On Design and Analysis of Channel Aware LTE Uplink and Downlink Scheduling Algorithms

by

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Abstract

In the past two decades, there has been a drastic increase in the mobile traffic, which is caused by the improved user experience with smart phones and its applications. In LTE system, the packet scheduler plays a vital role in the effective utilization of the resources. This field is not standardized and has immense scope of improvement, allowing vendor-specific implementation. The work presented in this thesis focuses on designing new scheduling algorithms for uplink and downlink to effectively distribute resources among the users. LTE scheduling can be categorized into two extremes, namely, Opportunistic scheduling and Fairness scheduling. The Best Channel Quality Indicator (BCQI) algorithm falls under the former category while Proportional Fairness (PF) algorithm under the later. BCQI algorithm provides high system throughput than PF algorithm, however, unlike BCQI algorithm, PF algorithm considers users with poor channel condition for allocation process. In this work, two new scheduling disciplines referred as Opportunistic Dual Metric (ODM) Scheduling Algorithm is proposed for uplink and downlink respectively.

The objective of the algorithm is to prioritize the users with good channel condition for resource allocation, at the same time not to starve the users with poor channel conditions. The proposed algorithm has two resource allocation matrices, H1 and H2, where H1 is throughput-centric and H2 is fairness-centric. The uplink algorithm uses the two resource allocation matrices to allocate the resources to the users and to ensure contiguous resource allocation. The downlink algorithm is an extension of the proposed uplink algorithm avoiding uplink constraints. The downlink algorithm employs the two resource distribution matrices to provide an efficient resource allocation by expanding the allocation for the users considering intermittent resources. The performance of ODM is measured in terms of throughput, fairness. Additionally, the uplink algorithm is analysed in terms of transmit power. From the results it is observed that the proposed algorithms has better trade-off in terms of all the performance parameters than PF scheduler and BCQI scheduler.

Acknowledgement

I would like to use this opportunity to express my gratitude to my thesis supervisor, Dr. Amiya Nayak, for his valuable guidance, patience and support which led me in the right path for the successful completion of this work.

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ACRONYMS

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
ACK	Acknowledgement
AM	Acknowledged Mode
AMC	Adaptive Modulation and Coding
BCQI	Best Channel Quality Indicator
BSR	Buffer Status Report
CN	Core Network
CQI	Channel Quality Indicator
dBm	Decibel (referenced to milliwatts)
DSCP	Differentiated Services Code Point
DL	Downlink
eNodeB	evolved NodeB
EPC	Evolved Packet Core
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
FDD	Frequency Division Duplex
GW	GateWay
HARQ	Hybrid Automatic Repeat reQuest
HM	Hybrid Mode
HSDPA	High Speed Downlink Packet Access
IEEE	Institute of Electrical and Electronics Engineers
IP	Internet Protocol
ITU – T	ITU - Telecommunication standardization sector

LTE	Long Term Evolution
LTE-A	LTE Advanced
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MM	MaxMin
NACK	Negative Acknowledgement
ODM	Opportunistic Dual Metric
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak to Average Power Ratio
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Control Protocol
PDSCH	Physical Downlink Shared Channel
PDU	Payload Data Unit
PHICH	Physical HARQ Indication Channel
PF	Proportional Fair
QoS	Quality of Service
RB	Resource Block
RF	Resource Fair
RLC	Radio Link Control
RR	Round Robin
RRM	Radio Resource Management
SC-FDMA	Single Carrier Frequency Division Multiple Access
SRS	Sound Reference Signal
TDD	Time Division Duplexing
TPR	Throughput to Power Ratio
UE	User Equipment
UL	Uplink
UMTS	Universal Mobile Telecommunications System

1 Introduction

1.1 Introduction

The evolution of the Third Generation Partnership Project Long Term Evolution (3GPP LTE) is a result of the growing need for enhancement in terms of data rate and latency improvements in the existing Third Generation (3G) system. LTE is predominantly accepted as a potential candidate for Fourth Generation (4G) system. In December 2004, the study on Universal Terrestrial Radio Access Network (UTRAN) [1] stated that

"With enhancements such as HSDPA (High Speed Downlink Packet Access) and Enhanced Uplink, the 3GPP radio-access technology will be highly competitive for several years. However, to ensure competitiveness in an even longer time frame, i.e. for the next 10 years and beyond, a long-term evolution of the 3GPP radio-access technology needs to be considered. Important parts of such a long-term evolution include reduced latency, higher user data rates, improved system capacity and coverage, and reduced cost for the operator. In order to achieve this, an evolution of the radio interface as well as the radio network architecture should be considered."

This marked the inauguration of the LTE standardization process. Consecutively, the first version of LTE was standardised by 3GPP under Release 8 [2] and Orthogonal Frequency Division Multiplexing (OFDM) is selected as the access technology. Although, LTE supports only packet-switched services, it can be completely integrated with the existing Second Generation (2G) and 3G system [3]. Since LTE provide high data rate, applications such as Voice over IP, Video Conferencing and Multimedia Streaming are supported.

1.2 Motivation

In order to improve the resource utilization, the LTE system employs Radio Resource Management (RRM) procedures such as link adaptation, Hybrid Automatic Repeat Request

(HARQ), resource scheduling, power control and Channel Quality Indicator (CQI) feedback. Each of these feature interact with one another to ensure better resource utilization. The scheduling algorithm is responsible for allocating the Resource Blocks (RB) to the users for every Transmission Time Interval (TTI). It formulates a decision function as a set of performance metrics and provides resource mapping by computing an optimal solution for maximising or minimising the decision function. According to [4], the scheduling algorithms can be classified into two extremes:

- Opportunistic Scheduling focuses on improving the transmission data rate of all the users by exploiting their instantaneous channel conditions. At each subframe, distributing resources to users with good channel conditions results in high cell throughput.
- Fair Scheduling schemes are designed to promote fairness in allocation by ensuring that every user is allocated with a minimum of radio transmission resources. Hence, the achieved cell throughput will be lesser when compared with the former scheme.

Most of the algorithms existing in the literature fall in between these two types. Based on the factors considered in the decision function, the algorithms tend to incline to either one of the above categories. Although increased spectral efficiency is one of the important criteria of the scheduler, fairness in resource allocation has to be maintained at a satisfactory level to ensure the user starvation is avoided. The motivation behind this work, is to design a new scheduling scheme which achieves an optimal trade-off in maximizing the system throughput without compromising on the fairness in resource allocation.

1.3 Objective

The objective of the thesis is to design a new scheduling algorithm for uplink and downlink, and to distribute the available resources among the active users, by exploiting their channel conditions. The channel conditions experienced by the users within the same cell vary with one another. This principle is used to prioritize the users with better channel conditions and thereby, achieving better spectral efficiency. At the same time, unfair allocation of resources is avoided by considering the allocation history of the users.

Problem Statement: The resource allocation is constrained by transmission power of eNodeB in the downlink and power headroom of the users in the downlink. Since the users are power-limited, it is vital that the uplink scheduling algorithm has to be energy-efficient. From [5], it is learned that contiguous allocation of resources is more energy-efficient when compared with intermittent resource allocation. Hence, the scheduling problem must consider these constraints while making the decision to allocate the resources. Thus, the scheduling algorithm which solves this constrained optimization problem is needed for efficiently distributing the resources among the users by providing a better trade-off between system throughput and fairness.

The work presented in this thesis focuses on finding the best possible solution for the problem statement mentioned above. The objective of the thesis can be summarized as follows:

- To design a new resource allocation strategy which solves constrained optimization problem considering channel quality and fairness requirements. The algorithm to be designed is expected to produce high throughput with less compromise on the fairness, in other words, a better trade-off in terms of system throughput and fairness.

1.4 Contribution

The main focus of the work mentioned in this thesis is to design a new and efficient scheduling strategy for uplink and downlink. Although, the core scheduling function is the same for both uplink and downlink, there are a few constraints which differentiate their scheduling problem. Ignoring those constraints will result in an inefficient allocation of resources. Considering this factor, this work presents a new scheduling algorithm for uplink and downlink.

This thesis presents two contributions as described below.

1. A novel uplink scheduling algorithm has been proposed which not only provides high throughput, but also increases the fairness in scheduling. This is achieved by introducing a dual metric scheduling scheme, where the primary metric is inclined towards improving the throughput of the system and the secondary metric is intended to promote fairness in resource allocation. This work has been selected in IEEE ICC SCPA ’15 [6].
2. The dual metric scheduling algorithm is extended for downlink by relaxing the uplink constraints. The algorithm maximises the utilization of the resources, by employing the primary and secondary metric matrices to consider the intermittent resources for allocation, and provides a better trade-off between throughput and fairness.

To analyse the proposed algorithms, the LTE Vienna Uplink and Downlink Simulator [7], [8] is used as the simulation tool. The LTE Vienna Simulator is MATLAB-based [9]. It provides range of configurations and support to validate the performance of the proposed scheme. The standard schedulers available in the simulator are used to compare the performance of the proposed algorithms. Due to the limitation in the simulator to test the performance of the algorithm in terms of transmit power, a transmit power evaluation model is introduced in this work. The power evaluation model adopted in this work is presented in Chapter 3. Also, the simulator does provides only full buffer traffic. Hence, it is assumed that all the users have infinitely backlogged data for transmission and reception.

1.5 Thesis Outline

The thesis is organized as follows:

Chapter 2 provides a brief introduction of LTE system, its architecture and radio access technology. The chapter also provides information about the key design aspects of a LTE packet scheduler, its classification and a brief outline of standard scheduling algorithms and related works. Chapter 3 analyses some of the standard scheduling algorithms outlined in the previous chapter. Chapter 4 introduces a new algorithm scheme for LTE uplink and LTE downlink. Chapter 5 discusses the performance of the proposed algorithms. The conclusion of the thesis and future direction are provided in Chapter 6.

2 Background

This chapter presents the background information of the LTE system. The chapter outlines the network structure and protocol architecture of LTE, followed by some aspects of the physical layer in LTE. Since the work mentioned in this thesis is based on the scheduling algorithm in LTE, a description on the essential features of a scheduling algorithm are provided. This chapter also provides a brief outline on some of the standard scheduling algorithms and summaries the existing works from the literature.

2.1 Introduction

The growing demands of telecommunication system to support applications with high data rates resulted in the evolution of LTE system. In mobile data communication the choice of modulation scheme and multiple-access technology is trivial in order to achieve good systems performance. Orthogonal Frequency Division Multiplexing (OFDM) is a multi-carrier transmission scheme which is widely deployed and suited for broadcast applications because of its low receiver complexity which makes it suitable for Multiple Input and Multiple Output (MIMO) technology in achieving high transmission rates. LTE system has evolved from its predecessor 3G Universal Mobile Telecommunications System (UMTS) with a major change in its wireless access technology and modulation schemes. LTE deploys two separate access techniques for downlink and uplink transmission. It uses Orthogonal FDMA (OFDMA) in downlink and Single Carrier FDMA (SC-FDMA) in uplink (explained in detail in Section 2.3) [2]. The following are the requirements put forth by International Mobile Telecommunication-Advanced (IMT-Advanced) during LTE standardization phase:

- A peak data rate of 100Mbps in downlink and 50Mbps in uplink
- Significant improvement in Spectral Efficiency (SE) (2-4 times of Release 6 UMTS SE)
- Reduced latency with radio round trip time below 10 ms
- Scalable bandwidth from 1.4 MHz to 20 MHz

- The system should be backward compatible with existing 3G network
- The system should be optimized for user mobility

Although LTE has met most of the requirements mentioned by IMT-Advanced, the later version of LTE known as LTE-Advanced have exceeded all the requirements and qualified as a true 4G technology.

2.2 LTE Network Architecture

One of the distinguishing features of the LTE system from the previous cellular systems is that LTE is designed to support only Packet Switched (PS) services and has no support for Circuit Switched services. Thus, from a network perspective, the LTE system is purely based on IP architecture, where all the network entities are connected thorough Internet protocol (IP). The network can be split into two parts namely, Radio Access Network (RAN) and Core Network (CN). The RAN is consists of Evolved Universal Terrestrial Radio Access Network (EUTRAN) and the CN, namely the Evolved Packet Core Network (EPC). Figure 2.1 shows the overall network architecture and the interfaces through which the network elements are connected.

The EUTRAN consists of clusters of the evolved NodeB (eNodeB). Since the EPC supports only PS services, the CN is connected to IP Multimedia Subsystem (IMS) for VoIP support. Each of the network elements has their role either in signaling traffic (control plane), user data traffic (user plane) or both. The different entities of LTE network and their primary functionalities [10] are listed below:

- **User Equipment** (UE) represents the mobile equipment which internally consists of modules such as Mobile Terminal, Terminal Equipment and Universal Integrated Circuit Card (UICC) also known as SIM. The SIM card contains the information such as user's phone number, home network identity and security keys. The radio interface between UE and Evolved NodeB (eNodeB) is known as LTE-Uu [11].

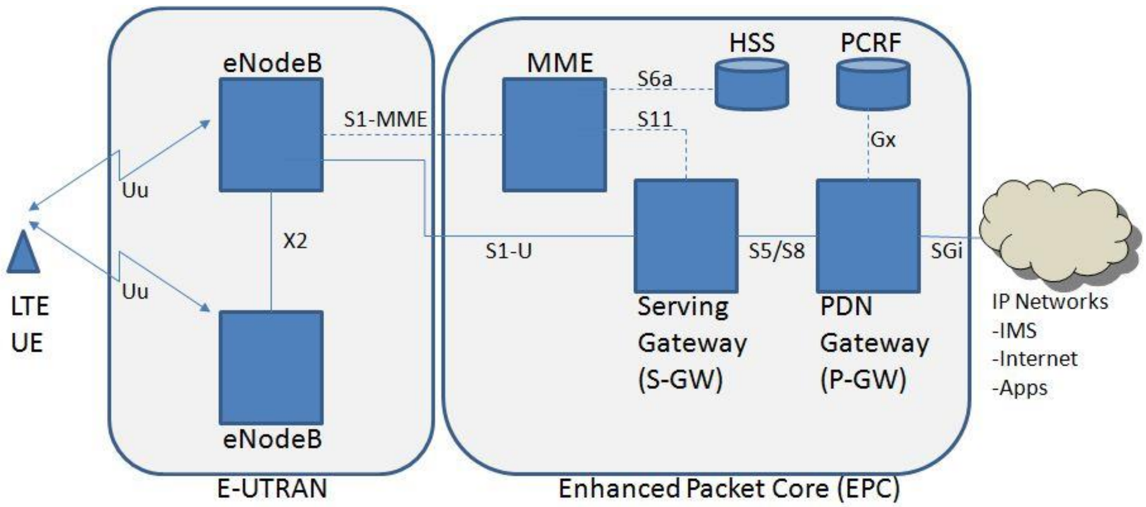

Figure 2.1 LTE Network Architecture [4]

- **eNodeB** is responsible for serving the UE by connecting them with the EPC [12]. The eNodeB is directly connected to the EPC using S1 interface and they are interconnected using X2 interface. The functionality of Radio Network Controller (RNC), which is present in 2G/3G systems, is decentralized among the eNodeBs. The eNodeB supports the transmission and reception of traffic over the air interface. It is also responsible for the various features such as Radio Resource Control, Mobility Management, and Radio Admission Control. Thus, the dynamic resource allocation, which is the prime focus of this work, is carried out by eNodeB.

The EPC is composed of the following functional entities [13]:

- **Home Subscriber Support** (HSS) is the network entity of the LTE system which replaces the Home Location Register (HLR) and the Authentication Center (AuC) of UMTS system. It consists of a database which stores and updates the user profile information and user identification and addressing. It is also responsible for generating security information from the user security keys, which is used for radio path ciphering and integrity protection.

- **Mobility Management Entity** (MME) is responsible for controlling the higher-level operation of mobile such as tracking user location, paging procedures, activation and deactivation of bearer channels and inter-network handover by means of signalling messages. It is connected with HSS using S6a interface.
- **Policy Charging and Rules Function** (PCRF) is a logical entity where decision making based on the policies and rules defined are done. It is also responsible for managing the service policy and rule information functionalities in the Policy Control Enforcement Function (PCEF).
- **Packet Data Network (PDN) Gateway** (P-GW) is responsible for connecting the LTE to the external IP networks. The Access Point Name (APN) is used to identify each of the external IP network which are connected to the system. It also supports policy enforcement features which are controlled by PCRF.
- **Serving Gateway** (S-GW) acts as the entry point for user plane traffic from the EUTRAN into the Core Network. It also acts as a mobility anchor for the users moving across eNodeB in EUTRAN, also referred as Intra EUTRAN mobility or between other 3GPP technologies. It is connected to MME using S11 interface and to P-GW using S5/S8 interface [14].

2.3 Radio Interface Technology

OFDM is a multi-carrier transmission scheme in which frequency selective wideband channel is divided into non-frequency selective narrowband channels that are orthogonal to each other. OFDM scheme along with channel coding and Hybrid ARQ makes it robust to time-variant channels. OFDM is implemented by means of Fast Fourier Transform (FFT). In the transmitter side, the incoming high data rate symbol is first converted serial-to-parallel to make the symbol period greater than the channel delay spread. If the high symbol data are transmitted serially with symbol period less than channel delay spread, it suffers from Inter Symbol Interference (ISI). Next, the parallel stream of inputs is given to IFFT processing with zeroes padded at the edges to make the number of sub-carriers equal to FFT size. The output of IFFT is the time domain OFDM signal.

The next improvement in OFDM is the insertion of Cyclic Prefix (CP) which is repeating a portion of time domain symbol at the end to the front. The main advantages of CP are:

- It retrieve back the OFDM symbol during FFT processing in the case of delay spread
- It eliminates the inter-symbol interference
- It allows the linear convolution of a frequency-selective multipath channel to be modelled as circular convolution

Cyclic prefix insertion is used to address the loss of orthogonality in time dispersive channels and makes signal robust to it. Delay spread is caused by time-dispersive channels. By adding CP at the prefix, the loss of data due to delay spread can be avoided. It is beneficial as long as the time dispersion does not exceed the cyclic prefix length. There are two types of CP: Normal and Extended CP. Extended CP length is larger when compared to Normal CP and hence used in high mobility and cell edge scenarios.

Orthogonal Frequency Division Multiple Access (OFDMA) is an extension of OFDM to the implementation of a multiuser communication system. OFDMA distributes subcarriers to different users at the same time, so that multiple users can be scheduled to receive data simultaneously. Usually, subcarriers are allocated in contiguous groups for simplicity and to reduce the overhead of indicating which subcarriers have been allocated to each user.

Despite all the advantages, the OFDMA has certain drawbacks such as high sensitivity to frequency offset and high Peak to Average Power Ratio (PAPR). Since, the eNodeB is a fixed entity with a constant power supply, the PAPR limitation has been overlooked by considering its various benefits for downlink transmission. However, considering the fact that the UE is power limited, 3GPP selected SC-FDMA to be employed in uplink transmission schemes to overcome the PAPR limitation of OFDMA. SCFDMA provides the desirable characteristics of OFDM with lower PAPR. Hence, it reduces the transmitter complexity and provide better power efficiency.

2.3.1 Physical Resource Organization

The LTE system has the flexibility to choose the bandwidth of operation from 1.4 MHz to 20 MHz depending upon the requirements. The LTE physical resource is defined in both time and frequency domain to provide the flexibility to the resource scheduler. Figure 2.2 depicts the LTE physical resource as time-frequency grid. Each subcarrier in LTE has a frequency spacing of 15 KHz. A Physical Resource Block (PRB) has a duration of 0.5 ms and a bandwidth of 180 KHZ. Thus one PRB 12 consecutive subcarriers in frequency domain and six or seven symbols (depending on the type of CP used) in time domain. The PRB is the minimum scheduling size for uplink and downlink resource allocation. Table 2.1 shows the number of LTE resource blocks for various supported system bandwidth according to 3GPP Release 8.

Table 2.1 Bandwidth and Resource blocks specifications

System BW (MHZ)	1.4	3	5	10	15	20
No. of RBs	6	15	25	50	75	100
No. of Subcarriers	72	180	300	600	900	1200

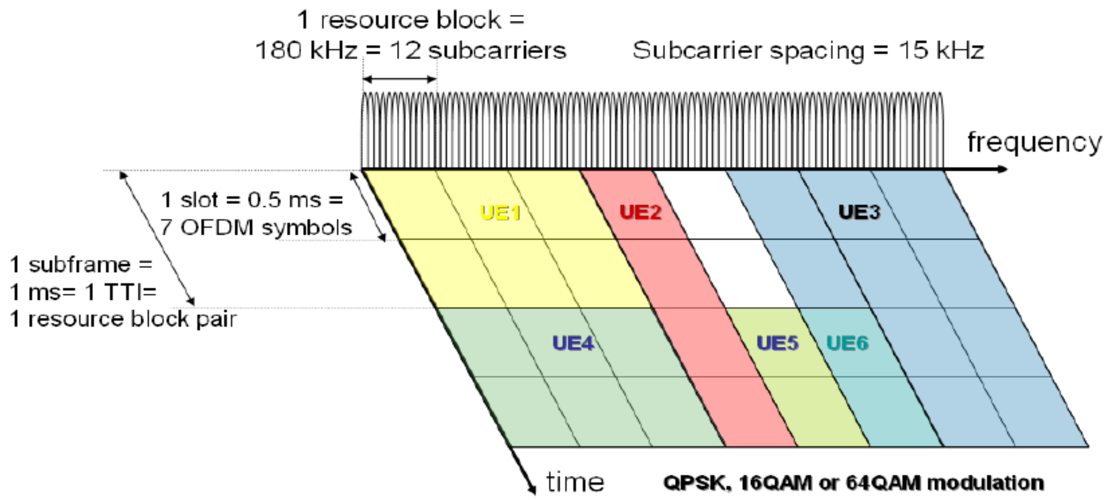

Figure 2.2 Physical Resource representation as Grid [10]

A radio frame of LTE has a duration of 10 ms, given that duration of one Transmission Time Interval (TTI) is 1ms. There are two types of LTE radio frames, known as Type 1 and Type 2. The Type 1 radio frames are used for FDD mode and it is divided into 10 subframes where each subframe consists of two slots of duration 0.5 ms each. The Type 2 radio frames are used for TDD mode and as shown in Figure 2.3, it is divided into 20 subframes where each subframe has one time slot of duration 0.5 ms.

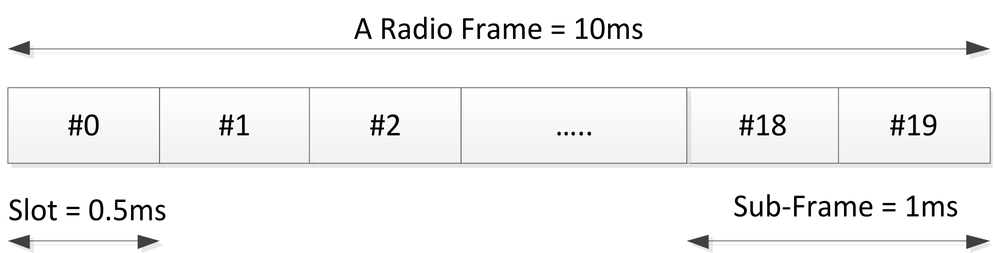

Figure 2.3 LTE Radio Frame

2.4 LTE Protocol Stack

The radio protocol structure of LTE is split into control plane stack and user plane stack. At user plane side, the application generates data packets that are managed and transported through the access stratum. The control plane is responsible for providing the signaling messages between the eNodeB and the UE for controlling the connection between the UE and the network. In both user plane and control plane, the information is processed by the sublayers in layer 2, before being given to the physical layer for transmission. The following section briefly explains the user plane and control plane sublayers and their functions.

2.4.1 User Plane Protocol Stack

The LTE user plane protocol stack is composed of the three sublayers. These sublayers form the Layer 2 [4].

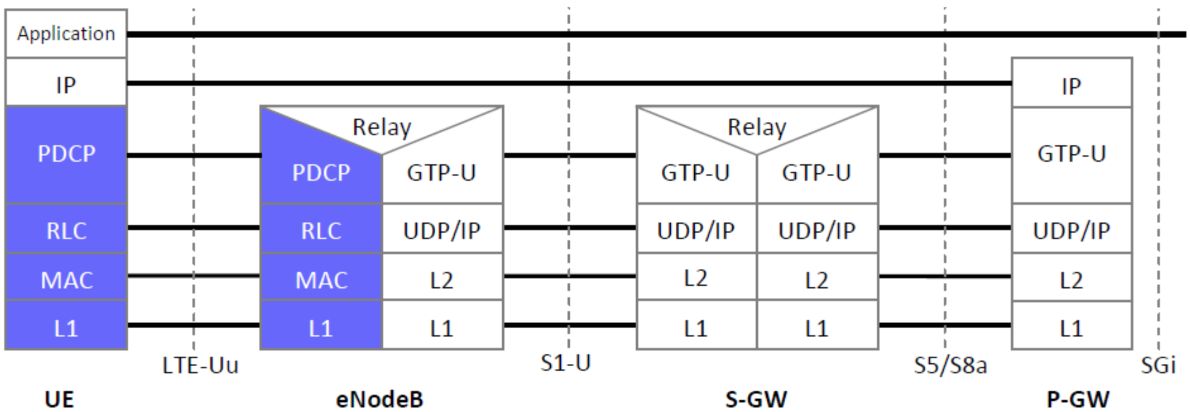

Figure 2.4 User Plane Protocol Stack [4]

Figure 2.4 shows the user plane protocol stack, which consists of the following [4]:

1. Packet Data Convergence Protocol Layer (PDCP)
2. Radio Link Control Layer (RLC)
3. Medium Access Control Layer (MAC)
4. L1 Layer

Packet Data Convergence Protocol Layer

PDCP layer is responsible for processing data from user plane as well as from control plane. It manages the RRC messages in control plane and IP packets in user plane. There are two types of Protocol Data Units (PDUs) supported in PDCP layer. They are Data PDUs and Control PDUs. The data format shown in Figure 2.5 is common for both control plane and user plane data. But some of the fields are not present in both of them. Table 2.2 shows the difference between control plane PDCP PDUs and user plane data PDUs.

Figure 2.5 PDCP Data PDU Format

The D/C field in the format is used to differentiate between Data and Control PDUs. From Table 2.2, it can be observed that, the three different data PDUs can be differentiated by the Sequence Number (SN) length. MAC–I field is exclusive to control plane data and it is used for providing integrity protection.

Table 2.2 PDCP PDU Types for User Plane and Control Plane

PDU Type	D/C	PDCP SN	MAC - I
User plane long SN	Present	12 bits	Absent
User plane short SN	Present	7 bits	Absent
Control Plane	Absent	5 bits	32 bits

The architecture of PDCP layer is different for control and user plane. Accordingly, the PDCP layer is responsible for some of the functions are excusive for each plane. The listed below are the major functions of PDCP layer.

Header Compression and Decompression

As LTE provides services in Packet-Switched (PS) domain, the header compression and decompression is vital in improving the efficiency of voice services closer to Circuit-Switched (CS) domain. PDCP layer uses RObust Header Compression (*ROHC) protocol for header compression. ROHC improves the header compression efficiency in two folds. Firstly, it allows the sender and receiver to store the static part of the header and to update them only if there are any changes in them. Secondly, it allows transmitting only the difference in dynamic parts from a reference clock maintained in both the transmitter and the receiver. Thus, for a VoIP packet, the overhead is compressed to four to six bytes from 40 bytes for IPv6 and 40 bytes for IPv4.

Handover Management

Handover is done to transfer an active call or data session when the UE moves from the coverage of one cell to the coverage of another cell. LTE supports two types of handover procedures:

1. Seamless Handover: Seamless handover is used for radio bearers supporting RLC Unacknowledged Mode (UM). These data are very sensitive to delays (e.g. voice services). Therefore, the handover process is designed to minimize the delays by decreasing the complexity. All the PDCP PDUs at the eNodeB that has not been transmitted will be forwarded to X2 interface for transmission to the target eNodeB. The PDCP PDUs at the UE that has not been transmitted will be transmitted after the handover is complete.
2. Lossless handover: Lossless handover is applied to radio bearers supporting RLC Acknowledged Mode (AM) where the data is tolerant to delays but less tolerant to loss. To support lossless handover, PDUs are sequenced. This sequence number is

used to acknowledge the reception of PDUs. All the PDUs that have not been acknowledged prior to handover are retransmitted.

Security

One of the main responsibility of PDCP layer is the implementation of security, by providing integrity protection and verification of control plane data and by encrypting and decrypting both user plane and control plane data. MAC-I field in RRC messages is used for integrity protection. Ciphering is done to protect the data from unauthorised access [15]. Since ROHC does not recognize the encrypted data, the security features are done after ROHC compression in transmit mode and decryption occurs before ROHC decompression.

Radio Link Control Layer

RLC layer is situated between PCDP layer and MAC layer [16]. RLC layers has different responsibilities in transmission and reception side. In the transmission side, RLC is responsible for segmenting PDCP PDUs into MAC layer Transport Blocks (TB). In reception side, it does the reassembly of MAC layer data and reconstructs PDCP PDUs. There are three data transmission modes in RLC [17], [18]:

1. Transparent Mode (TM)
2. Unacknowledged Mode (UM)
3. Acknowledged Mode (AM)

Transparent Mode

This mode has a very restricted use and it is mainly used for control signalling such as broadcast system information and paging messages. In this mode, the RLC overhead is not added to the data. In other words, TM is a pass-through mode which maps RLC Service Data Units (SDU) to RLC PDUs and vice versa.

Unacknowledged Mode

As explained in handover management, UM is used for traffic such as VoIP where delay is intolerable, however, loss of packets is tolerable. Similar to TM, UM provides unilateral data transfer. In this mode, the layer performs segmentation and concatenation of RLC SDUs, reordering and duplicate detection of RLC PDUs, and reassembly of RLC SDUs.

Acknowledged Mode

This mode is used to support traffic which are error sensitive but tolerant to delay. A Non-real time applications such as web browsing is an example of traffic supported by AM. The most distinguishing feature of this mode is that it allows the bidirectional data transfer where the RLC can both transmit and receive data. It performs the task of retransmission. It features Automatic Repeat reQuest (ARQ) to correct erroneous packets through retransmission of data. In the transmitting side, the RLC Data PDUs that are transmitted are stored in buffer before transmitting. Upon receiving the data, the receiving side provides Acknowledgement (ACK) and/or Negative Acknowledgement (NACK) indicating the information of received RLC Data PDUs. The transmitting side resegments the erroneous PDUs and transmits them again. In addition to the functions of the UM mode above, the RLC AM mode performs other functions such as Polling and Status Prohibit.

Medium Access Control Layer

MAC layer is the lowest sublayer in the user plane protocol stack. It is responsible for multiplexing and demultiplexing logical and transport channels [19]. It connects with RLC layer with the logical channels. In the transmitting side, it receives the MAC SDUs from the RLC layer and constructs MAC PDUs, which are sent to the physical layer with the help of transport channels. The MAC PDUs are also referred as Transport Blocks (TBs). In the receiver side, it reconstructs MAC SDUs from the MAC PDUs received from the physical layer.

Figure 2.6 shows the LTE channels mapping. The list of unicast logical and transport channels are given below [20]:

Logical Channels

1. Broadcast Control Channel Downlink CHannel (BCCH)
    a. It is used to broadcast system information
2. Paging Control Channel Downlink CHannel (PCCH)
    a. It is used to notify UE of incoming call or change in system configuration
3. Common Control CHannel (CCCH)
    a. It is used to deliver control information during connection establishment when no confirmed association between the UE and eNodeB has been established
4. Dedicated Control CHannel (DCCH)
    a. It is used to transmit dedicated control information to a specific UE
5. Dedicated Traffic CHannel (DTCH)
    a. It is used to transmit dedicated user data

Transport Channels

Downlink Transport Channels

1. Broadcast CHannel (BCH)
    a. It is used for part of the system information essential to access the DL-SCH
2. Downlink Shared CHannel (DL-SCH)
    a. It is used to transport downlink user data or control messages and system information not transported over the BCH
3. Paging CHannel (PCH)
    a. It is used to transport paging information

Uplink Transport Channels

1. Uplink Shared CHannel (UL-SCH)
    a. It is used to transport uplink user data or control messages
2. Random Access CHannel (RACH)
    a. It is used to access the network when the UE does not have allocated uplink transmission resources or when it has no accurate uplink timing synchronization

MAC layer has numerous functionality. It is responsible for HARQ operation, which is used for error correction [21]. In case of CRC failure (Cyclic Redundancy Check), it generates signaling messages (ACK or NACK) and accordingly the TBs are retransmitted. If the data is not retrievable, the MAC layer invokes the Automatic Repeat reQuest (ARQ) function of RLC layer to initiate retransmission of erroneous PDUs. MAC layer is also responsible for the timing alignment to ensure that there is no overlapping occurs during transmission of UEs and eNodeB.

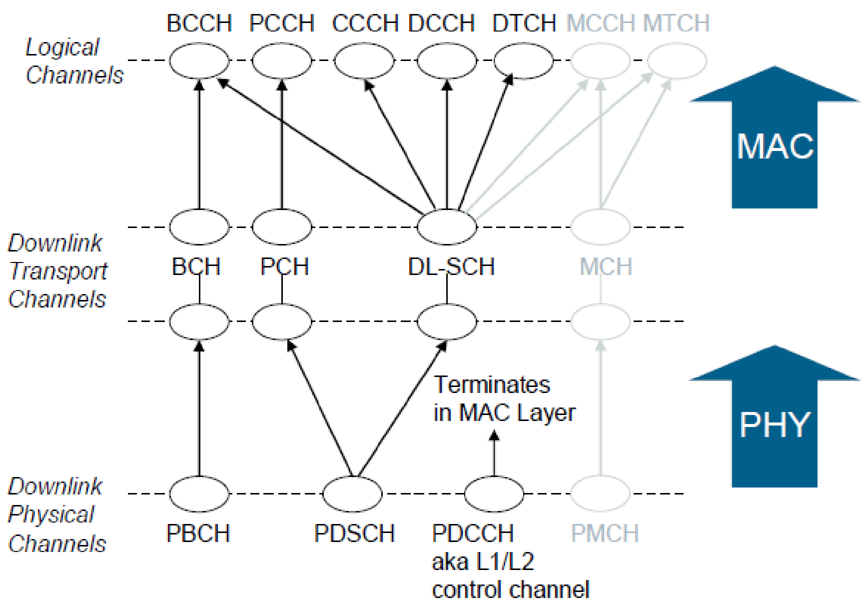

Figure 2.6 LTE Channel Mapping [3]

Scheduling

The important function of MAC layer, which is the prime focus of this work, is scheduling. MAC layer is responsible for allocating the available bandwidth to UEs which are active. The effectiveness of the scheduler determines the performance of the network. The implementation of the schedulers is specific to vendors as per their requirements and thus, it is open for research. The LTE scheduler design aspects and the existing scheduling disciplines are discussed in detail in Section 2.5.

L1 Layer

The LTE L1 layer, also known as Physical (PHY) layer, carries all the information from Layer 2 transport channels over the air interface. This section briefly covers the key concepts of PHY layer within the limitation of the work.

Physical Channels

The main purpose of the physical channel is to support the transmission of uplink and downlink transport channels. The physical channels are unidirectional. They are used to specify the modulation and coding schemes used and the way the information bits are transmitted over the air. Some of the important channels related to unicast are listed below:

1. Physical Control Format Indicator CHannel (PCFICH)
    a. It informs the size of the control region in terms of symbols.
2. Physical Hybrid-ARQ Indicator CHannel (PHICH)
    a. It used for carrying the ACK/NACK information of the data transmitted by the UE to the eNodeB.
3. Physical Downlink Control CHannel (PDCCH)
    a. It mainly signals the downlink scheduling assignments and uplink scheduling grants in the form of DCI (Downlink Control Information).

    b. Each PDCCH carries signalling information corresponding to a single or group of terminals.
4. Physical Downlink Shared CHannel (PDSCH)
    a. It is the main data bearing channel for downlink where data is transmitted as TBs from the MAC layer to the PHY layer on every TTI.
    b. It also carries the broadcast information which are not supported by Physical Broadcast CHannel and paging messages to the physical layer.
    c. It supports QPSK, 16 QAM and 64 QAM
5. Physical Random Access Channel (PRACH)
    a. It acts as an interface UE and eNodeB for ensuring time synchronisation of uplink transmission.
6. Physical Uplink Shared Channel (PUSCH)
    a. It is used to transfer both user data and control information from UL-SCH. The control information is multiplexed with user data using DFT-Spread.
    b. It supports QPSK and 16 QAM, while 64 QAM is optional.
7. Physical Uplink Control Channel (PUCCH)
    a. It is used to carry the Uplink Control Information (UCI) including HARQ ACK/NACK, Scheduling Request (SR), and Channel Quality Indicators, similar to PDCCH.

2.4.2 Control Plane Protocol Stack

Control plane protocols consist of layers which performs the same function as in user plane stack. However, the main controlling function which is done by 'Layer 3' in the stack, also known as Radio Resource Control (RRC) protocol is specific to control plane stack. The RRC is responsible for radio-specific functionalities and for configuring the lower sublayers between eNodeB and the UE. All the AS protocols terminate in the network side of the eNodeB. The Non-Access Stratum (NAS) sublayer is between the UE and the MME. Some of the major functions [4] that NAS control protocol performs are paging, authentication and EPS bearer management.

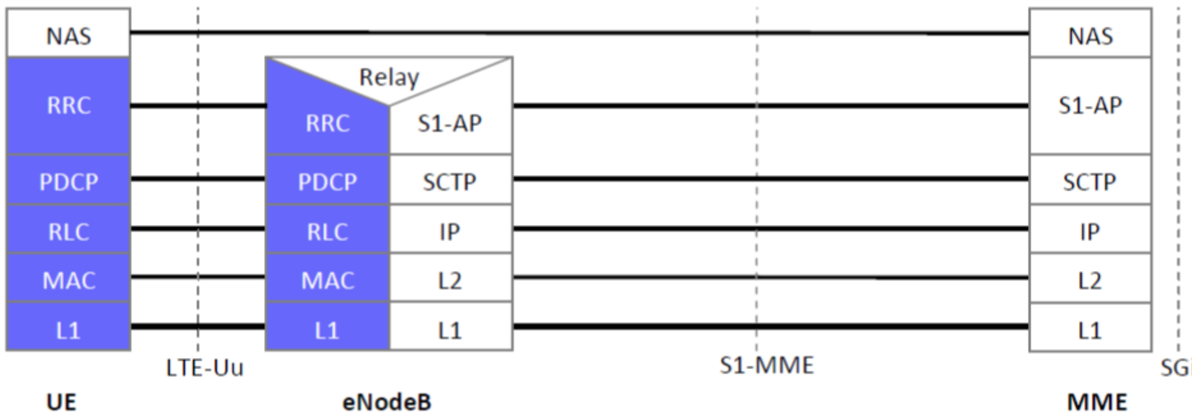

Figure 2.7 Control Plane Protocol Stack [4]

In addition to the RRC, the PDCP and RLC perform their functions on control plane data. This will be outlined in Section 2.4.1 where these layers are discussed as part of the user plane protocols.

Radio Resource Control

The RRC operates in between the UE and the eNodeB [22]. There are two RRC states in which a UE can exist. They are idle state and connected state. The functionality of RRC depends on the state of the UE.

When the UE is in idle state, it performs cell selection and reselection to find the ideal cell to camp. The UE monitors the paging channel to detect the incoming calls and to acquire system information. Based on the system information such as radio link quality, radio access technology and cell status, the RRC protocol performs cell selection and reselection procedures.

When the UE establishes an RRC connection, it enters RRC connected state. The following are the function covered by RRC protocol.

System Information

The RRC is responsible for broadcasting System Information (SI), some of which is applicable only for the UE in idle mode while a few SI is applicable for the UE in connected mode. The SI is defined by parameters known as System Information Blocks (SIBs). There are many types of SIBs and each of them is used to convey specific information. The master Information Block (MIB) consists of information related to some frequently used transmitted parameters that are essential for the UE's initial access to the network. All the SIBs constitute the SI message. When the SI changes, the E-UTRAN notifies regarding the changes to the UE using paging channel.

RRC Connection Control

RRC is responsible for connection control which includes procedures for connection establishment, modification and release for paging, security activation and other functions such as configuration of lower protocol layers. Figure 2.8 shows the possible combination of UE connection states. EPS Mobility Management (EMM) state denotes that UE is registered in the MME and the EMM state can be either Deregistered or Registered. The EPC Connection Management (ECM) state denotes that the UE is connected to the EPC. These states can be either ECM Idle or Connected modes. The transition between ECM Idle and Connected modes involves RRC connection establishment and release.

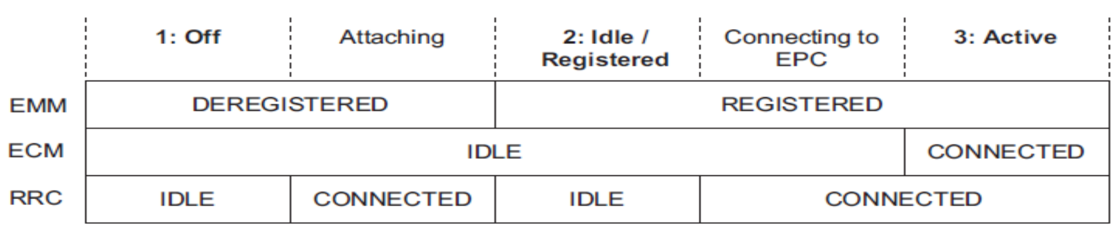

Figure 2.8 Possible Combinations of UE Connection State [4]

Measurement Configuration Reporting

The measurement information reported by the UE is used to support the mobility control. The E-UTRAN configures the UE to report using the following measurement configuration elements.

- **Measurement Objects**: It defines the parameters on which the UE is expected to perform the measurements. In addition, the measurement objects also include the associated parameters such as black-listed cells to help the UE to narrow the process of measurement.
- **Reporting Configurations**: It consists of the specifications related to a measurement report such as the criteria for the UE to send a report and the information required in the report.
- **Measurement Identities**: It identifies the measurement to be done and defines the measurement objects and reporting configuration
- **Quantity Configurations:** It is defined as the filtering to be used on each measurement.
- **Measurement Gaps**: It is defined as the time period where no transmission will be scheduled to facilitate the UE to perform the measurements.

Network Controlled Mobility

The other main function of RRC is the procedures for supporting mobility from LTE to another Radio Access Technology. After security procedures are activated, the handover to target RAN is done with the help of Network Assistance Cell Change (NACC) Order. Figure 2.9 depicts the mobility from LTE procedure and a brief note on the same is provided as follows:

- The UE sends the measurement report message to the source eNodeB
- The source eNodeB initiates the handover procedure to by requesting the target RAN along with the UE system information. The target RAN responds by generating a 'Handover Command'.
- The source eNodeB responds back to the UE with a 'Mobility Command' message which contains the information about the target frequency/cell.
- Upon receiving the 'Mobility Command' message the UE connects with the target node and the connection is established.

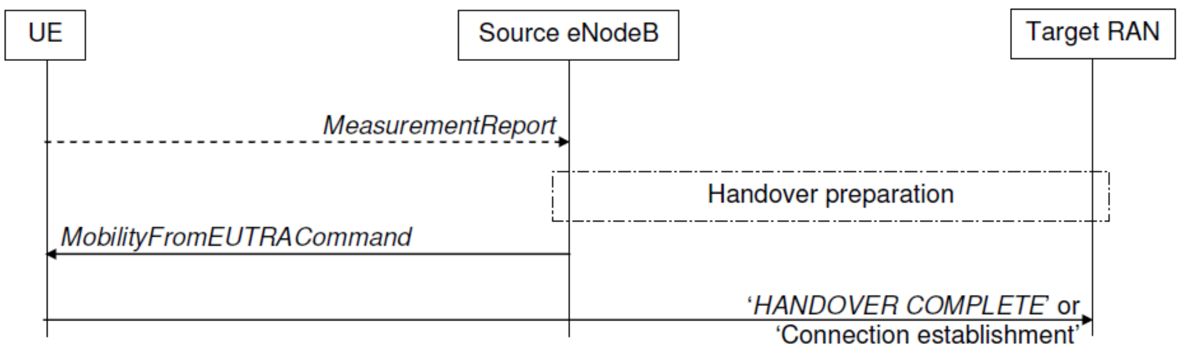

Figure 2.9 Mobility from LTE [4]

2.5 LTE Scheduler

The functionality of the LTE scheduler is present in eNodeB and operated in LTE MAC layer. The LTE scheduler assigns resources with granularity of one TTI in time domain and one RB in frequency domain. The scheduling decision is made for every TTI and it is valid until the next slot. This information is carried to each UE using PUCCH. The data required for scheduling decision problems is made available at eNodeB by feedback signals. The scheduler processes the reported feedback information and works on addressing the requirement of all the UEs which are active and under its control. The logical channel which is established between the UE and the eNodeB is known as a radio bearer. When the UE joins the network, a default bearer is established between the UE and eNodeB for setting up the basic connection and for exchanging control messages. This default bearer is maintained as long as the UE is active in the network. The user plane data is carried by the Data Radio Bearers (DRBs) and the control plane data is carried by the Signalling Radio Bearers (SRBs). The following are the control signalling (under the scope of this work) carried by the SRBs:

- **Buffer Status Report**

The eNodeB assigns resources for transmission to the UEs, if the UEs have data to be sent or received. On the downlink, the information related to the data received for the UEs is available at the eNodeB. However, the status of the data to be sent is not known to the eNodeB. Hence, the Buffer Status Reports (BSR) is used to signal the eNodeB regarding the availability of data to be sent at the buffer of each UE. The BSR are classified into two types: long BSR and short BSR. The long BSR is used to transmit the information about the availability of data in four logical channel groups and short BSR is used to inform the eNodeB about amount of data in only one logical channel group. Each of them is used depending on the amount of available resources to transmit the BSR.

- **Scheduling Request**

The Scheduling Requests (SR) is used to differentiate between the active UEs and idle UEs. Each active UE sends SR to request the eNodeB for resources for transmission.

- **Power Headroom Report**

The Power headroom Reports (PHR) indicates the transmission power available in the UE in addition to the power being used by it for the current transmission. This report is used by the eNodeB to determine the resource which can be supported by the UE in the current subframe.

- **Sounding Reference Signal**

The Sounding Reference Signal (SRS) is used to inform the eNodeB about the uplink channel capacity. It is transmitted only in LTE uplink in the last symbol of SC-FDMA of duration 1 ms.

- **Channel Quality Indicator**

The Channel Quality Indicator (CQI) is used to transmit measurements of channel quality between the UE and eNodeB.

- **Demodulation Reference Signal**

Demodulation Reference Signal (DMRS) is used for channel estimation when coherent demodulation is required. It is transmitted along with the user plane data in the fourth symbol of SC-FDMA and the eNodeB extracts the channel information of the current transmission, while SRS is periodically transmitted when there is no data transmission.

2.5.1 Design Aspects

There are several key aspects that are to be considered while building a scheduler that functions in an effective way. The key features [23] that are very essential for a scheduler are listed below.

- Spectral efficiency
  The main objective of scheduler is to effectively utilize the available resources. The wastage of resources is not tolerated. Maximization of the throughput is one of the primary objectives of any scheduler.
- Fairness
  Fairness is the measure of starvation due to unequal distribution of resources. A scheduler should consider that all the users. Irrespective of the channel conditions o the users, the scheduler must be provide with minimum resources to guarantee minimum performance.

- Energy consumption

  Energy consumption is a vital metric for devices with limited power. This is one important aspect for uplink schedulers as the UEs are limited in terms of power. Energy efficiency will be a key aspect in such scenarios.

- QoS provisioning

  For QoS aware schedulers, it is important to satisfy minimum service parameters like delay, packet loss rate and guaranteed bit rate for Real Time and Non-Real Time traffic..

- Complexity

  The scheduling algorithm must evaluate the metrics and operates for every TTI. Hence, complexity is a key feature in designing a scheduler.

2.5.2 Model of LTE Packet Scheduler

A model of LTE Packet scheduler is shown in Figure 2.10. The scheduler receives the Channel Quality Indicator (CQI) feedback from the UEs, which is based on the channel conditions, and evaluates a decision metric considering factors such as CQI feedback, average throughput, QoS requirements and buffer status reports.

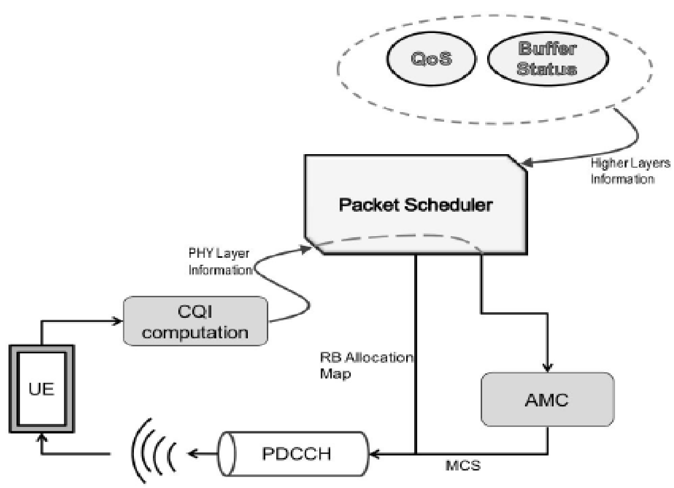

Figure 2.10 Model of Scheduler in LTE System [23]

CQI Feedback

The eNodeB decides the modulation and coding scheme (MCS) for each user based on the channel conditions. The UE is responsible for reporting the CQI feedback during uplink transmission. The eNodeB deciphers the data rate which can be supported by the channel from the CQI feedback. The CQI feedback reported by the UE is the highest MCS which can be decoded by it, given that the BLER does not exceed 10%. Hence, it is a measure of the channel conditions and the characteristics of the UE receiver.

Table 2.3 CQI Index

CQI Index	Modulation	Code Rate	Efficiency
0	'Out-of-range'	Nil	Nil
1	QPSK	0.076	0.1523
2	QPSK	0.12	0.2344
3	QPSK	0.19	0.3770
4	QPSK	0.3	0.6016
5	QPSK	0.44	0.8770
6	QPSK	0.59	1.1758
7	16QAM	0.37	1.4766
8	16QAM	0.48	1.9141
9	16QAM	0.6	2.4063
10	64QAM	0.45	2.7305
11	64QAM	0.55	3.3223
12	64QAM	0.65	3.9023
13	64QAM	0.75	4.5234
14	64QAM	0.85	5.1152
15	64QAM	0.93	5.5547

Since, the CQI feedback is the important input for deciding the MCS, the frequency of CQI reporting is critical. This is controlled by the eNodeB in two ways: periodic reporting and aperiodic reporting. The PUCCH is used for periodic reporting while PUSCH is used for aperiodic reporting and the eNodeB specially instructs each UE to send individual CQI reports. The CQI index value ranges from 0 to 15. Table 2.3 shows the CQI Index and the associated MCS and efficiency.

Adaptive Modulation and Coding (AMC)

In wireless communication system, due to factors such as interference and noise level, the channel quality experienced by each UE is different from one another. This principle is used by LTE system to adjust the modulation and coding rate of the users based on the channel conditions to increase the efficiency of the packet-switched services. This is referred to as link adaptation. The Adaptive Modulation and Coding Schemes (AMC) is used to provide the link adaptation in LTE system. The AMC has the flexibility in selecting the modulation and coding schemes for each UE. Depending upon the scenario, the modulation scheme can be selected between QPSK, 16 QAM and 64 QAM. Since QPSK has higher tolerance for interferences, it is chosen in case of poor channel condition. However, QPSK provides low transmission bit rate. Higher order modulation schemes such as 64 QAM overcome this hurdle by providing higher data rate; however it is highly sensitive to interference. Thus, it employed when channel conditions are good. The performance of 16 QAM falls in-between QPSK and 64 QAM and it is selected when the channel condition is moderate. Similar to the modulation schemes, the code rate is chosen based on the channel conditions. A lower code rate is chosen in case of poor channel conditions and a higher code rate is chosen when the channel conditions are good.

2.5.3 Scheduling Algorithm

The objective of the scheduling algorithm can be defined as distribution of the available resources among the active users in such a way to improve the performance of the system.

Hence, it can be modelled as a decision problem, where the decision metric is an objective function which is designed considering the key aspects addressed under Section 2.5.1. The effectiveness of the algorithm depends upon two factors:

1. Decision Metric
2. Scheduling Strategy

The following section briefly discusses the different decision metrics and scheduling strategies of various scheduling algorithm available in the literature.

Decision Metric Modelling

As mentioned earlier, the scheduling algorithm considers one or more factors mentioned under Section 2.5.1 and models a decision metric by defining an optimization problem to maximize or minimize them. Considering the desired system performance, the algorithm evaluates the metric value for each UE and RB pair.

Consider a system containing M active users and N available RBs. A resource allocation matrix or decision matrix is defined as a $M \times N$ matrix of decision metric, where the element $H(i,j)$ is formed by calculating metric value for the pair user i and RB j.

$$H(N,M) = \begin{pmatrix} H(1,1) & \cdots & H(1,M) \\ \vdots & \ddots & \vdots \\ H(1,N) & \cdots & H(N,M) \end{pmatrix} \qquad \text{Eq. 2.1}$$

$H(N,M)$ denotes the resource allocation matrix. The resource allocation matrix plays a vital role in the performance of the scheduler and differs for every algorithm. Some of the different algorithm from the literature and their decision metric are explained below.

The author [24] proposes an uplink scheduling algorithm considering best effort and delay sensitive traffic. The decision metric, which is referred as reward function by the author, is computed specific to the type of traffic flow. The reward function for best effort traffic is computed by formulating the achievable data rate as a function of current data rate and previously achieved throughput. The weightage to current data rate to past achieved throughput is decided as per user satisfactory level by using a variable, α_i. For delay sensitive traffic, a similar approach is followed. The algorithm computes the rate at which the UE has to be scheduled such that it minimizes the delay associated with the packets. The algorithm tries to greedily maximise the reward function for best effort traffic, on the other hand, it optimizes to minimal reward function for delay sensitive traffic.

In [25], the author proposes Channel-Adapted Buffer Aware (CABA) scheduling algorithm for LTE downlink. CABA algorithm has four objectives: 1. Maximizing system throughput, 2. Maximizing fairness in allocation, 3. Minimizing packet loss rate and 4. QoS provisioning. The algorithm computes a priority function by diving the assigning different priorities for Real Time and Non-Real Time traffic based on the CQI feedback. Additionally a buffer aware factor is introduced to minimize the packet loss rate. A weighted priority factor, which is computed by finding the ratio between Guaranteed Bit Rate to the average throughput achieved by the user, is added for Real Time traffic.

The author in [26] tries to increase the energy efficiency of the LTE system by proposing algorithm referred as Energy-Efficient Score Based Scheduler (EESBS). The algorithm works under the principle of bandwidth trade-off. Considering a LTE system with low traffic flow, each of the user in the system can support additional resources by decreasing their modulation order, provided the current achieved data rate is preserved. The author term this metric as energy metric and computes the metric for each UE-RB pair. Based on this energy metric and a penalty function for each user, a score (resource allocation matrix) is formed. The penalty function is introduced to promote the fairness in allocation process. The UE-RB pair having the least score values are mapped. This process is repeated until all the resources are mapped.

In [27], the author has presented a downlink scheduler for real time traffic. The scheduler operates in two levels: the upper level of the scheduler is used to define the amount of data the real time user can transmit under the permissible delay for each TTI and the lower level of the scheduler assigns the RBs to the user with a better trade-off between system throughput and fairness. It is to be noted that, the upper level of the scheduler is not channel aware, while, the lower level of the scheduler considers the channel quality for distributing resources among the users.

Scheduling Strategy

After evaluating the decision metric, the second part of the algorithm is to determine the suitable UE – RB pair such that the desired system performance is achieved. The algorithm accepts the resource allocation matrix as input and searches all the UE-RB pair to find the optimal solution. The execution of this scheduling strategy [28] can be categorized into two type:

1. Search by Maximum/Minimum Strategy

This is the conventional strategy employed by most of the algorithm where the scheduler searches the matrix for the maximum (in case of metrics such as system throughput, fairness, etc.,) or minimum (in case of metrics such as power consumption, packet delay, etc.,) value pair of UE_i and RB_j and assigns the RB_j to UE_i. The complexity of the algorithm is very less when search by maximum/minimum strategy is employed. The algorithm performs a recursive search until all the available RBs are mapped to suitable UEs.

2. Pattern-based Search Strategy

Pattern-based search strategy is used by the algorithm when the allocation process is does not follow the conventional recursive search process. The complexity of the algorithm may become higher depending upon the type of search pattern employed. [29] , [30] are a few examples of pattern based scheduling algorithm.

2.5.4 Types of Scheduling Algorithm

Based on the decision metric modelling followed by the schedulers, they can be classified into three types [23]:

1. Channel Unaware Schedulers
2. Channel Aware Schedulers
3. QoS Aware Schedulers

Each of the three types is explained in the sections below.

Channel Unaware Schedulers

This category of algorithms is widely used in wired connections. Hence, the performance of these algorithms are for LTE system is very low when compared to other categories. These algorithm do not count the CQI feedback given by the UEs. Hence, they consider all the UEs as equal and try to promote fairness among all the users. Although this reduces resource starvation among the users, the system performance becomes poor as the resources are not efficiently mapped among the UEs. The following algorithm fall under channel unaware category.

Round Robin Scheduling Algorithm

Round Robin (RR) is channel unaware decision based algorithm. Practically, it produces the worst results in terms of throughput among the other algorithm. The algorithm assigns resource blocks to every user in cyclic order without considering the channel conditions. Thus, the algorithm is very inefficient. It has to be noted that, the users with bad channel state will require more resources than the users with better channel condition. Hence, by distributing equal share in terms of resource, the algorithm fails in terms of fairness requirements. Also, some of the users may not have enough data to transmit in the allocated resources. Thus, the algorithm fails in spectral efficiency aspect as well.

Resource Fairness Scheduling Algorithm

Resource Fairness (RF) scheduler is a compromise between throughput and fairness. The algorithm is designed to achieve a high throughput under the constraint of minimum level of fairness. The users are given the same amount of resources. The algorithms suffers the same demerit as that of RR scheduler as the channel conditions are not taken into account while assigning resources.

Channel Aware Schedulers

The channel aware schedulers utilize the CQI feedback to interpret the channel condition and utilise it in the process of allocating resources to the users. The algorithms listed below are some of the standard channel aware schedulers.

MaxMin Scheduling Algorithm

The aim of MaxMin (MM) scheduler is to maximize the value of the minimum user throughput. The algorithm delivers a fair scheduling but in terms of throughput, the algorithm performs below par. The algorithm works by the principle of max-min fairness; therefore, the increase in allocation of resource of one UE must be compensated by decrease in resource of other UE. The algorithm considers the past achieved throughput and provides almost fair resources among all the users.

Best CQI Scheduling Algorithm

The primary object of BCQI is to maximize the date rate. The scheduling algorithm operates by assigning higher priority to the user with highest channel quality. Thus, UE with best channel condition will achieve higher rate and higher throughput for every TTI cycle. In terms of fairness, BCQI performs in a poor manner. This is due to the fact that, UEs with bad channel conditions are not allowed to compete in the resource planning. Thus BCQI is not a fair scheduler.

Proportional Fairness Scheduling Algorithm

The Proportional Fairness (PF) algorithm aims in maximizing the throughput of the user considering the past achieved throughput. The algorithm aims maximize the metric function by determining the ratio of long term achieved data rate to the past achieved throughput. Thus the algorithm achieve higher throughput as well as good fairness among the users.

QoS Aware Schedulers

The schedulers which falls under QoS aware category, considers QoS requirements of the users while mapping resources among the users. In addition to channel awareness, these category of schedulers considers QoS provisioning as one of the desired aspects while constructing the decision metric.

2.6 Summary

This chapter outlined the basics of LTE system, the access technology and its protocol stack. The various channels present in the system and their functionalities were briefed. Next, the model and the keys aspects behind designing LTE scheduler were explained. The generic version of scheduling algorithm and the types of scheduling algorithms were presented. Finally, some of the working standard scheduling disciplines were analysed.

3 Evaluation of Scheduling Algorithms

3.1 Introduction

The previous chapter explained the model of LTE packet scheduler and its desirable features. The effectiveness of a scheduler is measured in terms of performance parameters. Hence, the performance parameters are crucial for the comparison between different scheduling algorithms. In this chapter, the schedulers briefed falls under channel unaware and channel aware categories in Section 2.5.4 are compared in terms of throughput, fairness and transmit power. In order to focus on the allocation strategies of various algorithms, the simulation setup shall be considered as scenario with one eNodeB and 20 UEs with full-buffer traffic model. As the core scheduling functionality of these scheduling algorithms is the same for downlink and uplink, the performance of downlink schedulers is not provided to avoid redundancy.

3.2 Performance Parameters

The scheduling algorithms explained in the previous chapter can be classified into three types based on their objective functions. Each of them is designed to maximize specific system performance mentioned under section 2.5.1.

- Type 1: Best CQI scheduler work on maximizing the utilization of radio resources by prioritizing the users with good channel conditions over the users with poor channel conditions.
- Type 2: MaxMin scheduler and Round robin scheduler are designed to improve the fairness on resource allocation among UEs.
- Type 3: PF and RF schedulers are the hybrid schedulers and are designed to stand between the type 1 and type 2 category.

The performance factors which are used to evaluate and compare these schedulers are interdependent. For example, it is practically not possible to design a scheduler which will give max throughput and also provide perfect fairness. Hence, the algorithm must find a trade-off measure to compromise in terms of various performance parameters. This provides diverse options to the vendor to select scheduling algorithm based on specific needs. In order to evaluate the performance of each algorithm, the following metrics are used to analyse them and compare against each other.

3.2.1 System Throughput

System throughput is the measure of the UE's utilization of the resource provided. It is one of the primary objectives of any scheduling algorithms. It is defined as the number of bits effectively transmitted over the air interface from UE to eNB in a given time. It is represented as follows:

$$T = \frac{I_b}{t} \qquad \text{Eq. 3.1}$$

where I_b is the number of information bits successfully transmitted from UE to eNB and *t* is the number of subframes. Given the SNR value between a user and eNodeB, the achievable throughput can be calculated using Shannon's channel capacity formula.

3.2.2 Jain's Fairness Index

Jain's fairness is a quantitative measure of fairness in allocation of resources in a system. The idea is proposed by the author [31] to find fairness in resource allocation in shared computer systems. The concept can be reused for LTE system to evaluate the fairness in resource allocation.

Consider a simple LTE system composed of one eNB and N users. Jain's fairness index for resource allocation can be calculated using the following formula

$$J = \frac{[\sum_{n=1}^{N} T_n]^2}{N \times [\sum_{n=1}^{N} T_n]^2} \qquad \text{Eq.3.2}$$

where T_n is the throughput of the user *n*. *n* is subset of *N* where *N* is the total number of users. In an absolute fair system, the throughput of every user is the same. Hence the value of Jain's fairness index will be equal to one.

To understand Jain's fairness index, let us analyze using a simple LTE system with one eNB and 3 users: User A, User B and User C for the following three cases.

Table 3.1 Fairness Index for a scenario with three users

User A throughput	**User B throughput**	**User C throughput**	**Jain's fairness index (J)**
10 Mbps	0 Mbps	0 Mbps	0.33
10 Mbps	10 Mbps	0 Mbps	0.67
10 Mbps	10 Mbps	10 Mbps	1

The least fairness index value is 0.33, which can also be represented as 1/N where N (= 3 in this case) is the number of user in the system. When all the users achieve the same throughput, the fairness index is equal to 1. Thus, the fairness index value ranges from 1 to 1/N.

3.2.3 Throughput to Power Ratio

One of the key aspects in designing any uplink scheduler is consideration for power consumption. The users have limited battery power and it is vital for scheduling algorithm to allocate the resources in an energy efficient pattern to improve the battery life.

According to the specification given by [32], the UE Transmit power (P_{Tx}) is modeled as follows:

$$P_{Tx} = \min (P_{MAX}, P_0 + \alpha \cdot P_L + 10 \log10 (M) + \Delta MCS + f(\Delta i)) \qquad \text{Eq. 3.3}$$

Table 3.2 UE Transmit Power Parameters

Parameter	Meaning
P_{MAX}	The maximum user transmission power
M	The number of allocated PRB at a given TTI
P_0	Open loop path-loss power value. Typically -53 dBm per RB.
A	Open loop path-loss factor. Typically 0.4 to 0.6.
P_L	Downlink path-loss measured in the UE
ΔMCS	Cell dependent factor
f (Δi)	User specific closed loop P_{MAX}

Due to the limitation in the simulator, a simple power consumption model is constructed to evaluate the scheduler in terms of transmit power. Mads Lauridsen et al [33], have conducted experiments on LTE system to analyze the relation between resource allocation and the UE transmit power. The author has concluded that resource allocation is directly proportional to the UE transmit power.

From [32], the maximum UE transmit power (P_{max}) when UE gains access to a specific cell is equal to 23 dBm and the minimum UE transmit power (P_{min}) is calculated to be -30 dBm. By varying only the number of RBs and keeping other parameters fixed, the UE transmit power can be simplified as,

$$P_{Tx} = \min (P_{max}, P_{min} + 10 \log10 (M)) \qquad \text{Eq. 3.4}$$

Throughput to Power ratio (TPR) is defined as the ratio between utilization of resources by each UE to its corresponding transmit power for the given simulation time.

$$TPR = \left| \frac{T_n}{P_{TX}} \right| \qquad \text{Eq. 3.5}$$

This factor is used to evaluate the performance of the scheduling algorithm in terms of power consumption.

3.3 Simulation Setup

Table 3.3 Simulation Parameters

Parameter	Value
System Bandwidth	5 MHz
Number Of Resource Blocks	25
No. of Subcarriers	300 (12 Per RB)
No. of Subframes	100
No. of Users	20
Channel Model	PedA
Antenna Configuration	1 X 1
Traffic Model	Full Buffer Model
Receiver	Zero Forcing
Channel Estimation	Perfect

The simulation parameters are summarized in the Table 3.3. As aforementioned, a full-buffer traffic model is used in the simulation, i.e., in the given simulation time, each user has infinite data to transmit to the eNodeB.

3.4 Results

In this section, the comparison of different scheduling algorithm is shown in terms of performance metrics mentioned in Section 3.2.

3.4.1 Throughput Analysis

Figure 3.1 shows the throughput values of different resource allocation algorithms, evaluated using Eq. 3.1. As the users are spread over the SNR range 30dB to 0dB, it can be observed that the amount of resources that each user receives depends on the SNR that this user is assigned with. The type 1 scheduler, BCQI scheduler, shows high throughput value in the order of 21 mbps as it provides more resources to good-channel users. However, users with low-SNR are never scheduled. It is observed that comparing RF scheduler, PF achieves a better throughput value of 17.1 mbps since it allocates resources considering the good-channel users as well as the users past achieved throughput. All the UEs achieve the same constant throughput under MaxMin scheduling strategy. The channel unaware strategy of RR scheduler reflects on the cell throughput results and hence, RR scheduler delivers the lowest throughput of all.

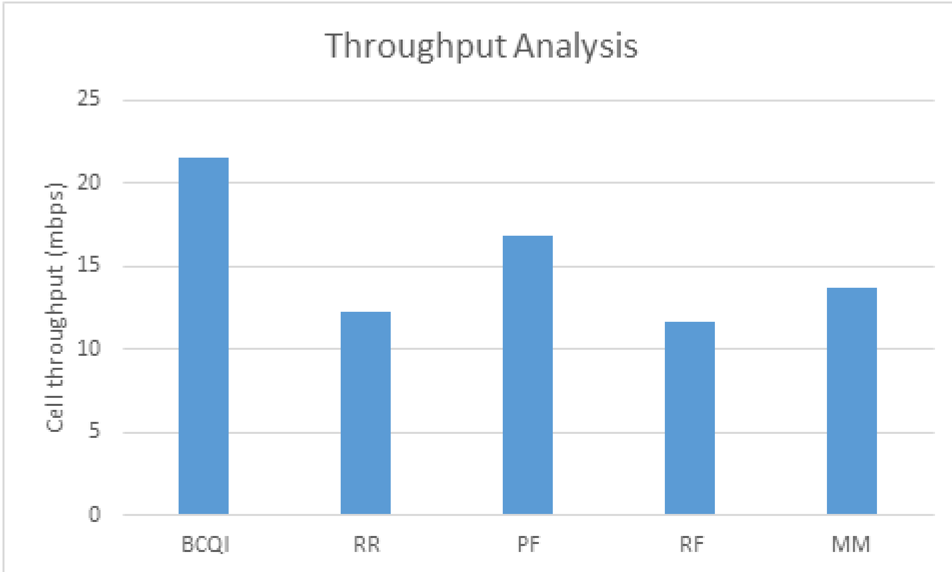

Figure 3.1 Throughput comparison of various schedulers

3.4.2 Fairness Analysis

Upon analysing the scheduling algorithms using fairness index given by Eq. 3.2, it is observed that fairness performance of schedulers is in contrast with their throughput performance. The MaxMin scheduler achieves the highest fairness value of 0.99 among all the schedulers. This near perfect fairness performance is due to the objective function of the MaxMin scheduling algorithm. But, in contrast, RR scheduler whose objective is to improve the fairness does not perform as expected. This is due to its channel unaware strategy which neglects the channel condition when allocating resources among the UEs. The result of Best CQI scheduler is the least among all the schedulers considered. This can be explained by the allocation strategy employed by BCQI scheduler where the users with poor channel conditions are neglected. Hence, it results in starvation for users with poor channel condition and thus, low fairness index. The RF and PF schedulers perform better than BCQI scheduler and provide optimal results in terms of fairness next only to MaxMin scheduler.

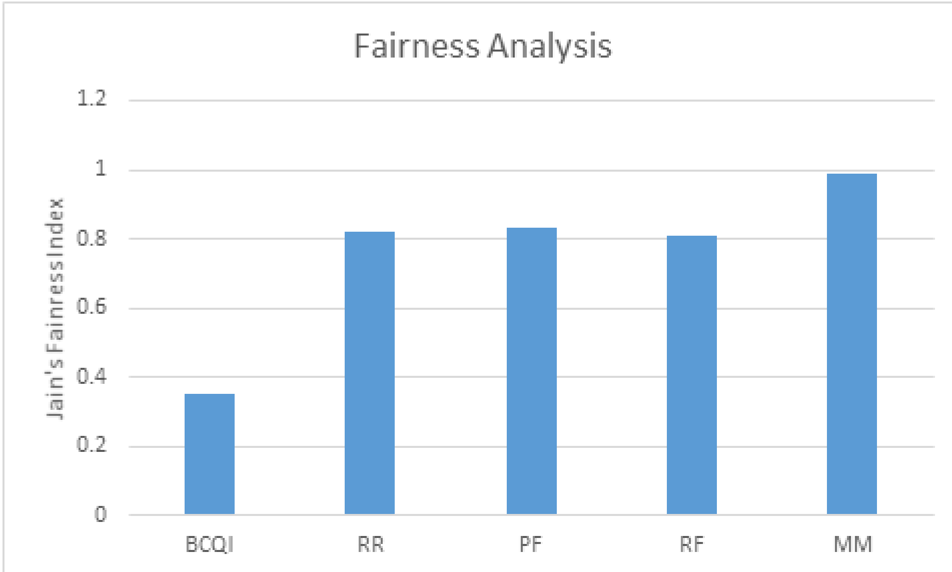

Figure 3.2 Fairness comparison of various schedulers

3.4.3 Throughput to Power Ratio Analysis

The power efficiency performance is critical for LTE Uplink scheduling algorithm. The throughput to power ratio performance of the different uplink scheduling algorithm is analysed in this section. Figures 3.3, 3.4, 3.5 and 3.6 depict the TPR performance of the schedulers evaluated using Eq. 3.5. In order to analyse the energy efficiency of the schedulers in detail, the TPR results are grouped under three cases.

Case 1: Best Channel Conditions

Users indexed from 1 to 5 have the best possible channel condition. Figure 3.3 shows the throughput to power ratio performance of these user for all the schedulers discussed earlier. The standout algorithm in this case are BCQI scheduler. Users with better channel condition show much better spectral efficiency than the rest of the schedulers. Upon comparison, the rest of the schedulers performs poorly in this case. To analyse their performance, the throughput to power ratio results of these schedulers are focused excluding BCQI scheduler.

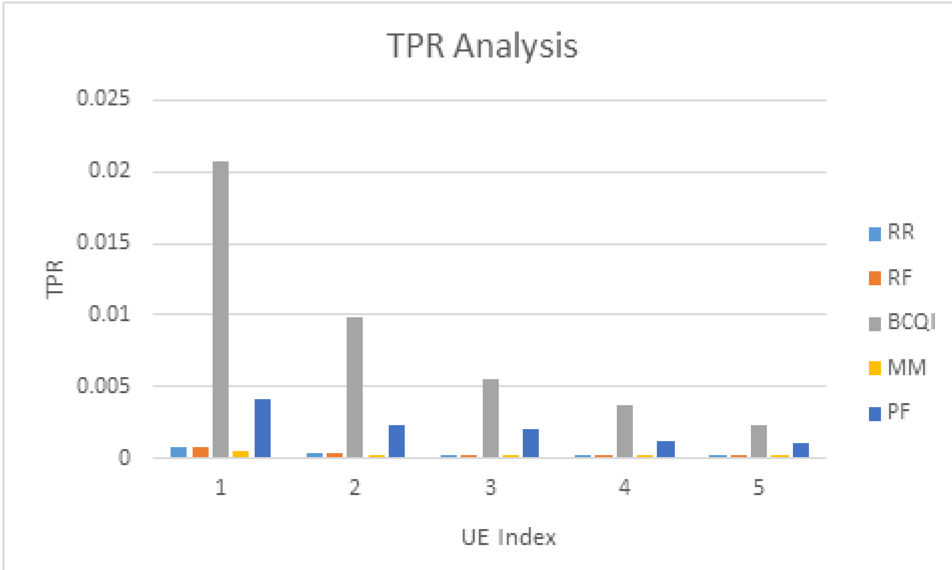

Figure 3.3 Case 1: Throughput to power ratio comparison

Figure 3.4 shows the case 1 TPR result of selected schedulers excluding BCQI. It can be observed that PF algorithm ranks second in terms of throughput to power ratio in the case 1 and shows marginally better performance than the rest. Though RF and RR performance are quiet similar, MaxMin scheduler falls flat in terms of throughput to power ratio.

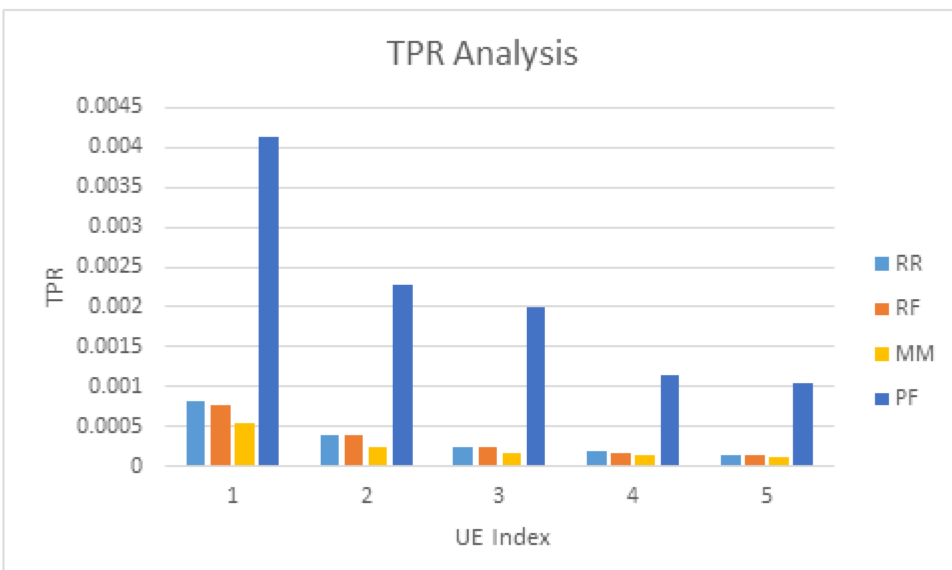

Figure 3.4 Case 1: Throughput to power ratio comparison (excluding BCQI scheduler)

Case 2: Better to Moderate Channel Conditions

Figure 3.5 compares the TPR result for users having better and moderate channel conditions. The trend is similar to previous case for RF, RR and MM scheduler. However, it is important to notice the performance of BCQI scheduler. The TPR values dramatically drops for BCQI schedulers when compared to previous case and at one point, PF scheduler starts to perform with better TPR value than BCQI scheduler.

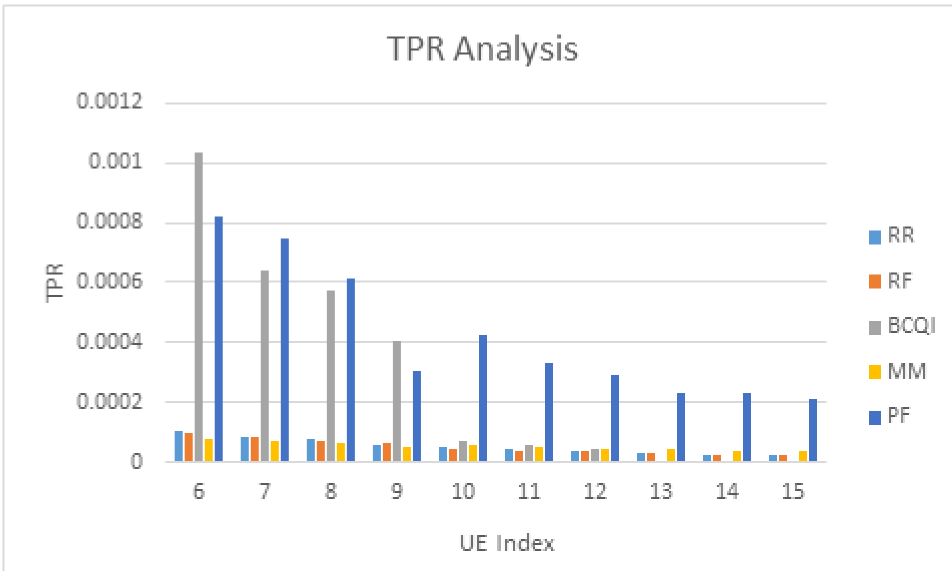

Figure 3.5 Case 2: Throughput to power ratio comparison

Case 3: Moderate to Poor Channel Conditions

Figure 3.6 shows the TPR results of users with moderate to poor channel conditions. The most important part to be noticed this case, is the performance of BCQI scheduler. In stark opposite of their performance in the case 1, its TPR values falls flat at zero for users with moderate channel conditions. This poor performance is due to the strategy employed by these algorithm to allocate most of the resources to users with best channel condition. PF scheduler is the best performer in this case, although MaxMin scheduler maintain a near constant TPR value for all the users.

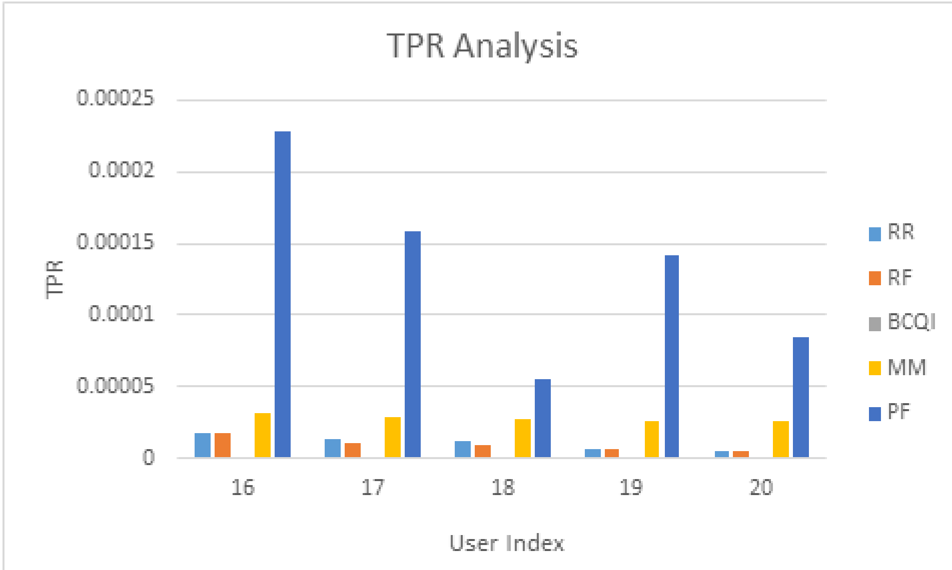

Figure 3.6 Case 3: Throughput to power ratio comparison

3.5 Conclusion

This section focused on comparing a selected group of standard scheduling algorithms in terms of performance metrics: throughput, fairness and throughput to power ratio. From the results, it has been observed that, PF scheduler performs optimally well and has better trade-off between the all the performance metrics when compared with other schedulers. Although BCQI scheduler are lopsided and favours only the users with best channel conditions, its throughput to power ratio performance in case 1 will be useful for comparison with the proposed algorithm. Hence, PF and BCQI algorithms are chosen out of the selected schedulers for comparison with proposed scheduling algorithm.

4 Opportunistic Dual Metric Scheduling Algorithms for LTE Uplink and Downlink

4.1 Introduction

The channel-aware scheduling exploits the knowledge of the channel conditions to allocate resources such that the system throughput can be maximised. The achievable data rate of the user *n* over the RB *m* can be computed using Shannon's Channel Capacity, provided the Signal-to-Noise Ratio (SNR) between the user *n* and the RB *m* is known. It is represented by the formula below:

$$R_n(m) = \log(1+SNR(n,m)) \qquad \text{Eq. (4.1)}$$

This section presents the design and implementation of a channel aware uplink and downlink algorithm which aims to provide a good trade-off between throughput and fairness in allocation.

4.2 Opportunistic Dual Metric Strategy

As explained in section 2.5.3, the decision metric of any scheduling algorithm gives priority to specific parameters. For example, RR scheduler follows fairness as primary metric by allocating the same number of RBs for all the users while BCQI schedulers gives priority to user with good channel condition. The motivation behind the proposed algorithm is to improve the system performance in terms of throughput at the same time to provide fair allocation of resources.

ODM scheduler consists of two resource allocation matrices, Primary metric matrix (H_1) and Secondary resource allocation matrix (H_2). The metric is the improvised version of

Opportunistic Proportional Fairness metric proposed in [34] for any wireless communication. Consider an LTE network comprising of single eNB and N UEs. Let the available bandwidth consists of M RBs. In a given subframe t, let $R_n(m)$ be the achievable data rate of the user n over RB m computed using Eq. (4.1) and $\dot{T}_n$ be the average throughput of user n over previous subframes. The element $H_{n,m}$ in the NxM resource allocation matrix (H) is the scheduling metric, calculated for the (UE,RB) pair UE_n and RB_m by the following equation:

$$H_{n,m} = \left\{ \alpha \cdot \left(\frac{R_n(m)}{\dot{T}_n} \right) + \beta \cdot \left(\frac{R_n(m)}{\max\limits_{\forall i} (R_i(m))} \right) \right\} \qquad \text{Eq. 4.2}$$

The factor $\frac{R_n(m)}{\dot{T}_n}$ in Eq. 4.2 represents the PF scheduling metric and the factor $\frac{R_n(m)}{\max\limits_{\forall i} (R_i(m))}$ in the equation represents the BCQI scheduling metric. Hence, the constants α and β determine the performance of the scheduler. When $\alpha = 1$ and $\beta = 0$, then metric becomes PF scheduler. Similarly, when $\alpha = 0$ and $\beta = 1$, the metric becomes BCQI scheduler. Experiments were conducted to determine the ideal values of (α,β) for uplink and downlink and the results are presented under section 4.3.2 and section 4.4.3 for uplink and downlink respectively.

4.3 Opportunistic Dual Metric Scheduling Algorithm for LTE Uplink

4.3.1 Constraints

The resource allocation process needs to follow a certain constraints for achieving effective system performances. Some of the constraints that are considered in the proposed uplink scheduling algorithm are explained in this section.

Singularity Constraint

In each subframe, any RB can be allocated to single UE only. RBs cannot be assigned to multiple UEs. However, the converse is possible. Let $\Delta(\mathrm{n},\mathrm{m})$ be the allocation vector of user n to RB m in the given subframe. It can be defined as follows:

$$\Delta(\mathrm{n},\mathrm{m}) = \begin{cases} 1, & \text{if } \mathrm{RB_m} \text{ is assigned to } \mathrm{UE_n} \\ 0, & \text{if } \mathrm{RB_m} \text{ is not assigned to } \mathrm{UE_n} \end{cases} \qquad \text{Eq. 4.3}$$

Then, in each subframe, the singularity constraint can be denoted as:

$$\sum_{\mathrm{i}=1}^{\mathrm{N}} \Delta(\mathrm{i},\mathrm{m}) \leq 1 \qquad \text{Eq. 4.4}$$

Contiguity Constraint

SCFDMA has two types of subcarrier mapping. They are Localized FDMA (LFDMA) and Interleaved FDMA (IFDMA). According to [5], in channel-dependent scheduling, LFDMA shows higher throughput performance than IFDMA when scheduling. Thus, allocation of contiguous resources will result in increased performance than allocation of intermittent resources. This condition is termed as contiguity constraint.

Power Constraint

According to the uplink power budgets mentioned in the 3GPP specifications [32], the maximum transmit power threshold of any user is equal to 23 dBm for a class 3 UE. This can be represented as follows:

$$\sum_{j=1}^{M} \Delta(n,j) P_{Tx}(n) \leq 23\text{dBm} \qquad \text{Eq. 4.5}$$

where $P_{Tx}(n)$ is the total transmit power of user n for each subframe.

4.3.2 Evaluation of the parameters α and β for Uplink

The main shortcoming in [7] is that α and β are assumed to be 1.5 and 1 by the author, however, the reasons behind the selection of these values are not provided. Hence, an experiment is conducted to determine the values of the coefficients.

A simple simulation scenario is setup with one eNB and 20 randomly distributed UEs experiencing different average SNRs. The throughput and fairness performance of the algorithm is analyzed by varying both α and β in the range of 0.25 to 1 in steps of 0.25.

Table 4.1 shows the throughput and fairness index value averaged over 20 simulation iterations. From the results, the coefficients of metric matrices H_1 and H_2 are determined. The primary metric is throughput centric. Hence, the coefficients which provides maximum throughput are chosen. The secondary metric is chosen to be fairness centric. Hence, the coefficients which provides maximum fairness index are chosen. Therefore, from Table 4.1, the coefficients of primary and secondary metrics are chosen to be (1, 0.25) and (0.75, 0.5) respectively.

Table 4.1 Performance Comparison varying Metric Coefficients for Uplink

Α	β	Cell Throughput, $\widehat{T}_P$ (mbps)	Jain's Fairness Index, J
0.25	0.25	19.13	0.5526
0.25	0.5	18.96	0.5281
0.25	0.75	18.45	0.5132
0.25	1.00	18.57	0.5118
0.50	0.25	19.34	0.5749
0.50	0.50	19.21	0.5487
0.50	0.75	18.99	0.5515
0.50	1.00	19.23	0.5273
0.75	0.25	19.32	0.5632
0.75	0.50	18.96	0.5776
0.75	0.75	19.26	0.5411
0.75	1.00	19.31	0.5567
1.00	0.25	19.42	0.5671
1.00	0.50	19.35	0.5672
1.00	0.75	19.27	0.5644
1.00	1.00	19.39	0.5571

4.3.3 Proposed Algorithm for LTE Uplink

The proposed algorithm consists of two resource allocation matrices, H_1 and H_2. The primary and secondary matrices are employed to provide an efficient distribution of resources among the active users, under the constraints mentioned under section 4.3.1. The pseudo-code of the proposed uplink scheduling algorithm is given below:

Algorithm: ODM scheduling for LTE Uplink

{Inputs}

1. Coefficients (α_1, β_1) which gives maximum $\hat{T}_P$
2. Coefficients (α_2, β_2) which gives maximum J

{Initialization}

3. N ←Number of UEs
4. I_{RB} ←Number of unallocated RBs
5. Compute H_1 using Eq. (4.2) where coefficients are (α_1, β_1)
6. Compute H_2 using Eq. (4.2) where coefficients are (α_2, β_2)

{Main Iteration}

//Computing the optimal solution for each unallocated RBs

7. **for each** $RB_j \in I_{RB}$ **do** *//Consider the j^{th} column of H_1*
8. Find the maximum of j^{th} column, $H_1[i, j]$ and select UE_i
9. **if** UE_i satisfies power constraint (Eq. (4.5)) **then**
10. Assign RB_j to UE_i
11. Remove the j^{th} column from the matrices H_1 and H_2 and update I_{RB}
12. **end if**

//Examine H_1 matrix to satisfy contiguity constraint

13. Find the maximum of i^{th} row, $H_1[i, k]$ and select RB_k
14. **if** RB_k is adjacent to previously allocated RB and Eq.(4.5) is satisfied, **then**
15. Assign RB_k to UE_i
16. Remove the k^{th} column from the matrices H_1 and H_2 and update I_{RB}

//Examine H_2 matrix to satisfy contiguity constraint

17. **Else**
18. Find the maximum of the i^{th} row, $H_2[i, l]$ and select RB_l
19. **if** RB_l is adjacent to previously allocated RB and Eq.(4.5) is satisfied, **then**
20. Assign RB_l to UE_i
21. Remove the l^{th} column from the matrices H_1 and H_2 and update I_{RB}
22. **end if**
23. **end if**
24. **end for**

4.4 Opportunistic Dual Metric Scheduling Algorithm for LTE Downlink

The algorithm proposed in the previous section is specific to uplink scheduling. In order to utilize the algorithm for LTE downlink, a few modifications are required. For example, the contiguous allocation of resource is not a constraint for downlink. Hence, an alternate rule is used for expanding the resource allocation for the users. A pattern-based scheduling strategy, search-tree pattern is used in the proposed downlink algorithm. In [30], the author has adopted a search-tree pattern for resource allocation. However, the allocation process is obsolete, as each user was allocated with only one resource. The algorithm proposed in this section introduces a new method for constructing a search-tree pattern. The search-tree used is a simple pattern with one root node and two branch nodes. Hence, the complexity is very less when compared with the pattern constructed in [30]. This section explains the modification done to ODM scheduling discipline for effective scheduling for LTE downlink.

4.4.1 Constraints

Fairness Constraint

The previous section explained a new scheduling discipline for LTE uplink. Although LTE downlink scheduling problem requires distributing the resources among the users, the algorithm proposed in the previous section cannot not be employed for LTE downlink. As explained earlier, the uplink scheduling algorithm consists of two resource allocation matrices, H_1 and H_2, which are employed to effectively map resources among the users following contiguity constraint mentioned in Section 0. However, the continuous resource allocation is not major constraint in LTE downlink, since, the eNodeB is not power-limited when compared with the UE. Thus, the algorithm need not satisfy the contiguity constraint.

In order to adapt the ODM scheduling for LTE downlink for effective resource allocation, a fairness constraint is introduced. The ODM downlink algorithm consists of two levels. The primary resource allocation matrix, H_1, is used in the first level to find the UE-RB pair with maximum metric value. The secondary recourse allocation matrix, H_2, is used to expand the allocation for the UE selected in the first level. The fairness constraint is used in second level as a checkpoint before expanding the allocation process. The objective of the fairness constraint is to ensure that mapping at second level for expanding the allocation in the current TTI does not result in starvation for other users.

As explained, the fairness constraint is employed in the second level of allocation process to avoid unfair mapping. This is evaluated by computing the number of resources assigned to the user in the past TTIs. It can be formulated as follows:

$$\text{Fairness Constraint Index, } \digamma = 1 - \frac{RB_i}{N\_RB} \qquad \text{Eq. 4.6}$$

where RB_i is the number of resources allocated to the user i over the past TTI and N_RB is the sum of total number of resources available for allocation at each TTI. Consider a LTE system where the bandwidth is selected to be 1.4 MHz. Then, the number of RBs available for allocation, N_RB, is equal to 6. Table 4.1 show the values of $\digamma$, assuming user allocation over two past TTIs.

Table 4.2 Fairness Constraint Index Range for 1.4 MHz Bandwidth

Number of RBs assigned over the past TTI to user *i*, RB_i	Fairness Constraint Index, f
0	1.0000
1	0.9167
2	0.8333
3	0.7500
4	0.6667
5	0.5833
6	0.5000
7	0.4167
8	0.3333
9	0.2500
10	0.1667
11	0.0833
12	0

4.4.2 Search-Tree Pattern-Based Scheduling Strategy

As explained earlier, the modified ODM algorithm for downlink consists of two levels. The first level uses the primary allocation matrix, H_1, to find the UE-RB pair which has the maximum metric value. In the second level, a search-tree is built using both primary and secondary allocation matrices, H_1 and H_2, to expand the allocation of resources to user from the first level. This section explains in detail about the formation of the search-tree pattern adopted in the proposed algorithm for LTE downlink.

The search-tree pattern used in the algorithm accepts the user index from the first level of the algorithm as input. This forms the root node of the search-tree. A root node has two branch nodes. Each branch node in the pattern has a node score. The node score of the left branch node is calculated using the matrix H_1 and the node score of the right branch node is calculated using the matrix H_2. Node score can be defined as the ratio between metric value of the RB with maximum value for the selected UE (row-wise maximum) and the maximum metric value that RB (column-wise maximum). If RB_m is the best RB for the user UE_n , then the node score of the node formed by user UE_n and RB_m can be formulated as follows:

$$\Omega_s(k) = \frac{H_k(n,m)}{\max_{\forall i} H_k(i,m)} \qquad \text{Eq. 4.7}$$

where the value of k varies from 1 and 2. The root node in the search-tree forms the branch nodes, provided the fairness constraint is satisfied. Consider the following 4 x 5 primary and secondary allocation matrices, H_1 and H_2, where each row represents the UE and each column represents the RB as shown in Figure 4.1.

$$H_1 = \begin{bmatrix} 3.5 & 7.7 & 5.1 & 0 & 1.3 \\ 0.5 & 1.2 & 2.8 & 0 & 1.5 \\ 1.7 & 4.3 & 5.4 & 0 & 2.4 \end{bmatrix} \qquad H_2 = \begin{bmatrix} 2.7 & 6.9 & 4.3 & 0 & 0.3 \\ 4.4 & 3.1 & 3.8 & 0 & 3.5 \\ 0.9 & 9.5 & 7.6 & 0 & 2.7 \end{bmatrix}$$

Figure 4.1 Example H_1 and H_2 Matrices for Search-Tree Construction

Assume that the UE index 2 is assigned with RB index 4 in the first level of the algorithm. Hence, column 4 is made zero in both H_1 and H_2. The primary root node obtained from first level of the algorithm is Node(2,4).

Consider the fairness constraint is satisfied. Then, the left branch node's score can be calculated using H_1 matrix as follows:

The RB index with maximum value for the UE index 2 in H_1 is 3 { N(2,3) = 2.8}. The maximum metric value for RB index 3 falls on UE index 3 {N(3,3) = 5.4.} Hence, the left branch node's score is,

$$\Omega_s = \frac{2.8}{5.4} = 0.51$$

Similarly, the right branch node's score is calculated using H_2. The RB index with maximum value for the UE index 2 in H_2 is 1 {N(2,1) = 4.4}. The maximum metric value for RB index 1 also falls on UE index 2. Hence, the left branch node's score is,

$$\Omega_S = \frac{4.4}{4.4} = 1$$

Hence the left branch node's score is 0.51 and the right branch's score is 1. Figure 4.2 shows the branch nodes constructed for Node(2,4) in the scenario mentioned above.

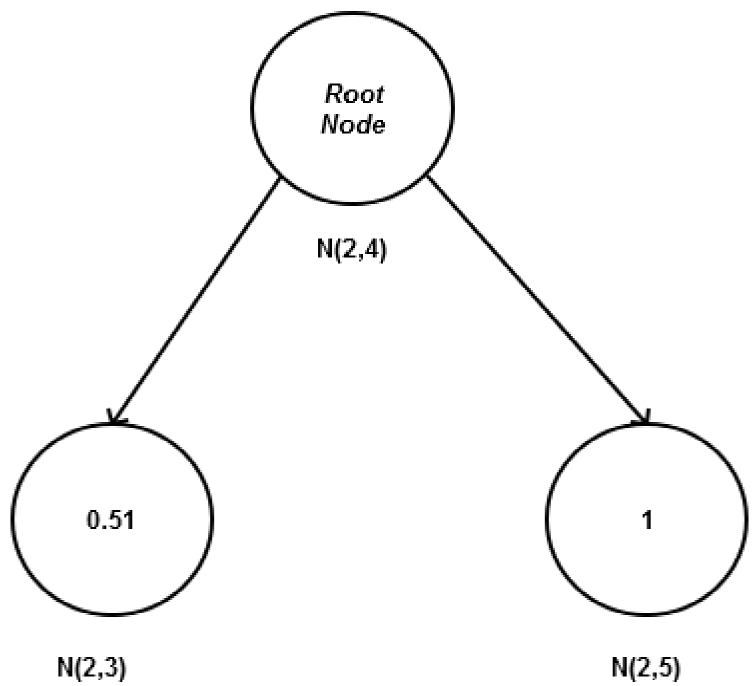

Figure 4.2 Sample Search-Tree Pattern

The downlink algorithm uses a minimum cut-off, Ω, for the node score to select the RB. This value affects the throughput performance of the system. The section 5.4.1 shows the performance of the system by varying the acceptable node score cut-off for resource allocation expansion.

4.4.3 Evaluation of the Parameters α and β for Downlink

The experiment done in section 4.3.2 is repeated for downlink scenario. The same simulation model, with one eNodeB and 20 UEs, is selected. The UEs are randomly distributed and they experience average SNRs different from one another. The throughput and fairness performance of the system is evaluated for the decision metric given by Eq. (4.2) by varying both α and β in the range of 0.25 to 1 in steps of 0.25. The results are tabulated below:

Table 4.3 Performance Comparison varying Metric Coefficients for Downlink

α	Β	Cell Throughput, $\widehat{T}_P$ (mbps)	Jain's Fairness Index, J
0.25	0.25	19.53	0.6826
0.25	0.5	19.75	0.6821
0.25	0.75	19.87	0.6932
0.25	1.00	20.57	0.6320
0.50	0.25	19.85	0.6850
0.50	0.50	20.72	0.6474
0.50	0.75	20.89	0.6553
0.50	1.00	20.43	0.6623
0.75	0.25	20.30	0.6932
0.75	0.50	20.24	0.6776
0.75	0.75	20.44	0.6676
0.75	1.00	20.98	0.6012
1.00	0.25	19.89	0.6977
1.00	0.50	20.71	0.6377
1.00	0.75	21.07	0.5968
1.00	1.00	20.86	0.6075

From Table 4.3, the coefficients of H_1 and H_2 are chosen to be (1, 0.75) and (1, 0.25) respectively.

4.4.4 Proposed Algorithm for LTE Downlink

Algorithm: ODM scheduling for LTE Downlink

{Inputs}
Coefficients (α_1, β_1) which gives maximum $\hat{T}_P$
Coefficients (α_2, β_2) which gives maximum J
{Initialization}
N ←Number of UEs
I_{RB} ←Number of unallocated RBs
Compute H_1 using Eq. (4.2) where coefficients are (α_1, β_1)
Compute H_2 using Eq. (4.2) where coefficients are (α_2, β_2)
{Main Iteration} //Computing the optimal solution for each unallocated RBs
{First level of allocation}
for each $RB_j \in I_{RB}$ **do** *//Consider the j^{th} column of H_1*
Find the maximum of j^{th} column, $H_1[i, j]$ and select UE_i
if UE_i satisfies singularity constraint (Eq. (4.4)) **then**
Assign RB_j to UE_i
Remove the j^{th} column from the matrices H_1 and H_2 ,and update I_{RB}
end if
{Second level of allocation}
//Constructing search-tree using H_2 matrix to expand the allocation
// Input: UE index i and RB index j
if Eq.(4.6) (i.e.) fairness constraint is satisfied, **then**
Root node← Node(i,j)
Compute the left branch node's score, $\Omega_s(1)$, of the using H_1 in the Eq.(4.7)
Compute the right branch node's score, $\Omega_s(2)$, of the using H_2 in the Eq.(4.7)
if $\Omega_s(1)$ is greater than or equal to Ω, **then**
Assign k ← *Left branch node's RB index*
else if $\Omega_s(2)$ is greater than or equal to Ω, **then**
Assign k ← *Right branch node's RB index*
end if
Assign RB_k to UE_i
Remove the k^{th} column from the matrices, H_1 and H_1, and update I_{RB}
end if
end for

The pseudo-code explaining the proposed ODM scheduling algorithm for LTE downlink. The algorithm accepts the metric coefficients (α_1, β_1) and (α_2, β_2) as inputs. Using these coefficients values, the primary and secondary allocation matrices are computed. The first level of allocation is similar to ODM uplink scheduling. The second level uses the search-tree concept explained in Section 4.4.2. One of the important factor in the second level of the algorithm is node score cut-off, Ω and fairness constraint index, ғ. The values of ғ and Ω are always less than or equal to one and their value affect the system performance. A detailed analysis on the impact of ғ and Ω on system performance is done in section 5.4.1.

4.5 Conclusion

In this chapter, the design and the implementation of the proposed algorithm was discussed. The uplink algorithm employed search by maximum strategy to find the best UE for each RB so that the system performance is maximised. The algorithm employed the throughput-centric primary matrix to determine the UE-RB mapping. Next, the primary matrix and the fairness-centric secondary matrix were used expand the allocation to satisfy the contiguity constraint. This strategy is modified to implement scheduling for LTE downlink. The constraints related to uplink are relaxed for the downlink algorithm. The primary matrix was used to find the best UE-RB pair for mapping. The secondary matrix was used to expand the allocation for the UE by scanning the remaining available resources.

5 Results and Discussion

5.1 Introduction

In this section, the simulation results consisting of performance of ODM algorithm is compared against BCQI and PF algorithm. The simulation is carried out using “Vienna LTE Link Level Simulator” [7] and [8]. The comparison is done based on the parameters mentioned in section 3.2.

5.2 Simulation Setup

The simulation setup consists of a single cell LTE network with one eNodeB and the network is evaluated for different scenarios varying the number of UEs in the cell. Since the simulator does not have a GUI, Figure 5.1 is used to depict the simulation model with single LTE cell and randomly distributed UEs. All the UEs in the cell are modelled to have average SNRs ranging from 0 to 30 dB. To analyze the algorithm in better way the SNRs are assigned to users in decreasing order from UE index 1 to the last UE. Also, to simplify the simulation, it is assumed that all the users have infinitely backlogged data to transmit. Table 5.1 tabulates the simulation parameters.

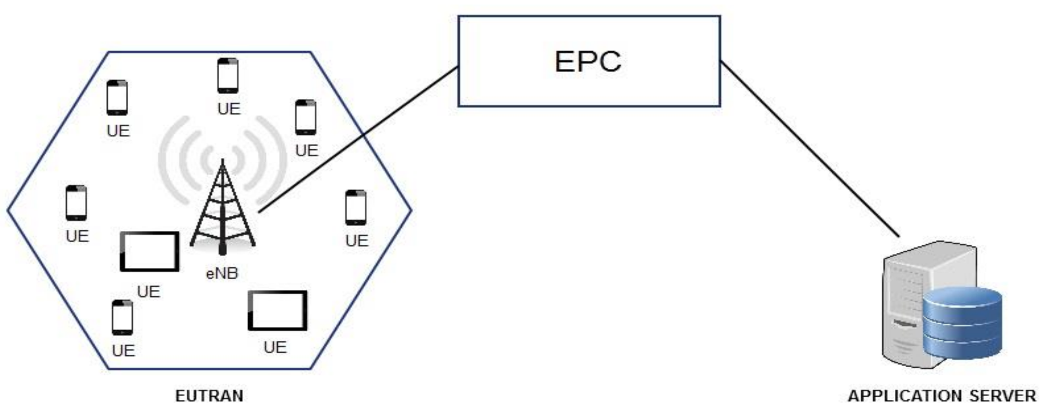

Figure 5.1 Simulation Setup

Table 5.1 Simulation Parameters

PARAMETER	VALUE
System bandwidth	5 MHz
Number of RBs	25
Number of users	20, 30, 40
TTI Duration	1 ms
Average SNR of users	30 dB to 0 dB
Channel Model	3GPP TU
Antenna configuration	1 transmit chain, 1 receive chain (1X1)
Receiver	Zero Forcing
Schedulers	BCQI, ODM, PF

Three simulation scenarios are modelled by varying the number of UEs (20, 30 and 40 respectively) in the cell. Each scenario is simulated over 20 iterations and the results are averaged. Thus, the proposed algorithm has been analysed to determine if the performance is affected by the network volume.

5.3 Results for ODM Uplink Scheduling

5.3.1 Throughput Analysis

Figure 5.2 shows performance of BCQI, ODM and PF scheduler in terms of throughput calculated using Eq. (3.1). BCQI scheduler sets the bench mark for the maximum achievable throughput as its only objective is to maximize the throughput. Consider the first simulation scenario which has 20 UEs in the cell. On comparing with BCQI scheduler, it is observed that ODM scheduler achieves throughput value 94.2% while PF algorithm achieves throughput values of 78.1%. This gain in throughput when compared with PF scheduler is due to the β factor in the metric. This factor assigns extra priority to users with better channel condition and hence, the increased throughput. Also, from Figure 5.2 it can be observed that, the throughput performance follows the same pattern irrespective of the number of UEs in the cell. ODM scheduler achieves nearly 92% throughput on an average for all the simulation scenarios while PF achieves an average around 75% throughput when compared with BCQI scheduler.

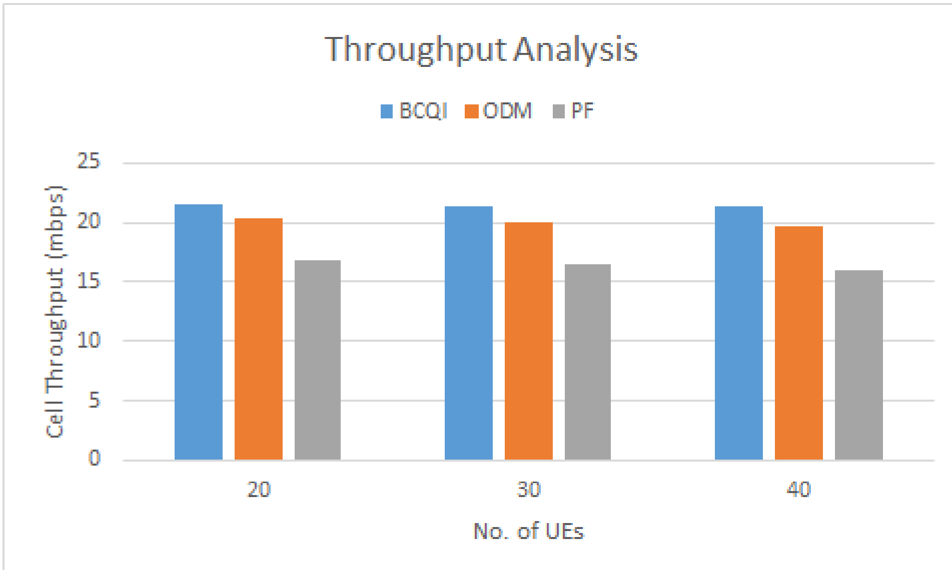

Figure 5.2 Throughput Analysis of Uplink Scheduling Algorithms

5.3.2 Fairness Analysis

Figure 5.3 shows the fairness analysis done using Jain's fairness metric calculated using Eq. (3.2). The range of Jain's fairness index is between $\frac{1}{N} \leq J \leq 1$ where N is the number of UEs in the cell. As expected, BCQI shows poor fairness due to starvation of users with bad channel condition. Comparing with BCQI results, ODM scheduler shows nearly 33% to 35% increase in fairness index value (more than 0.7 in all three scenarios), however, shows mildly less fairness value than PF scheduler. This is a trade-off as users with better channel conditions are given more preference to achieve better throughput performance. Similar to throughput performance, the fairness performance of all three schedulers are similar for all three simulation scenarios, however, it mildly decreases with the increase in number of UEs in the cell. This behaviour is expected as the network volume increases, the demand for resource increase thereby more resources are given to users with better channel condition.

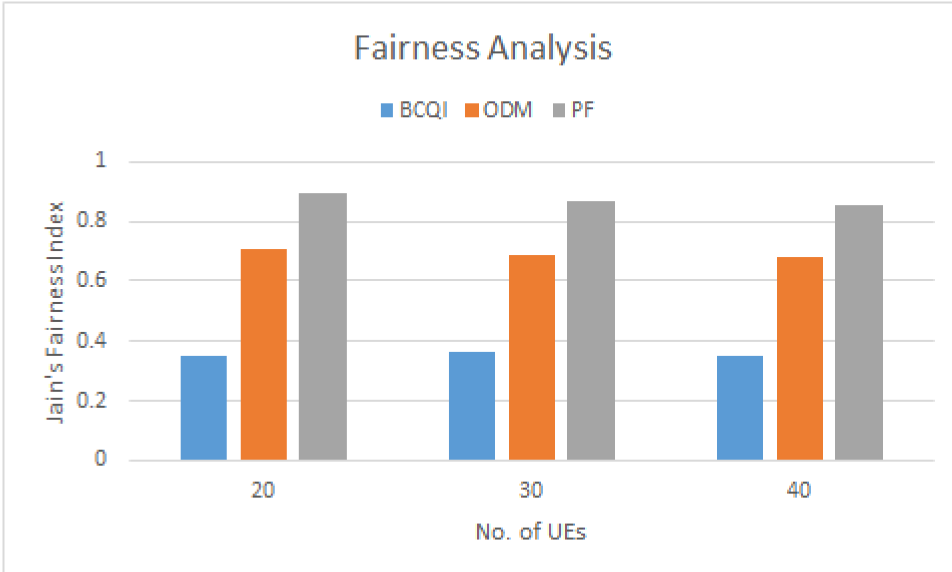

Figure 5.3 Fairness Analysis of Uplink Scheduling Algorithms

5.3.3 Throughput to Power Ratio Analysis

The Throughput-to-Power Ratio of each user is evaluated using Eq. (3.5). The performance of all three schedulers in 20 UEs per cell scenario is shown in Fig.5a and Fig. 5b. The results of TPR values is similar for 30 UEs per cell and 40 UEs per cell (Not provided to avoid repetition). As per the simulation scenario, the channel conditions of the users progressively decreases with their user index. In order to study the performance, the TPR result of the simulation scenario is divided into two cases.

Case 1: Users with best channel conditions

The Case 1 TPR results of all three schedulers is shown in Figure 5.4. From the figure it can be observed that users with best channel condition show maximum TPR value. BCQI scheduler is the best performer in this case while ODM scheduler shows marginally better performance than PF scheduler. This result is observed because BCQI favours users with good channel conditions. As the channel condition gets bad, all three schedulers show fall in throughput-to-power ratio.

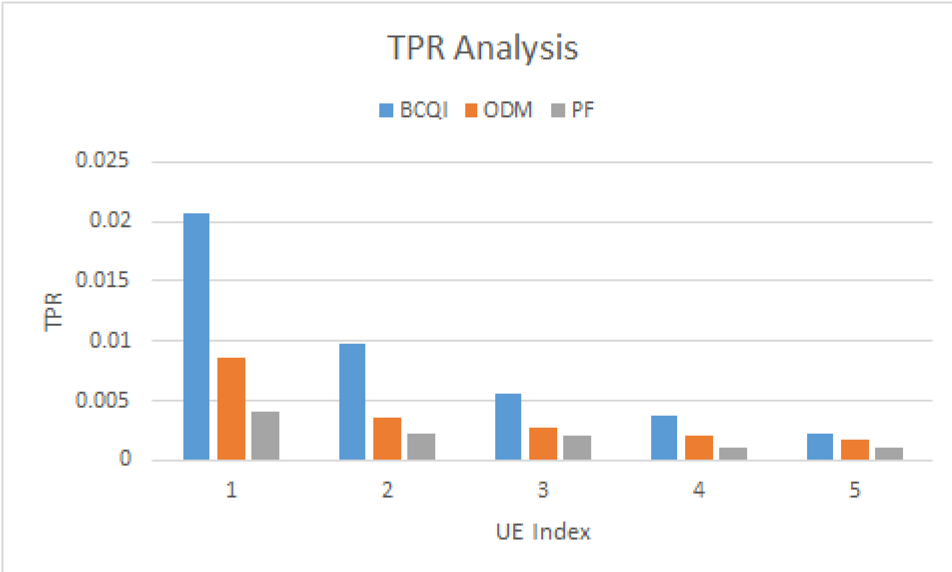

Figure 5.4 TPR Analysis of Uplink Scheduling Algorithm (Case 1)

Case 2: Users with good and poor channel conditions

Figure 5.5 shows the Case 2 TPR results of all three schedulers. ODM algorithm shows much improved performance for users under Case 2. The results indicate that the proposed algorithm outperforms other two schedulers for users with good and average channel conditions and marginally falls short for users with poor channel condition when compared with PF scheduler. Another important point to be noted is the drastic fall in TPR values of BCQI scheduler. In stark contrast to the performance in Case 1, BCQI scheduler shows almost null value for users in Case 2. As explained earlier, this behavior is due to the unfair resource mapping favoring users with best channel condition. Thus, comparing both the cases, ODM scheduling algorithm shows much balanced TPR results than the other two schedulers. Hence, it can be concluded to be a better energy-efficient algorithm than PF and BCQI scheduler.

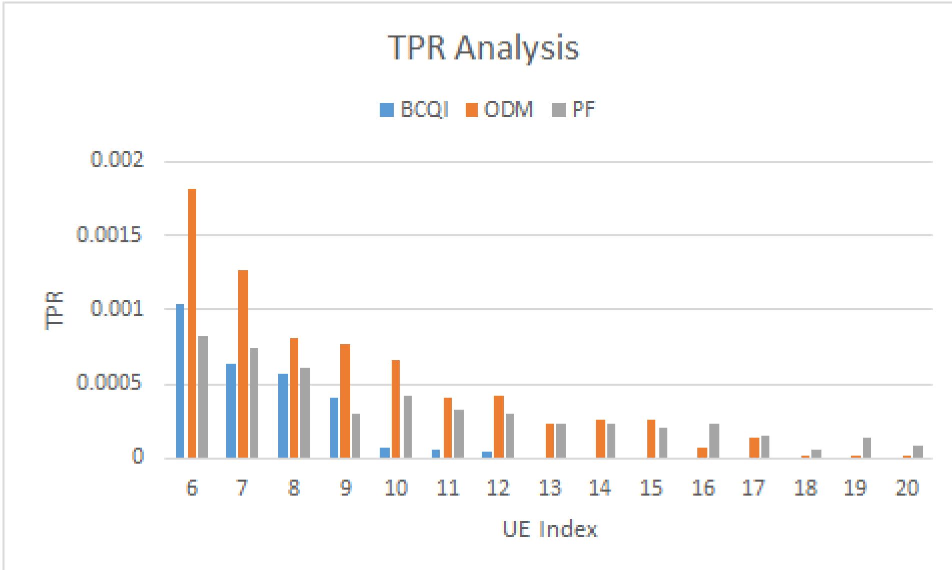

Figure 5.5 TPR Analysis of Uplink Scheduling Algorithm (Case 2)

5.4 Results for ODM Downlink Scheduling

5.4.1 Analysis on Impact of ꟻ and Ω on System Performance

The throughput and fairness performance of the proposed algorithm is analysed for the node score cut-off, Ω, ranging from 0.25 to 1.0 and fairness constraint index, ꟻ, ranging from 0.25 to 0.90. The value of Ω decides the effectiveness of the algorithm in finding the best UE-RB pair. When Ω = 1, it signifies that the RB selected has the maximum metric value in the resource allocation matrix and it is expected to provide the best performance for a given UE. When Ω < 1, it signifies that the selected RB is the best for the given UE, however, the selected RB is expected to deliver better performance with another UE. The impact of value of Ω, assuming ꟻ being set to 1, can be observed from the results shown in Figure 5.6. The throughput performance of the algorithm reduces with lower values of Ω. As explained, this is because when node score cut-off is less than 1, the RB is mapped to an UE although the selected RB will give better performance with another UE.

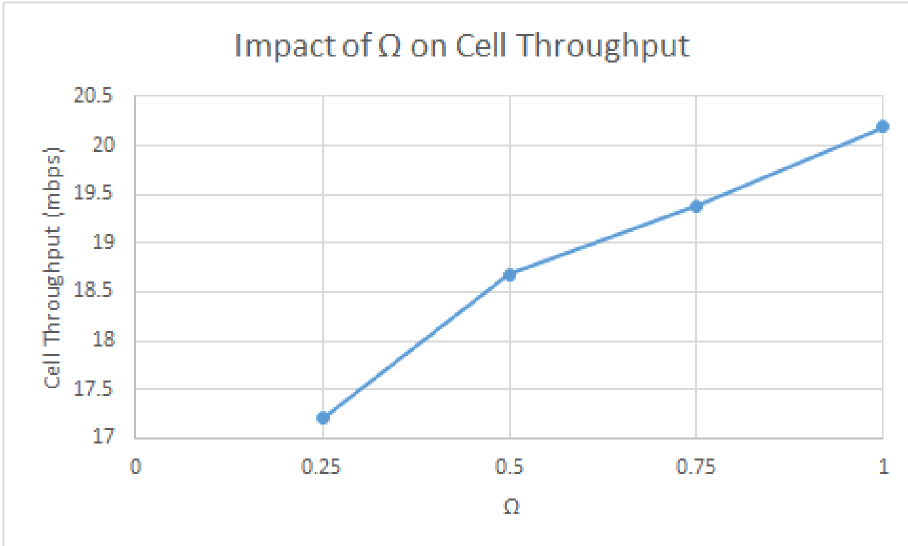

Figure 5.6 Impact of Ω on Cell Throughput

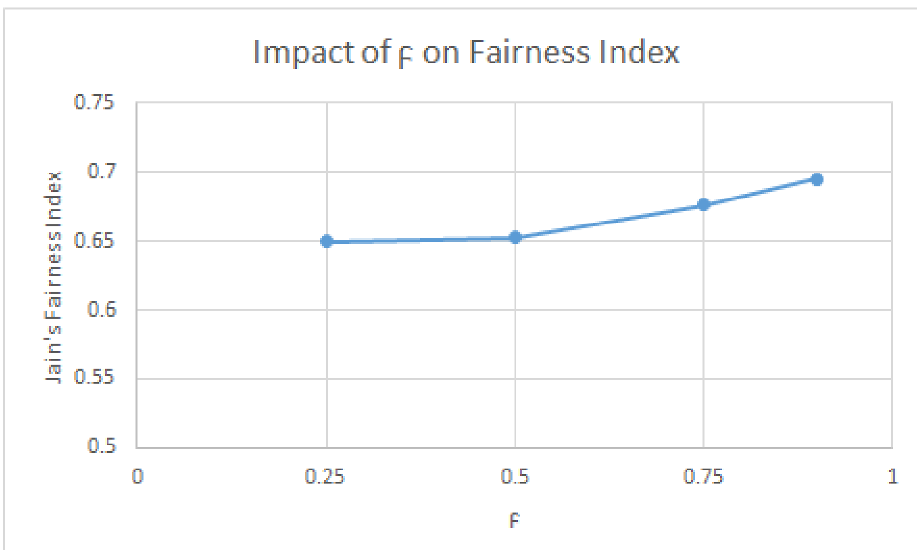

Figure 5.7 Impact of ꞅ on Fairness Index

Figure 5.7 depicts the fairness index results of the proposed algorithm for different values of ꞅ, with Ω being set to 1.0. As the ꞅ value decreases, the resource allocation process is extended for users by relaxing the fairness constraint explained in section 4.4.1. Thus the fairness index value of the proposed algorithm decreases with the decrease of fairness constraint index, ꞓ. From the results discussed in this section (5.4.1), it can be concluded that for the effective performance of the algorithm, the values of (ꞓ,Ω) must be equal to (0.90, 1.0).

5.4.2 Throughput Analysis

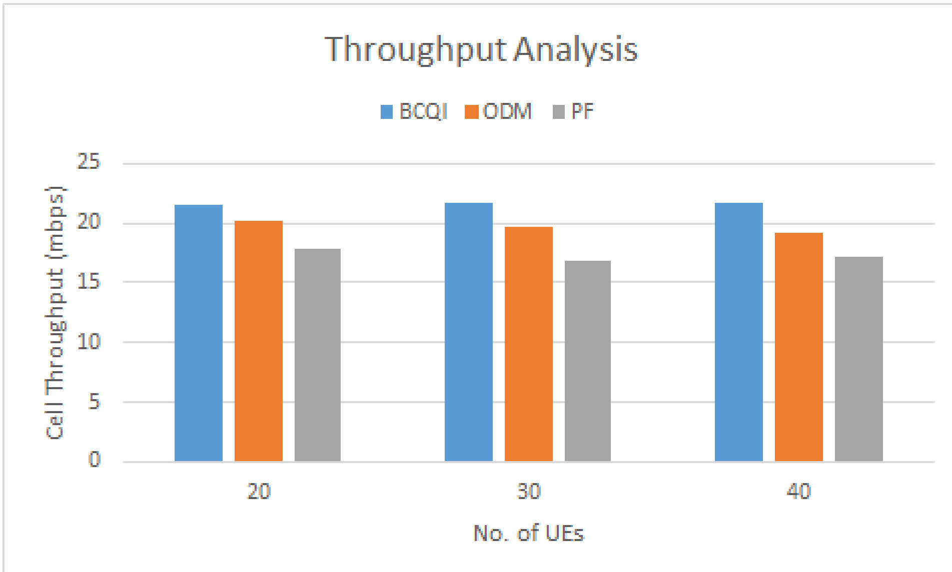

Figure 5.8 Throughput Analysis of Downlink Scheduling Algorithms

The node score cut-off, as explained in section 5.4.1, determines the effectiveness of the proposed algorithm in terms of throughput. The throughput performance shown in Figure 5.8 of the proposed ODM downlink algorithm is similar to performance discussed in section 5.3.1. The performance of proposed algorithm falls marginally short of BCQI algorithm, however, the results are better than PF algorithm. Assuming that BCQI algorithm gives maximum result, tor the simulation scenario with 20 UEs with SNR averaged between 30 dB and 0dB, the proposed algorithm provides 93.2% throughput assuming BCQI to give the maximum performance, whereas PF algorithm 79.3% throughput results. The results are quite similar for simulation scenarios with 30 and 40 UEs in the cell.

5.4.3 Fairness Analysis

The performance of the proposed algorithm in terms of fairness is dependent on the value of F. Although the performance of ODM algorithm falls short of PF algorithm, the fairness index value is approximately 36% to 45% more than BCQI algorithm. The fairness performance of the algorithm improves as the number of users are increased in the cell and the fairness index value of the proposed algorithm reaches nearly 0.8 and comparable with PF algorithm value of 0.9. Figure 5.9 shows the fairness index value of the proposed algorithm and standard downlink algorithms for simulation scenarios with 20, 30 and 40 UEs.

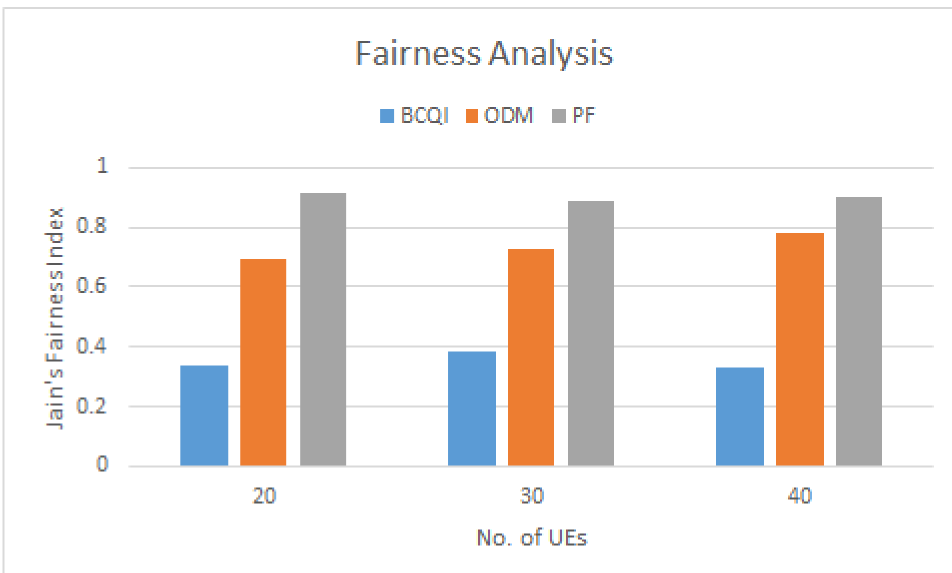

Figure 5.9 Fairness Analysis of Downlink Scheduling Algorithms

5.5 Conclusion

In this chapter, we discussed the performance of the uplink and the downlink scheduling algorithm against BCQI and PF algorithms. The proposed uplink algorithm is additionally analysed in terms of Throughput to Power ratio to determine the energy efficiency of the scheduler. The proposed algorithm was shown to outperform the standard scheduling algorithm for users with good and poor channel conditions.

From the results, it is observed that the network load does not affect the performance of ODM scheduler. The results of all three scenarios follow similar pattern as expected. It can be concluded that the proposed algorithm provides better trade-off by providing an optimal value of throughput and fairness when compared against BCQI and PF scheduling schemes.

Throughput and fairness performance of the uplink and downlink scheduler is summarized below:

Uplink Scheduling Algorithm (Cell Throughput in mbps)			
No. of UEs	BCQI	ODM	PF
20	21.59	20.33	16.85
30	21.43	20.12	16.43
40	21.41	19.63	16.03
Downlink Scheduling Algorithm (Cell Throughput in mbps)			
No. of UEs	BCQI	ODM	PF
20	21.61	20.13	17.13
30	21.67	19.75	16.81
40	21.48	19.45	16.11

Uplink Scheduling Algorithm (Jain's Fairness Index)			
No. of UEs	BCQI	ODM	PF
20	0.3526	0.7049	0.8971
30	0.36391	0.6857	0.8671
40	0.3515	0.6778	0.8551
Downlink Scheduling Algorithm (Jain's Fairness Index)			
No. of UEs	BCQI	ODM	PF
20	0.3351	0.6943	0.8758
30	0.3828	0.7249	0.8856
40	0.3311	0.7820	0.8992

6 Conclusion and Future Work

6.1 Conclusion

This work mainly focuses on designing an efficient algorithm for LTE UL and DL, considering the constraints associated with them. The algorithm is expected to perform spectrally efficient under satisfactory level of fairness. The standard channel-aware scheduling algorithms were analysed and compared against the proposed algorithms. These algorithms provide solution for the scheduling problem without satisfying the constraints associated with LTE UL and DL. Thus, there exists a need for new and improved scheduling strategy. Hence, the work mentioned in this thesis presents two distinctive scheduling algorithms for LTE UL and DL respectively. The proposed algorithm is compared against the standard scheduling schemes, namely PF and BCQI algorithms.

Chapter 4 presents the scheduling strategy of LTE UL and DL. The uplink scheduling algorithm consists of two resource allocation matrices, primary matrix H_1 and secondary matrix H_2. The matrices combine the benefit of BCQI and PF algorithm such that, H_1 is throughput-centric and H_2 is fairness-centric. The primary matrix is initially employed to identify the UE-RB with highest metric and mapping that RB to the UE. The contiguity constraint is satisfied by considering the adjacent RBs of the previously allocated RB to the same user. The secondary matrix is employed additionally consider the contiguous allocation of the UE given that the previous loop on the primary matrix fails. Before assigning RB to any UE, the power constraint is checked to ensure energy efficiency.

The downlink scheduling algorithm is an extension of the dual metric uplink scheduling algorithm with appropriate modification for LTE DL. Since the eNodeB is not as power-limited as the UE, avoiding power and contiguity constraints will result in better throughput performance. Similar to UL algorithm, the modified downlink algorithm consists of the primary and secondary resource allocation matrices. The algorithm consists of two phases, with primary matrix being used in the first phase and both primary and secondary matrices are used in the second phase. In the first phase the scheduler identifies the RB-UE with highest metric and map the selected RB to the UE, similar to the uplink algorithm. The second phase is used to extend the allocation for the user provided the fairness is not compromised. This is achieved by introducing a fairness constraint based on the resource allocation in the past subframes. The second level of the algorithm constructs a search-tree with two branch nodes evaluated for the intermittent RBs overruling contiguity constraint to the RB mapped. If any of the branch node satisfy a permissible level (Node Score Cut-off), then the corresponding RB is assigned to the user.

Chapter 5 analyses the performance of the proposed algorithm against standard scheduling algorithms. Assuming BCQI to give 100% throughput performance, the proposed uplink scheduling algorithm achieves around 91% to 94% system throughput and PF algorithm achieves about 74.8% to 78% throughput performance. ODM uplink algorithm provides 32% to 35% more fairness when compared with BCQI algorithm and 17% to 19% less fairness than PF algorithm. In terms of transmit power, the proposed uplink algorithm outperforms PF and BCQI algorithm for the users with good and moderate channel conditions. Similarly, the proposed downlink algorithm produces better trade-off between throughput and fairness when compared against PF and BCQI algorithm. Assuming BCQI to give 100% throughput performance, ODM downlink algorithm shows 90% to 93% system throughput which is nearly 14% more than the performance of PF algorithm. In terms of fairness, the proposed scheme shows 11% to 18% less performance than PF and 36% to 45% more performance fairness than BCQI algorithm.

6.2 Future Scope

The proposed algorithm fulfilled the objective of the work. However, overcoming the limitations of the simulator, the algorithm can be extended to include finite buffer traffic model and HARQ retransmission scenarios to take the scheduler closer towards real world scenario. Moreover, the proposed algorithm is designed with no QoS awareness. Given the flexibility of the proposed algorithm, adding QoS constraints over the existing constraints will be another direction for the work presented in this thesis.

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