IEEE.

[4] Yen, C. M., Chang, C. J., & Wang, L. C. (2010). A utility-based TMCR scheduling scheme for downlink multiuser MIMO-OFDMA systems. Vehicular Technology, IEEE Transactions on, 59(8), 4105-4115.

[5] Chung, W. C., Chang, C. J., & Wang, L. C. (2012). An intelligent priority resource allocation scheme for LTE-A downlink systems. Wireless Communications Letters, IEEE, 1(3), 241-244.

[6] Capozzi, F., Piro, G., Grieco, L. A., Boggia, G., & Camarda, P. (2013). Downlink packet scheduling in LTE cellular networks: Key design issues and a survey. Communications Surveys & Tutorials, IEEE, 15(2), 678-700.

[7] Lee, C. C. (1990). Fuzzy logic in control systems: fuzzy logic controller. II.Systems, Man and Cybernetics, IEEE Transactions on, 20(2), 419-435.

[8] Dahlman, E., Parkvall, S., Skold, J., & Beming, P. (2007). 3G evolution: HSPA and LTE for mobile broadband. Academic press.

[9] Channels, P. (2009). Modulation (Release 8), 3GPP TS 36.211 V8. 6.0.

[10] Rebekka, B., & Malarkodi, B. (2014). Performance evaluation of resource allocation schemes in LTE downlink. In Electronics and Communication Systems (ICECS), 2014 International Conference on (pp. 1-4). IEEE.

[11] Sun, Z., Yin, C., & Yue, G. (2006). Reduced-complexity proportional fair scheduling for OFDMA systems. In Communications, Circuits and Systems Proceedings, 2006 International Conference on (Vol. 2, pp. 1221-1225). IEEE.

[12] [Online]. Available; https://www.nt.tuwien.ac.at/ltesimulator

[13] Hallahan, R., & Peha, J. M. (2010). Policies for public safety use of commercial wireless networks. TPRC.

[14] Ikuno, J. C., Wrulich, M., & Rupp, M. (2010). System level simulation of LTE networks. In Vehicular Technology Conference (VTC 2010-Spring), 2010 IEEE 71st (pp. 1-5). IEEE.

[15] Technical Specification Group RAN. (2006). E-UTRA; Physical Layer Aspects for Evolved UTRA, (Release 7). 3GPP, V7.1.0, TR 25.814.

[16] Xiao, L., Zhou, S., & Yao, Y. (2003). QoS-oriented scheduling algorithm for mobile multimedia in OFDM. In Personal, Indoor and Mobile Radio Communications, 2003. PIMRC 2003. 14th IEEE Proceedings on (Vol. 1, pp. 545-549). IEEE.

[17] Jain, R., Chiu, D. M., & Hawe, W. R. (1984). A quantitative measure of fairness and discrimination for resource allocation in shared computer system (Vol. 38). Hudson, MA: Eastern Research Laboratory, Digital Equipment Corporation.

[18] Viswanath, P., Tse, D. N., & Laroia, R. (2002). Opportunistic beam forming using dumb antennas. Information Theory, IEEE Transactions on, 48(6), 1277-1294.

[19] Assaf, S. S. (2014). Performance analysis of prioritization in LTE networks with the Vienna LTE system level simulator.

[20] Nsiri, B., Mallouki, N., Mhatli, S., Ghanbarisabagh, M., Ammar, M., & Hakimi, W. (2015). Modeling and Performance Evaluation of Novel Scheduling Algorithm for Downlink LTE Cellular Network. Wireless Personal Communications, 83(3), 2303-2316.

[21] Lima, F. R. M., Maciel, T. F., Freitas Jr, W. C., & Cavalcanti, F. R. P. (2012). Resource assignment for rate maximization with QoS guarantees in multiservice wireless systems. Vehicular Technology, IEEE Transactions on, 61(3), 1318-1332.

[22] Rebekka, B., Sudheep, S., & Malarkodi, B. (2015). An Optimal and Priority Based Rate Guaranteed Radio Resource Allocation Scheme for LTE Downlink. Wireless Personal Communications, 83(3), 1643-1661.

[23] Jeong, S. S., Jeong, D. G., & Jeon, W. S. (2006). Cross-layer design of packet scheduling and resource allocation in OFDMA wireless multimedia networks. In Vehicular Technology Conference, 2006. VTC 2006-Spring. IEEE 63rd (Vol. 1, pp. 309-313). IEEE.

[24] Yu, J., Cai, Y., Ma, Y., Zhang, D., & Xu, Y. (2007). A cross-layer design of packet scheduling and resource allocation for multiuser MIMO-OFDM systems. In Information, Communications & Signal Processing, 2007 6th International Conference on (pp. 1-5). IEEE.

[25] Guan, N., Zhou, Y., Tian, L., Sun, G., & Shi, J. (2011). QoS guaranteed resource block allocation algorithm for LTE systems. In Wireless and Mobile Computing, Networking and Communications (WiMob), 2011 IEEE 7th International Conference on (pp. 307-312). IEEE.

[26] Sundari, K. G., Gunasundari, R., & Jayanthi, K. (2015). Prioritized dynamic multi-traffic scheduler for downlink in LTE. In Electronics and Communication Systems (ICECS), 2015 2nd International Conference on (pp. 1469-1473). IEEE.

[27] Chung, W. C., & Chang, C. J. (2010). A fuzzy logics based scheduling for downlink OFDMA/SDMA systems with multimedia traffic. In Communications and Information Technologies (ISCIT), 2010 International Symposium on (pp. 232-237). IEEE.

[28] Ku, M. L. (Ed.). (2012). Cognitive Radio and Interference Management: Technology and Strategy: Technology and Strategy. IGI Global.

[29] Chung, W. C., Chang, C. J., Huang, C. Y., & Teng, H. Y. (2013). A green radio resource allocation scheme for LTE-A CoMP systems with multimedia traffic. In Communications in China (ICCC), 2013 IEEE/CIC International Conference on (pp. 758-762). IEEE.

[30] Tsai, C. F., Chang, C. J., Ren, F. C., & Yen, C. M. (2008). Adaptive radio resource allocation for downlink OFDMA/SDMA systems with multimedia traffic. Wireless Communications, IEEE Transactions on, 7(5), 1734-1743.

[31] Mehlführer, C., Ikuno, J. C., Simko, M., Schwarz, S., Wrulich, M., & Rupp, M. (2011). The Vienna LTE simulators-Enabling reproducibility in wireless communications research. EURASIP J. Adv. Sig. Proc., 2011, 29.

[32] Technical Specification Group RAN. (2008-2009). E-UTRA; LTE RF system scenarios. 3GPP, Tech. Rep. TS 36.942.

[33] Technical Specification Group RAN. (2010). E-UTRA; further advancements foe E-UTRA physical layer aspects. 3GPP, Tech. Rep. TS 36.814.

[34] The System Level simulator documentation, Vienna University of Technology; http://www.nt.tuwien.ac.at/fileadmin/topics/simulators/LTEsystemDoc.pdf

APPENDICES

Appendix A: Running a Simulation

The LTE-A Downlink System Level Simulator is published under a non-commercial academic use license and it is freely available in [12]. Simulations are started from a main launcher file, which is stored in the folder sim_main_launcher_files. In this folder, various demo launcher files are available. The following tasks are performed:

- Loading a configuration file of choice.
- Executing the LTE_sim_main.m, which is the main simulation file, which calls all the required routines and contains the main simulation loop.

The simulation parameters are loaded via the LTE_load_params.m script, which applies the specific parameters from one of the setups as specified in +simulation_config. Note that the LTE_load_params_dependant.m script is used for automatically generating additional simulation parameters from the base parameters specified. In Appendix B, you can find a basic list of parameters that can be configured in the configuration parameters files, which are found in the +simulation_config simulator subfolder (For more information see [34]). At last, the IPF scheduler is added to the simulator as a new scheduling algorithm which you can find it in Appendix C.

Appendix B: Simulation Parameters

```
close all force;

clc;

cd ..

simulation_type = 'tri_sector'
simSet = [4 2 2];
%% Base configuration
LTE_config = LTE_load_params (simulation_type);
LTE_config.eNodeB_tx_power         = 46; % eNB maximum transmit power
LTE_config.bandwidth               = 20e6; % 20 MHz
LTE_config.scheduler               = 'prop fair traffic';
LTE_config.UE_speed                = 5/3.6; %5 Km/h
LTE_config.UE_distribution         = 'constant UEs per cell';
LTE_config.network_geometry        = 'regular_hexagonal_grid';
LTE_config.shadow_fading_type      = 'none';
LTE_config.UE_per_eNodeB           = 20; % number of UEs per cell
LTE_config.simulation_time_tti     = 100; % Simulation time
LTE_config.trace_version           = 'v1';
LTE_config.show_network            = 2; % 2= show ALL plots
LTE_config.keep_UEs_still          = true;
% true: keeps the UEs still regardless of the set UE speed.
LTE_config.compact_results_file    = true;
LTE_config.delete_ff_trace_at_end  = true;
% delete microscale fading      trace from the results
LTE_config.always_on               = true;
% false: if no UEs are attached to the eNB, don`t radiate power
LTE_config.tx_mode                 = simSet (1);
LTE_config.nTX                     = simSet (2);
LTE_config.nRX                     = simSet (3);
ticIdx                             = tic;
output_results_file                = LTE_sim_main (LTE_config);
time                               = toc(ticIdx);
simulation_data                    = load (output_results_file);
GUI_handles.aggregate_results_GUI = LTE_GUI_show_aggregate_results
(simulation_data);
GUI_handles.positions_GUI          = LTE_GUI_show_UEs_and_cells

(simulation_data,GUI_handles.aggregate_results_GUI);
```

Appendix C: Scheduler Settings

```
classdef PropFair_Traffic < schedulers.lteScheduler

% Proportional Fair scheduler that supports traffic models

  properties

     % See the lteScheduler class for a list of inherited attributes

     av_throughput % exponentially weighted throughputs

     lambda
     alpha
     test_id

  end

  methods

     % Class constructor. Just specify where to attach the scheduler
     function obj = PropFair_Traffic(scheduler_params,attached_eNodeB_sector)
        % Fill in basic parameters (handled by the superclass constructor)
        obj      =
obj@schedulers.lteScheduler(scheduler_params,attached_eNodeB_sector);
%           obj.alpha = scheduler_params.alpha;
        obj.name  = 'PropFair_Traffic scheduler';
        obj.test_id = attached_eNodeB_sector.id;
     end

     % Dummy functions required by the lteScheduler Abstract class implementation
     % Add UE (no memory, so empty)
     function add_UE(obj,UE_id)
     end
     % Delete UE (no memory, so empty)
     function remove_UE(obj,UE_id)
     end

     % Schedule the users in the given RB grid
%       function
%       schedule_users(obj,RB_grid,attached_UEs,last_received_feedbacks)
%RB_grid removed!!!
     function schedule_users(obj,attached_UEs,last_received_feedbacks)
        % Power allocation
```

```
        % Nothing here. Leave the default one (homogeneous)
        RB_grid = obj.RB_grid;
        RB_grid.size_bits = 0;

% For now use the static tx_mode assignment

        RB_grid.size_bits = 0;
        tx_mode = obj.default_tx_mode;
        current_TTI = obj.clock.current_TTI;
        N_UE = length(attached_UEs);
        N_RB = RB_grid.n_RB;
        UE_id_list = zeros(N_RB,1);

        if ~isempty(attached_UEs)

            for u_ = 1:N_UE
               attached_UEs(u_).traffic_model.check_TTI;
            end

             %% Compute Gama

            Gama = zeros(1,N_UE);
            for u_ = 1:N_UE
               attached_UEs(u_).traffic_model.type;
                 if strcmp(attached_UEs(u_).traffic_model.type,'voip') ||
strcmp(attached_UEs(u_).traffic_model.type,'video') ||
strcmp(attached_UEs(u_).traffic_model.type,'gaming')
                   Gama(u_) = 2;
               elseif strcmp(attached_UEs(u_).traffic_model.type,'http')
                   Gama (u_)= 1;
               else
                   Gama(u_) = 0;
                 end
            end

            %% compute efficiency
            [c,user_ind] = obj.get_efficiency(N_UE,N_RB,last_received_feedbacks);
            c = c';

             %%Compute CIK =average Channel Quality Indicator
          MAXCQI = 15;
          CQIs_per_UE = reshape(last_received_feedbacks.CQI,[],N_UE);
          last_received_feedbacks.CIK = ((mean
(CQIs_per_UE(1:N_RB,:)))/MAXCQI);
```

```
            CIK = last_received_feedbacks.CIK ;

              %% Compute UIK
              UIK = zeros(1,N_UE);
              for u_ = 1:N_UE
                  attached_UEs(u_).traffic_model.type;
                    if strcmp(attached_UEs(u_).traffic_model.type,'voip') ||
strcmp(attached_UEs(u_).traffic_model.type,'video') ||
strcmp(attached_UEs(u_).traffic_model.type,'gaming')
                        Dstar = attached_UEs(u_).traffic_model.delay_constraint;
                        DK = obj.clock.current_TTI -
attached_UEs(u_).traffic_model.Origin_Time;
                        UIK(u_) = (Dstar - DK) / Dstar;
                  elseif strcmp(attached_UEs(u_).traffic_model.type,'http')
                        Dk = obj.clock.current_TTI -
attached_UEs(u_).traffic_model.Origin_Time;
                        rate_constraint = attached_UEs(u_).traffic_model.rate_constraint;
                        UIK(u_) = 0.1.*(floor(attached_UEs(u_).traffic_model.bit_count./
rate_constraint )- Dk);

                  else
                       UIK(u_) = attached_UEs(u_).traffic_model.average_data_rate;
                    end
              end

%% Compute TIK
            TIK = IntelligentFuzzy(CIK,UIK);

%% Compute Alpha
            Alpha = Gama + TIK' ;
            obj.alpha = log10(max(Alpha,eps));

%% update average throughput
             TTI_to_read = max(current_TTI-obj.feedback_delay_TTIs-1,1);
% Realistically read the ACKed throughput
             for uu = 1:N_UE
                  obj.av_throughput(uu) =
obj.compute_av_throughput(uu,last_received_feedbacks,TTI_to_read);
             end

%% Proportional fair traffic scheduler
```

```
                RBs = obj.Propfair_Traffic_scheduler(N_UE,N_RB,c,last_received_feedbacks,user_ind,attached_UEs);
                for r_ = 1:N_RB
                    RB_tmp = RBs((r_-1)*N_UE+1:r_*N_UE);
                    ind = find(RB_tmp == 1);
                   if ~isempty(ind)
                     UE_id_list(r_) = attached_UEs(user_ind(ind)).id;
                   end
                end
                RB_grid.user_allocation(:) = UE_id_list;
                % CQI assignment. TODO: implement HARQ
%                obj.schedule_users_common(RB_grid,attached_UEs,last_received_feedbacks,current_TTI,tx_mode);   %RB_grid removed!!!
                obj.schedule_users_common(attached_UEs,last_received_feedbacks,current_TTI,tx_mode);
            end
        end

        function RBs = Propfair_Traffic_scheduler(obj,N_UE,N_RB,c,last_received_feedbacks,user_ind,attached_UEs)
% core scheduling function (same in LL and SL except for factor 2 --> 2RBs are scheduled)

            if ~mod(obj.clock.current_TTI-1,5)
                overhead = obj.overhead_ref+obj.overhead_sync;
            else
                overhead = obj.overhead_ref;
            end
            alpha_temp   = 1;
            RBs          = zeros(N_RB*N_UE,1);
            bits_left    = zeros(N_UE,1);
            isbits       = false(N_UE,1);
            metric       = ones(N_RB,N_UE)*-Inf;
            RB_set       = true(N_RB,1);
            RB_UEs       = false(N_RB,N_UE);

            for ii = 1:N_UE          % Check if data is available
                 if strcmp(attached_UEs(user_ind(ii)).traffic_model.type,'fullbuffer')
                     bits_left(user_ind(ii)) = 1;
                 else
```

```
                  bits_left(user_ind(ii)) =
attached_UEs(user_ind(ii)).traffic_model.bit_count;
              end
              isbits = logical(bits_left);

          end

% Precalculated values taken out from the loop (speeds up simulations)
          cleaned_c_log_matrix = log10(max(c,eps)*2*12*7);
          avgd_UE_throughputs  = (obj.av_const-1)*obj.av_throughput(user_ind);

          last_received_feedbacks.Alpha = obj.alpha(user_ind);

          % Calculate metric for each RB and attached user
          for rr = 1:N_RB
             if sum(bits_left)
                res                  = find(RB_set);
                metric                 = -Inf(N_RB,N_UE);
                UE_avgd_pre_metric     = -
alpha_temp*log10(max(avgd_UE_throughputs+sum(RB_UEs.*c,1)*2*12*7,eps));
                UE_avgd_pre_metric_mat = UE_avgd_pre_metric(ones(1,N_RB),:);
                Alpha_mat =last_received_feedbacks.Alpha(ones(1,N_RB),:);
                metric(res(1:sum(RB_set)),:) =
((cleaned_c_log_matrix(res(1:sum(RB_set)),:)+UE_avgd_pre_metric_mat(res(1:sum
(RB_set)),:)))+ (Alpha_mat(res(1:sum(RB_set)),:));
                metric(:,~isbits(user_ind)) = -Inf;
% if there are no bits left, set metric to -Inf
                maxi           = max(metric(:));
                [RB_idx UE_idx] = find(metric == maxi);
                ind            = randi(length(RB_idx));

                tmp_UE         = UE_idx(ind);
                tmp_RB         = RB_idx(ind);

                RB_set(tmp_RB)               = false;
                RB_UEs(tmp_RB,tmp_UE)        = true;

% coarse decrease for UE who got the current RB and check if there are still bits left
                if ~strcmp(attached_UEs(tmp_UE).traffic_model.type,'fullbuffer')
                   if sum(RB_UEs(:,tmp_UE)) <= 1
%coarse decrease with crc-bits subtracted (only for non-fullbuffer)

attached_UEs(tmp_UE).traffic_model.coarse_decrease(c(tmp_RB,tmp_UE)*(2*12*
7-overhead-24));
```

```
                    else
%crc is subtracted only once

attached_UEs(tmp_UE).traffic_model.coarse_decrease(c(tmp_RB,tmp_UE)*(2*12*
7-overhead));
                    end
                    bits_left(tmp_UE) = attached_UEs(tmp_UE).traffic_model.bit_count;
                    isbits(tmp_UE)    = logical(bits_left(tmp_UE));
                end
            end
        end
        RB_UEs = RB_UEs';
        RBs = RB_UEs(:);
    end
  end
end
```