Addis Ababa University

Addis Ababa Institute of Technology

School of Electrical and Computer Engineering

Telecommunication Engineering Graduate Program

Comparative Analysis of Resource Scheduling Algorithms for LTE

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A Thesis Submitted to School of Electrical and Computer Engineering,
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Declaration

I, the undersigned, declare that this thesis is my original work, has not been presented for a degree in this or any other University, and all sources of materials used for the thesis have been fully acknowledged.

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Abstract

As wireless communication services demand grows, new challenges in the design and operation of cellular networks arise. Despite the fact that LTE cellular wireless network is one of the most well-accepted and fastest-growing technologies in communications, network resources are limited, and they need to be allocated efficiently. As a key design factor in enhancing the performance of LTE systems, managing radio resources is crucial. With the expansion of LTE networks by ethio telecom and their growing usage among all mobile users in the country, the necessity to efficiently manage the available radio resources becomes more and more essential, in order to maintain Quality of Service (QoS) levels. Since the Third Generation Partnership Project (3GPP) does not specify a resource scheduler mechanism, researchers have come up with several approaches either to attain fairness among users or to achieve maximum throughput. This enables wide options in resource allocation, thereby allowing several different scheduling algorithms to flourish, with different aims. Comparing the performance of such algorithms in different scenarios is therefore great interest of this thesis. Henceforth, performance analysis of five existing LTE downlink scheduling schemes; namely Maximum Largest Weighted Delay First (MLWDF), Exponential_Rule (EXP-Rule), Exponential/Proportional Fair (EXP/PF), Logarithmic_Rule (LOG-Rule), and Frame Level Scheduler (FLS) are done in a macro cell with interference environment for both non-real-time and real-time traffic flows. While varying the number of users and user speed, it examines the performance of each scheduling algorithm with respect to throughput, packet loss ratio (PLR), fairness, and energy efficiency. Results show that among the five algorithms considered here, for real-time flow the FLS scheme outperforms the other four schemes in terms of throughput, PLR, and fairness metrics, whereas the rest algorithms perform well for best-effort (BE) flow.

Keywords: *LTE, Downlink scheduling algorithms, QoS, Fairness, Energy efficiency*

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Lists of Acronyms

2G	2nd Generation
3G	3rd Generation
3GPP	3rd Generation partnership project
4G	4th Generation
5G	5th Generation
AMC	Adaptive Modulation and Coding
C/I	Carrier-to-interference
CDMA	Code Division Multiple Access
CQI	Channel Quality Indicator
CSI	Channel State Information
DCI	Downlink Control Information
ECR	Energy Consumption Rate
eNodeB	Evolved NodeB
EPC	Evolved Core Packet
EPF	Enhance Proportional Fair
ERG	Energy Reduction Gain
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
EXP/PF	Exponential/Proportional Fairness (EXP/PF)
EXP-Rule	Exponential Rule
FD	Frequency Domain
FDD	Time Division Duplex
FLS	Frame Level Scheduler
GBR	Guaranteed Bit Rate
GSM	Global System for Mobile
HOL	Head of Line
HSPA	High-Speed Packet Access
IP	Internet Protocol
ITU	International Telecommunication Union

KPI	Key Performance Indicator
LOG-Rule	Logarithmic Rule
LTE	Long Term Evolution
LTE-A	Long-Term Evolution Advanced
MAC	Medium (Media) Access Controller
Max C/I	Maximum Carrier-to-Interference
Mb/s	Megabits Per Second
MCS	Modulation and Coding Scheme
MIMO	Multiple Input Multiple Output
MLWDF	Modified Largest Weight
MME	Mobility Management Entity
ms	Milliseconds
NRT	Non-Real time
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
PDCCH	Physical Downlink Control Channel
PDN	Packet Data Network
PDSCH	Physical Downlink Shared Channel
PF	Proportional fair
P-GW	PDN Gateway
PLR	Packet Loss Ratio
PUCCH	Physical Uplink Control Channel
PUSCH	Physical Uplink Shared Channel
QCI	QoS Class Identifier
QoE	Quality of Experience
QoS	Quality of Service
RAT	Radio Access Technology
RB	Resource Block
RLC	Radio link control

RNC	Radio Network Controller
RNP	Radio Network Planning
RR	Round Robin
RRM	Radio Resource Management
RT	Real time
SC-FDMA	Single-Carrier Frequency Division Multiple Access
S-GW	Serving Gateway
TDD	Time Division Duplex
TDMA	Time-division multiple access
TTI	Transmission Time Interval
UE	User Equipment
UMTS	Universal Mobile Telecommunications System

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1. Introduction and Background

Wireless and particularly mobile communications have become increasingly popular with consumers in this day and age. The telecommunication industry has witnessed several advancements in the last few decades and LTE technology represents an important evolutionary step in the development of mobile technology. Long-Term Evolution (LTE) is characterized by improved spectral efficiency, high peak data rate, and flexible transmission bandwidth from 1.4MHz to 20MHz to utilize operators’ available spectrum [1].

In Ethiopia, about two decades have passed since the official Global System for Mobile communications (GSM) service launched for the first time in Addis Ababa. Since then ethio telecom keeps deploying other enhanced mobile technologies and currently it runs multi Radio Access Technology (RAT) such as GSM, Universal Mobile Telecommunications System (UMTS), and LTE together. And also, LTE-Advanced (LTE-A) is deployed in some parts of the country. The number of mobile subscribers is growing unlike before and now passed 43.6 million in the first quarter of 2019/2020 as shown in Figure 1.1 [2]. Mobile broadband has become the primary means of accessing the Internet across the nation because of its relatively easy accessibility. According to recent data from ethio telecom [3], 96% of total customers use mobile service.

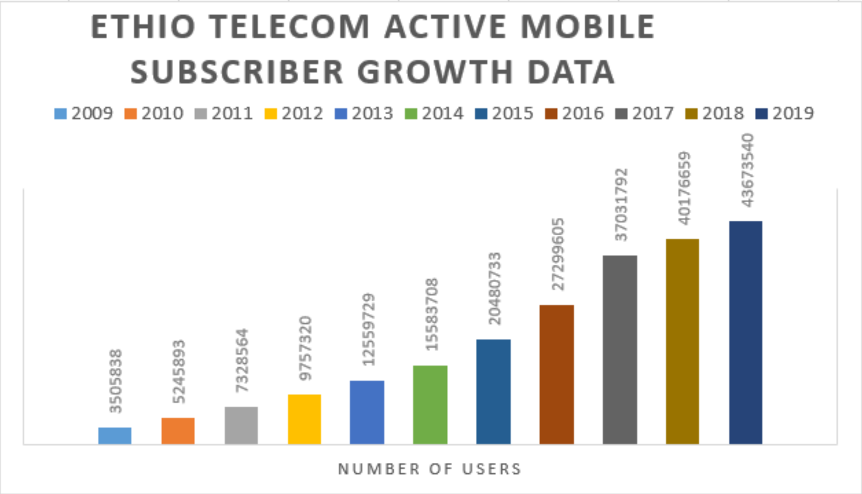


Figure 1.1 *Ethio Telecom Mobile Subscribers Growth For the Past 10 Years.*

Recently, LTE has been hailed as the most promising cellular technology and deployed in main cities of the country, which allows the transfer of various multimedia applications in a large bandwidth network. However, the demand for mobile broadband services is increasing in the country, especially in Addis Ababa [4], and this causes capacity challenges. Hence, efficient usage of available capacity (radio resource) is one important task.

In mobile technology, spectrum is the most valuable resource. Therefore, effective radio resource management (RRM) systems are vital for the operation of cellular networks. One of the key RRM mechanisms is packet scheduling, which distributes the available resource among existent connections, have been recognized as a key component of these wireless systems. By assigning radio resources, such as power, time slots, frequency channels, or a combination of these resources, a scheduler determines when and how users will share a wireless radio channel. The resource allocation is done at the evolved NodeB (eNodeB) Medium Access Control (MAC) layer and is responsible for allocating the available RBs to one or more user equipment (UE) according to the specific scheduling metric (Figure 1.2).

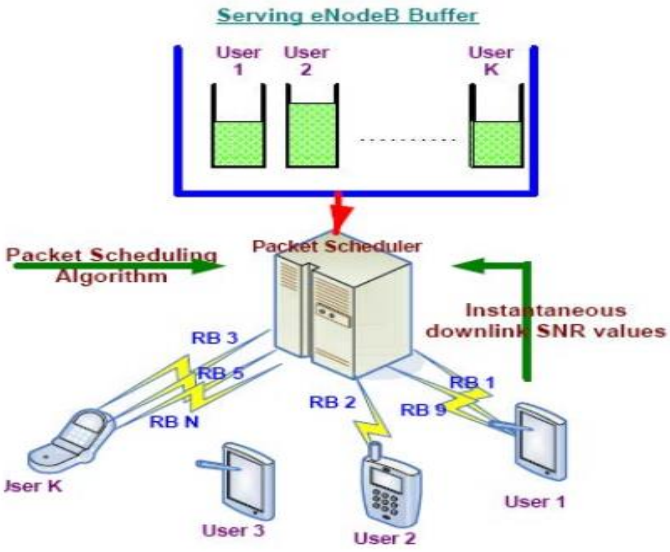


Figure 1.2 *Packet Scheduling Operation [5].*

The three most common scheduling algorithms in LTE and other previous technologies are Round Robin (RR), Maximum carrier-to-interference (Max C/I), and Proportional fair (PF) [6][7]. Their brief description is summarized in Table **1.1**.

Table 1.1 *Common Scheduling Algorithms Description* [7].

Algorithm	Description
RR	Allocates resources to all potentially served user equipment (UE) sequentially. Users' time fairness is guaranteed but the cell throughput is low.
Max C/I	Assigns resources to the UE with the best channel conditions that can support highest data rate at each Transmission Time Interval (TTI). This maximizes the cell throughput.
PF	Allocates resources to the UE according to the current radio condition and the achieved throughput. The higher the channel quality is, the more opportunity for the user to be scheduled. The lower the achieved data rate is the more the user can be scheduled. It involves a tradeoff between fairness and cell throughput.

However, these algorithms' aim is limited to throughput improvement and/or fairness among users. Hence, they are less efficient for real-time (RT) users as they don't fulfill certain Quality of Service (QoS) metrics like delay and packet loss ratio requirements. This led to the development of several other schedulers which enhance network performance and better user satisfaction. In today's cellular networks, the design and choice of schedulers are left to the operators and vendors as it is not defined in the Third Generation Partnership Project (3GPP) specifications and other standardization bodies [7]. As a result, scheduling algorithms have become a popular research topic because of their significant influence on network performance. The aforementioned facts serve as a source of motivation for this thesis work, since every effort to improve radio resource utilization efficiency can have a major impact and, in turn, some commercial value for the telecom provider. In this thesis, five existing QoS-aware scheduling algorithms are studied and their performance evaluated. The analysis and comparison of these algorithms are carried out by simulations. For performance evaluation, packet loss ratio (PLR), average system throughput, fairness, and energy efficiency are used as metrics.

1.1. Statement of the Problem

Many customers of the sole service provider, ethio telecom, frequently complain about poor network quality, especially on the cellular data network. Though deployment of LTE network in Addis Ababa improves the network capacity and quality, yet users complain continued [8] [9]. There may be different reasons for this both from the customer and provider sides. In ethio telecom, the problem ranges from coverage to capacity shortage.

Mobile network capacity is not unlimited, so it is vital to have intelligent schedulers that can distribute scarce radio resources very efficiently so that most of the users can get good QoS and a good Quality of Experience (QoE). Huge growing demand for these very expensive radio resources implies that the continuous improvements and evolution of telecom technologies are becoming a necessity rather than a luxury, and it forces researchers in the field of telecommunication to continuously improve radio resource utilization. Over the past years, several scheduling strategies have been proposed, some aimed at maximizing UE throughput, while others worked toward achieving lower delay and best fairness. These days energy efficiency has also become one more requirement. Nevertheless, all have their own drawbacks, and selecting one and adapting to our context is vital.

Even though optimizing or developing the right and good performance algorithm has an important role in determining the overall system performance, no previous work is done here on this particular topic as of yet. This work will fill the gap and put a foundation for future related works in the ethio telecom context.

1.2. Objective

1.2.1. General Objective

The main objective of this thesis is to assess selected existing LTE downlink scheduling schemes and perform comprehensive performance comparisons against some QoS metrics and energy efficiency.

1.2.2. Specific Objectives

The specific objectives of the thesis are:

- To understand issues and constraints related to cellular resource scheduling algorithms.
- To assess the current industry practice as well as research advancements related to LTE network scheduling algorithms.
- To model, simulate, validate, and evaluate current well-known packet scheduling techniques from QoS and energy perspectives.
- To recommend an algorithm that allocates scarce radio resources very efficiently and can provide good QoS, energy efficiency for the operator, ethio telecom.

1.3. Literature Review

As one of the key elements of the resource management process in mobile networks with heterogeneous QoS requirements such as delay, packet loss rate, or throughput, scheduling algorithms play a crucial role. In an environment with random propagation nature and the use of advanced physical layer technologies to deal with it, further complicates the design of a simple, fair, scalable, and efficient resource allocation scheme [10]. Several papers address this issue and propose different optimized algorithms for various scenarios. Some of the related researches are discussed here.

In [10], the authors attempt to present key factors that play a role in the design of resource allocation algorithms for UMTS/LTE cellular systems. In their study, they conclude that it is impossible to design a wireless scheduling algorithm that is impartial, simple, efficient, and capable of ensuring real-time delay guarantees at the same time. While some approaches raise the overall network capacity, others focus on specific QoS metrics such as delay and fairness. Thus, a tradeoff will always be present. Classical approaches based on Maximum Throughput (MT), PF, and RR[11] are not strictly applicable to handle real-time multimedia services as they miss some important features like delay control and packet loss. In order to address this problem, several recent studies propose channel-aware algorithms which prioritize data traffic flows with head-of-line packets close to the deadline. They differ from one another mostly in terms of the weighting functions applied to maximize fairness in bandwidth allocation, as well as on-time delivery of packets.

To examine the impact of the number of UE and speed variations on the performance of scheduling algorithms, the paper[12][12][12] compares some algorithms namely, MT, RR, PF, Resource Fair (RF), and Best CQI. They attest increasing the number of UEs and speed will cause throughput degradation for all scheduling algorithms and affect spectral efficiency. But their assessment doesn’t take into account real-time (RT) traffic and only QoS-unaware schedulers are considered for simulation.

In the literature, few studies are dedicated to evaluating scheduling mechanisms from the energy efficiency perspective. Among the three conventional scheduling algorithms, namely Max C/I, RR, and PF algorithm in LTE downlink transmission, Max C/I is the best in terms of energy efficiency while RR is the least. Due to Max C/I not being a QoS-aware scheduler, the delay and PLR are not taken into account. Paper in [13] further studied improved versions of the PF schedulers: EXP-PF (Exponential Proportional Fair), and MLWDF (Modified Largest Weighted Delay First) energy consumption in a single cell and fixed mobility scenario. The latter outperforms in terms of QoS and energy efficiency. In the work [14], four different scheduling approaches were assessed. They are Channel and Quality of Service Aware Frequency Fading (CQA_Ff), CQA Proportional Fair (CQA_PF), Priority Set Scheduler Carrier Over Interference to Average (PSS_CoItA), and PSS Proportional Fair (PSS_PF) based on the evaluation metrics of QoS and energy consumption ratio (ECR). It is shown that the CQA scheme for both approaches (CQA_PF and CQA_Ff) is the most energy-efficient algorithm from the other compared approaches. But the assessment is done on a single cell environment with fixed user mobility mode without considering neighbor cells' interference on edge users.

The above works of literature revealed that there is a lot to consider while designing or selecting optimal algorithms for our context based on the traffic type and user characteristics as fulfilling all requirements simultaneously is difficult.

1.4. Scope and Limitation

This thesis focuses on detailed study and comparisons of existing downlink scheduling algorithms in LTE cellular networks. Uplink scheduling algorithms are not covered in this work as they have some different constraints from the downlink one as they use different multiple access techniques. Since there are no firm provisions that are set by 3GPP for controlling the LTE packet scheduling mechanisms, various algorithms are kept emerging to fulfill specific objectives. Therefore, this thesis work assesses only those selected major downlink scheduling algorithms. Due to proprietary concerns, vendors don’t reveal their scheduling algorithm's detailed mathematical descriptions. Hence, ethio telecom’s actual scheduling algorithm is not implemented in this thesis. When evaluating and comparing different scheduling algorithms, it is common to prepare one’s own algorithm for comparative purposes. However, this is beyond the scope of this particular thesis. So no novel algorithm will be proposed.

1.5. Contributions

Managing radio resources in an LTE network is considered as a crucial part of improving overall system performance. After thoroughly investigating and comparing the available major techniques, this thesis will point out problems of existing algorithms and recommend an optimal algorithm in order to use our limited resources efficiently. The result obtained in this thesis work can be used as a baseline for future studies and an input for the operator, ethio telecom while negotiating with vendors.

1.6. Thesis Outline

This thesis consists of five Chapters. In Chapter 1 an introduction along with problem statement, objectives, and literature review are included. The next section, Chapter 2, provides the overall description of resource allocation in the LTE network and outlines the scheduling schemes being considered in this thesis for comparison. Chapter 3 introduces the methodology used while doing the thesis and elaborate the tool used for simulation and various scenarios for the evaluation. Then, Chapter 4 discusses the simulation result and performance analysis of selected scheduling strategies against some metrics. Finally, Chapter 5 summarizes the thesis work along with future work.

2. Resource Scheduling In LTE

The growing demands of broadband services, such as real-time gaming, social networking, conversational video, location-based services, live streaming, and so on, together with the storage and data processing capabilities of end terminals, such as tablets, smartphones, are causing the exponential upsurge of mobile data traffic in recent years [15]. 3GPP standardize and release the LTE mobile network to address these issues by offering high peak data rates, high spectral efficiency, low user plane latency, improved capacity and coverage, low operating expenses, enhanced support of an end-to-end QoS, and spectrum flexibility [16]. LTE introduces new all IP system architecture along with some physical layer technologies such as Single Carrier Frequency Division Multiple Access (SC-FDMA) in the uplink side, Orthogonal Frequency Division Multiple Access (OFDMA) in the downlink, and multiple antenna mechanisms [17].

From an architecture point of view, LTE release 8 is a major development in the radio access network (RAN) of 3GPP families to date. In previous technologies, the Radio Network Controller (RNC) controls the base stations and plays an intermediate role in connecting base stations (NodeB) to the core network. But in LTE release 8, this network element does not exist; instead, the eNodeB is connected directly to the core network, Evolved Core Packet (EPC) [16], as shown in Figure 2.1. The functions of the removed RNC are split between the remaining parts, the eNodeB, and the core network. Most of these functionalities were inherited by eNodeB, such as radio resource management mechanisms.

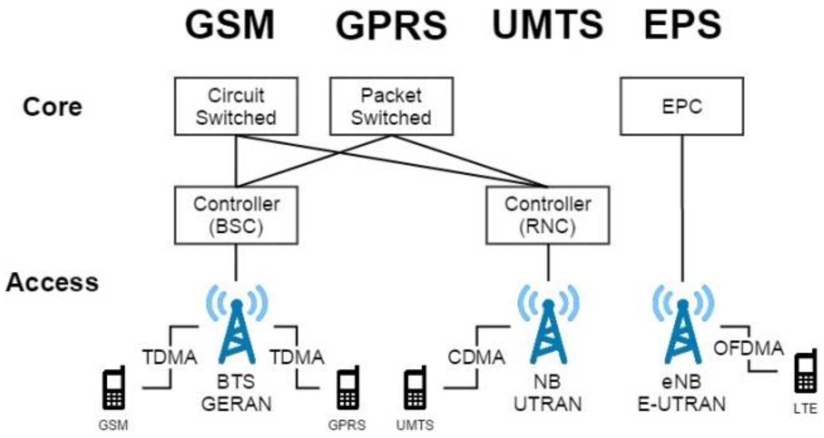


Figure 2.1 *Radio Access Network Solution From GSM to LTE* [16].

2.1. LTE Air-Interface

2.1.1. LTE Spectrum

LTE can operate in various spectrum bands so that it can be deployed anywhere in the world, supporting as many regulatory requirements as possible. Evolved Universal Terrestrial Radio Access (E-UTRA) operating frequency bands currently start from 700 MHz up to 2.7GHz. In addition, there is flexibility in available bandwidths between 1.4 MHz and 20 MHz. Both time division duplex technology (TDD) and frequency division duplex technology (FDD) are supported in LTE. The FDD bands have two pairs of frequencies, each one for the uplink and downlink separately whereas TDD uses a single band for both but downlink and uplink are separated by time. As a result, there are different LTE band allocations for TDD and FDD. Depending on the scenario, these bands may overlap, so it may be possible that both TDD and FDD transmissions may occur on a particular LTE frequency band, although this is unlikely. In Rel-8 there are 15 bands specified for FDD and eight bands for TDD. In release 9 four bands were added for FDD [16]. The two modes are shown in Figure 2.2 where the majority of systems deploy FDD due to market preference including ethio telecom.

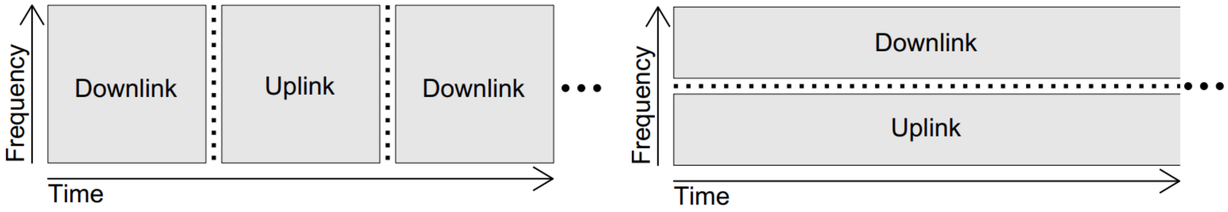


Figure 2.2 *TDD & FDD Modes of Transmission* [18].

FDD and TDD modes have different pros and cons. In FDD mode, the bandwidths of the uplink and downlink are fixed and are usually the same. This makes it suitable for voice communications, as It is designed for symmetric traffic and does not require guard time like TDD. In TDD mode, the system can adjust how much time is allocated to the uplink and downlink. This makes it suitable for applications such as web browsing, in which the downlink data rate can be much greater than the data rate on the uplink. This is possible due to the dynamic allocation of time slots without altering the bandwidth once allocated. TDD mode can be badly affected by interference so it requires stringent phase/time synchronization. This makes TDD suitable for networks that are made from isolated hotspots because each hotspot can have different timing and resource allocation. Due to the requirements of more base stations (eNodeB), deployment and operating costs are higher in TDD. In contrast, FDD is often preferred for wide-area networks that have no isolated regions. Even though it reduces the number of base stations required, FDD has higher hardware costs [15].

2.1.2. Multiple Access Schemes

Radio resource allocation schemes are closely related to the radio access technologies used in mobile networks. Multiple access techniques are used to allow many mobile users to share simultaneously a finite amount of radio spectrum. The 3GPP selected a multicarrier method for multiple access to attain high radio spectral efficiency, and also to allow resource scheduling to be accomplished in both time and frequency domains. LTE implements SC-FDMA in the uplink and OFDMA in the downlink [19]. Both techniques are represented in Figure 2.3.

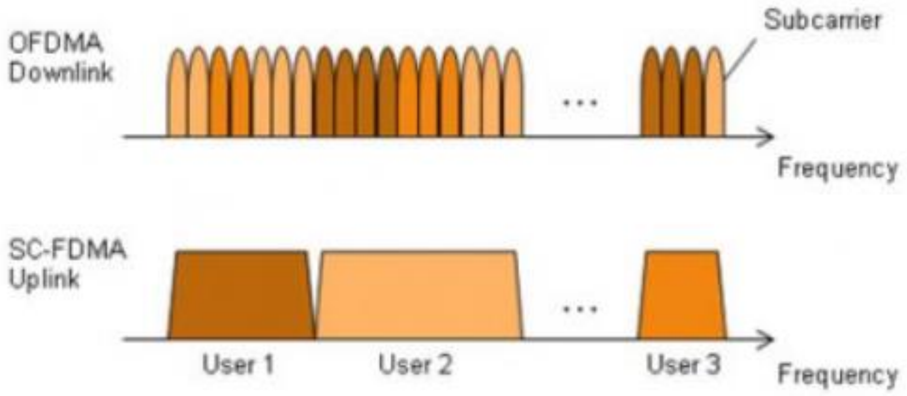


Figure 2.3 *LTE OFDMA and SC-FDMA in Frequency-Domain View* [16].

OFDMA extends the multi-carrier technology of Orthogonal Frequency Division Multiplexing (OFDM) to offer a very flexible multiple-access scheme. OFDM subdivides the bandwidth available for signal transmission into multiple equally spaced narrowband subcarriers, arranged to be mutually orthogonal (to avoid inter-carrier interference), which either individually or in groups can carry independent information streams. In OFDMA, this sub-division of the available bandwidth is exploited in sharing the subcarriers among multiple users. OFDMA is also used by other radio communication systems, such as wireless local area networks (IEEE 802.11) and

WiMAX (IEEE 802.16), as well as in digital television and radio broadcasting. Yet, LTE is the first system to have made use of SC-FDMA [15].

The transmitter design for OFDM is somewhat expensive, as the Peak to Average Power Ratio (PAPR) of an OFDM signal is relatively high, resulting in a need for a highly linear RF power amplifier. The high PAPR of OFDM poses a problem for the transmitter of the mobile terminal since a compromise must be made between the output power required for good outdoor coverage, the power consumption, and the cost of the power amplifier hardware [20]. For that reason, SC-FDMA is used on the uplink. SC-FDMA is a modified version of OFDMA and has similar performance and basically equivalent overall complexity OFDMA. Like OFDM, SC-FDMA also consists of subcarriers but it transmits on subcarriers in a sequence, not in parallel which is the case in OFDM, which prevents power fluctuations in SC-FDMA signals i.e. low PAPR. Hence, it resolves to some extent the dilemma of how the uplink can benefit from the advantages of multicarrier technology while avoiding extra cost for the user terminal transmitter and retaining a reasonable degree of commonality between uplink and downlink [21].

2.1.3. Resource Blocks (RB)

In LTE, information is organized as a function of frequency as well as time, using a resource grid as shown in Figure 2.4. It is structured into radio frames of 10 ms long [15]. Each frame is split up into ten equally sized sub-frames. The sub-frame has a duration of 1 ms, also called TTI. Moreover, each sub-frame is further divided into two equally sized time slots (each 0.5 ms long). A slot contains 7 OFDM symbols in the time domain (TD) and is also divided in the frequency domain (FD) into sub-channels of 180 kHz each (12 consecutive 15KHz subcarriers). A resource element (RE) is the fundamental unit of the grid, and it extends one symbol by one subcarrier. Each RE can carry two, four, or six physical channel bits, depending on the modulation scheme, QPSK, 16-QAM, or 64-QAM respectively, used. These REs are together assembled into resource blocks (RBs), each extent 0.5 ms in time (one slot) and 180 kHz in the frequency domain (12 sub-carriers).

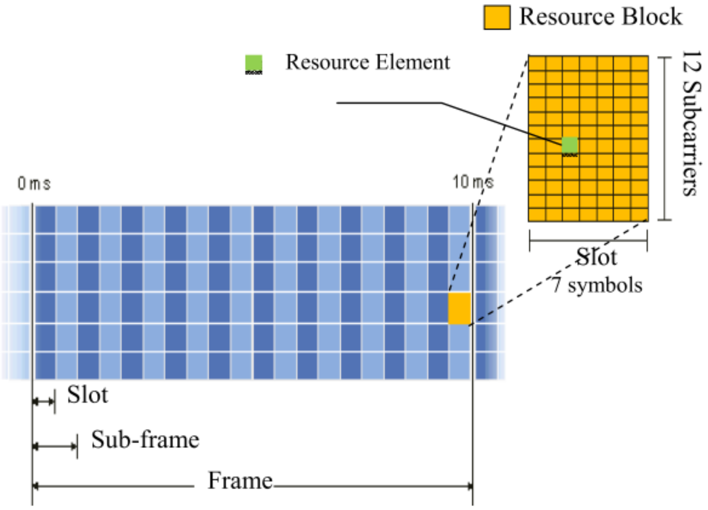


Figure 2.4 *Resource Block and Resource Element Definition* [22].

The minimum resource piece that can be assigned to a user during each TTI (sub-frame) is a Scheduling Block (SB), which comprises two consecutive RBs [13]. Scheduling is done at eNodeB and is responsible for allocating the SBs to one or more UEs as per the requirement.

In LTE, a cell can be configured with different bandwidths [15], which are listed below in Table **2.1**. The amount of available RBs will therefore vary based on the LTE signal bandwidth. In a 10 MHz band, for example, the base station transmits using 50 RBs (600 sub-carriers), giving a transmission bandwidth of 9 MHz. In that arrangement, there is room for guard bands at both the upper and lower edges of the frequency band, which reduces interference with the next band. The two guard bands are typically the same width, but the network operator can adjust them if needed by shifting the center frequency in units of 100 kHz.

Table 2.1 *Cell Bandwidths Supported By LTE.*

Total bandwidth	Number of resource blocks	Number of sub-carriers	Occupied bandwidth	Usual guard bands
1.4 MHz	6	72	1.08 MHz	2 × 0.16 MHz
3 MHz	15	180	2.7 MHz	2 × 0.15 MHz
5 MHz	25	300	4.5 MHz	2 × 0.25 MHz
10 MHz	50	600	9 MHz	2 × 0.5 MHz
15 MHz	75	900	13.5 MHz	2 × 0.75 MHz
20 MHz	100	1200	18 MHz	2 × 1 MHz

The existence of all these bandwidth options makes it easy for network operators to deploy LTE in a variety of spectrum management regimes and this feature is called scalable bandwidth [23]. For instance, 1.4 MHz is close to the bandwidths previously used by CDMA2000 and TD-SCDMA, 5 MHz is the same bandwidth used by WCDMA/HSPA, while 20 MHz allows an LTE base station to operate at its highest possible data rate.

2.1.4. QoS in LTE

One purpose of optimized resource allocation is to satisfy high QoS requirements for diverse users with different types of services. In the LTE 3GPP systems, Evolved Packet System (EPS) bearers are responsible for offering different QoS for diverse users [21]. An EPS bearer can be thought of as a bi-directional logical data pipe, which routes IP traffic on the correct path through the network and with the right QoS. The bearer runs between the UE and the PDN gateway if the S5/S8 interface is based on Gateway Tunneling Protocol (GTP) or between the mobile and the serving gateway if the S5/S8 interface is based on Proxy Mobile IP (PMIP) [15].

The EPS bearer passes through three different nodes in a GTP-based S5/S8, so it cannot be done directly. To deal with this problem, the EPS bearer is broken down into three smaller bearers, namely the radio bearer, the S1 bearer, and the S5/S8 bearer. Each of these is itself linked with a set of QoS parameters and obtains a share of the EPS bearer’s maximum error rate and maximum delay. Both a radio bearer and an S1 bearer together sometimes known as an evolved radio access bearer (E-RAB).

If the S5/S8 interface is implemented using PMIP, then mobile has only one Generic Routing Encapsulation (GRE) tunnel on that interface, which handles all the data packets that the mobile is transmitting or receiving without any QoS guarantees [15]. Together, EPC and UTRAN are responsible for setting up and releasing bearers as needed by applications. The overall EPS bearer service architecture is shown in Figure 2.5.

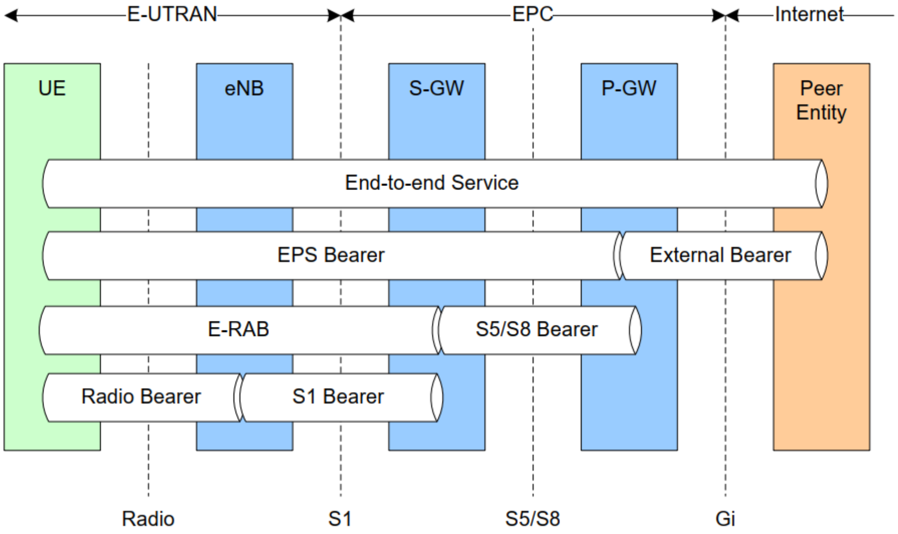


Figure 2.5 *EPS Bearer in LTE* [24].

The first time the UE connects to the wireless network, one EPS bearer/E-RAB called default bearer is created, and this bearer remains active throughout the connection so that the UE has an always-on IP connection to that PDN. Once connected to the PDN and a default bearer has been established, the UE can then get one or more dedicated bearers that link it to the same network [24]. Nevertheless, new IP addresses are not allocated as a result of this; instead, each dedicated bearer retains the IP address of its parent default bearer. In general, a default bearer is assigned to UE in order to exchange control messages and connection establishment whereas dedicated bearers are allotted to UE for transmitting traffic as per the QoS requirement. Dedicated bearers are classified into two kinds known as a Guaranteed Bit rate (GBR) or a Non-GBR bearer while the default shall always be a Non-GBR bearer. A UE can have up to 11 EPS bearers to allow the connection to multiple networks with different QoS requirements [15].

To specify the types of services and applications, traffic data are categorized as Conversational, Streaming, Interactive & Background classes. The sensitivity of traffic to delay is what differentiates these traffic classes, for example, conversational traffic is delay-sensitive, whereas background traffic is delay insensitive. The Streaming and Conversational classes transport real-time traffic data, whereas Interactive and Background classes are mainly intended to carry other Internet applications such as email and FTP. The 3GPP has standardized QoS features called QoS Class Identifier (QCI)s for nine traffic classes mainly according to their priority, delay tolerance, packet loss rate, and resource type (e.g. GBR) [24]. Table 2.2 shows the standardized QCIs requirements and example services.

Table 2.2 *Standardized QCIs for LTE* [24].

QCI	Resource type	Priority	Packet Delay Budget (ms)	Packet Loss Rate	Example service
1	GBR	2	100	10^{-2}	Conversational Voice
2		4	150	10^{-3}	Conversational Video (live streaming)
3		3	50	10^{-3}	RT gaming
4		5	300	10^{-6}	Non-conversational video (Buffered streaming)
5	Non-GBR	1	100	10^{-6}	IMS signaling
6		6	300	10^{-6}	Video (Buffered Streaming) TCP-Based (for example, www, email, chat, ftp, p2p, and the like)
7		7	100	10^{-3}	Voice, Video (Live Streaming), Interactive Gaming
8		8	300	10^{-6}	Video (Buffered Streaming) TCP-Based (for example, www, email, chat, ftp, p2p, and the like)
9		9			

2.2. Radio Resource Management (RRM)

For every telecom operator, the resources to invest and expand its radio network are always limited, such as frequency bandwidth and capital [21]. Moreover, the demand to offer customers the best service with good quality and wide coverage continues to drive the telecom engineers to find better solutions with these scarce resources. There are four objectives that the network operator mainly focuses on: Capacity, Coverage, Efficiency, and Quality. These objectives are quite contradictory and compete with each other and it requires a considerable effort to design, plan, control, and optimize a cellular network [5]. In the initial phase, it is the Radio Network Planning (RNP) task, which includes design, dimensioning, planning, etc. and the later phase is Radio Resource Management (RRM). RNP makes the network setup and run, while the RRM optimizes it.

RRM refers to the whole functionality of managing the use of radio channels, co-channel interference, and other radio transmission features [19]. As part of RRM, various methods are used to ensure efficient use of radio resources, allowing users to receive service according to the configured QoS parameters. RRM encompasses a wide range of techniques and procedures, including admission control, power control, and packet scheduling. Figure 2.6 shows an overview of the protocol stacks and their mapping with corresponding RRM operations.

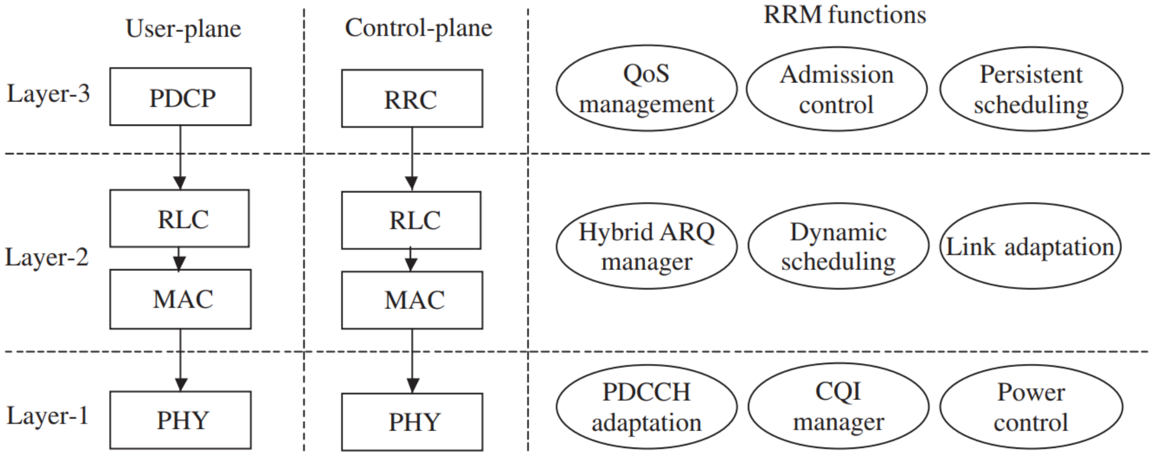


Figure 2.6 *eNodeB User and Control Plane Protocol Architecture and Corresponding RRM Functions* [25].

The basic RRM functionalities are executed at various network layers. Layer 3 RRM functions such as admission control, are characterized as being semi-dynamic mechanisms since they are mainly performed at the time of new data flow setup. The other algorithms at layer 2 and 3 are very dynamic with new actions executed at every transmission time interval (TTI) of 1 ms and therefore characterized as being fast dynamic [25].

In LTE, 3GPP only defines RRM related signaling without specifying the actual algorithms and strategies to be adopted. As such, LTE offers the vendors and operators a degree of freedom to use the RRM functions according to different design issues of their respective networks [19]. This thesis work solely focuses on one of the main RRM functions, the packet scheduling algorithm, and the next subsection will discuss it in more detail.

2.2.1. Scheduling Algorithms

One of the most important aspects of RRM in LTE systems is packet scheduling which refers to the process of selecting users' packets intelligently to guarantee fairness, improve system performance and satisfy QoS requirements. The packet scheduler, which resides at the eNodeB in the MAC layer, has become the one outstanding feature in LTE. Scheduling in the downlink LTE system is performed at every TTI which consists of two time slots, or on an SB basis. Within a TTI, a user receives two consecutive RBs. Figure 2.7 illustrates a generalized resource scheduler in the LTE network.

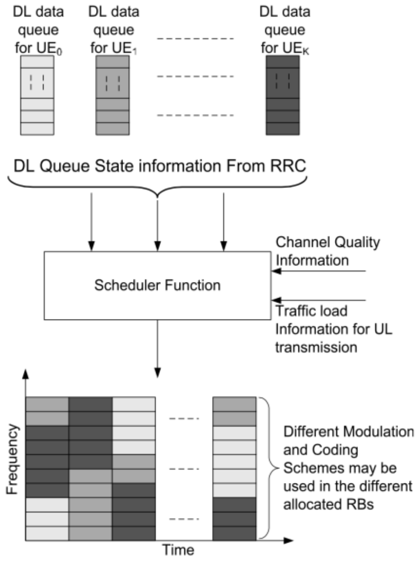


***Figure 2.7** General View of LTE Packet Scheduler* [25].

The three basic input parameters that are needed to perform scheduling are [26]:

- **Channel Quality Indicator (CQI):** It's a quantized and scaled measure of SINR (Signal to Interference Plus Noise Ratio). On every TTI, each user reports its CQI computed from its downlink instantaneous channel condition to the serving eNodeB which is carried either by the physical uplink control channel (PUCCH) or physical uplink shared channel (PUSCH). As can be seen from Table **2.3**, LTE has 15 CQI values ranging from 1 to 15 (the higher the better channel quality). Based on the CQI value, the adaptive modulation and coding (AMC) block selects the proper modulation and coding scheme (MCS) to maximize the supported system throughput for a given target block error rate. The chosen MCS and resource allocation map are sent on the physical downlink control channel (PDCCH) in the form of downlink control information (DCI). eNodeB uses Physical Downlink Shared Channel (PDSCH) to transmit downlink data to the UE. [23].

- **QoS requirement:** It is a set of rules that come from the core which define priority, packet loss rates, guaranteed bit rate (GBR), and latency requirements for different connections to the UE depending on service types (RT and Non-Real time (NRT)).
- **Buffer status information:** It comes from the upper layers (RLC) about how much data is queued up waiting for transmission.

Table 2.3 *4-bit CQI Table* [27].

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

It is important to mention here that the packet scheduler interacts closely with the HARQ (Hybrid Automatic Repeat Request) manager as it is responsible for scheduling retransmission which is performed through the exchange of ACK/NACK between eNodeB and UE. The downlink LTE system uses QPSK (Quadrature Phase Shift Keying), 16QAM (Quadrature Amplitude Modulation), and 64QAM together with channel coding to provide support for high data rates. Besides being used to determine the number of bits that a user can support in two consecutive RBs in each TTI, the effective SINR value is used to determine a user's priority in channel-dependent scheduling.

By using this information, the eNodeB scheduler algorithm optimizes the assignment of radio resources to the UEs, always within reasonable fairness, and meeting QoS requirements while being efficient from a spectral point of view.

Among the main features of LTE is its ability to allocate resources both in the time and the frequency domain [23]. Thus, a scheduler can allocate all the resources in a given time interval to a single user, or partition them also in the frequency domain, assign fractions of the available bandwidth to different users in the same time slot. The scheduler can hence choose between a simple Time-Domain (TD) allocation policy in which a single user gets all the resources in a given time slot, and a more complex Frequency- Domain (FD) approach, where resources are allocated with finer granularity, also exploiting the frequency dimension.

In general, LTE supports the following three modes of scheduling [25]:

a) **Dynamic Scheduling:** Every 1ms, the scheduler checks for the UEs to be scheduled, the data availability for each UE to be scheduled, and the feedback from the UE on the Channel conditions. This gives the network full flexibility in assigning the resources to the UE at the cost of transmission of resource allocation information on PDCCH in every subframe which creates high overhead over a scarce radio channel.

b) **Persistent Scheduling:** Fixed allocation of RBs to users for the period of usage, similar to the circuit-switched fashion. Control signaling (PDCCH) is required only at the initial. There is no link adaptation which in turn may reduce user experience but save energy.

c) **Semi-Persistent Scheduling:** It is a hybrid way, which tries to overcome the downsides of the above two scheduling. Unlike dynamic scheduling this schedules resource every 20ms. It is designed for services such as VoIP. For these services, the data rate is low, so the overhead of the scheduling message can be high. However, the data rate is also constant, so the base station can confidently use the same resource allocation from one transmission to the next.

The hypothetical basis of an energy-efficient scheduling strategy is mostly contributed by the low transmit power from the base station and UE. The amount of transmitted power from the base station is influenced by the bandwidth, channel quality, load, and modulation mode. To achieve optimal energy efficiency researchers try various strategies like minimizing the number of wake-up time (TTIs) for the UE's receiver circuit through discontinuous reception (DRX) procedures [28], lowering transmit power [29], and optimally adjusting the MCS of the RBs set assigned to non-priority users at the cost of spectral efficiency [30][31]. Among the few algorithms, most energy-efficient scheduling strategies only realize energy reduction, but they are fair to the main purpose of packet scheduling, namely throughput, and fairness. A good scheduling scheme should be able to achieve a better compromise among the above several metrics. We cannot acquire a comprehensive performance of a wireless network where transmit power is greatly reduced at the cost of throughput or fairness.

Since 3GPP doesn't impose any restriction on the usage of particular scheduling algorithms, there are many algorithms that exist in the actual operation as proprietary and in literature. Efficient spectrum utilization could be achieved by the use of the right scheduling algorithm that meets with the environment's conditions and the users' requirements demands. In general, these algorithms can be broadly classified into three main groups: channel-unaware/QoS-unaware, channel-aware/QoS-unaware, and channel-aware/QoS-aware [32].

Huawei supports four packet scheduling algorithms in LTE: Max C/I, RR, PF and, Enhanced proportional fair (EPF) [35]. Both dynamic & semi-persistent scheduling schemes are supported in Huawei. ZTE also supports the three basic algorithms and adds two more special schemes, Equal Rate (ER) and EPF of their own. Except for the basic ones all others are unique and propriety to the vendors. Because of this, they are not open to the public.

This thesis is interested in evaluating the QoS performance and energy consumption of five well-known channel-aware/QoS-aware scheduling algorithms for various service types.

To obtain the metric, scheduler algorithms usually need to know the average transmission data rate $\overline{R_i}$ of the $i-th$ flow, as well as the instantaneous available data rate of the receiver UE for the $j-th$ subchannel [32]. This knowledge is useful when the metric has to take into account information about the performance guaranteed in the past to each flow to perform fairness balancing. In particular, for every TTI, the estimation of $\overline{R_i}$ is given by:

$$\overline{R_i}\,(k) = 0.8\overline{R_i}(k-1) + 0.2R_i(k) \qquad (2.1)$$

Where $\mathrm{R_i(k)}$ is the data rate achieved by the $i-th$ flow during the $k-th$ TTI, and $\mathrm{R_i(k-1)}$ is the estimation in the previous TTI.

In what follows, a detailed description of the considered algorithms working principle is stated along with their priority metric.

2.2.1.1. Modified Largest Weighted Delay First (MLWDF)

M-LWDF is an improved version of LWDF, a channel-unaware scheduling scheme, which has been altered to become aware of its channel state and provisions for delays in constrained packet transmissions. It was first proposed for a Code Division Multiple Access-High Data Rate (CDMA-HDR) system and yet, has been vastly adopted in LTE [33]. The MLWDF scheduling algorithm is designed to support multiple RT data users by considering their different QoS requirements. The scheduling decision is based not only on the channel conditions but also on the QoS requirements mainly the delay. In the implementation of this scheme, the method distinguishes between NRT and RT traffic. As a result, RT packets can be prioritized based on their head-of-line delay (HOL). The priority metric for making the decision to choose the user is based on:

$$w_{i,j} = \alpha_i D_{HOL,i} \frac{r_{i,j}}{\overline{R_i}} \qquad (2.2)$$

$$\alpha_i = -\frac{\log \delta_i}{\tau_i} \qquad (2.3)$$

Where:

- $D_{HOL,i}$ Head of Line packet delay (time difference between the current time and the time at which the packet arrived)
- $r_{i,j}$ the achievable data rate according to the instantaneous channel state.
- $\overline{R_i}$ an average past data rate of user i
- δ_i is the maximum probability of HOL packet delay of user i to exceed the delay threshold.
- τ_i is delay threshold of user i

This scheme combines a QoS service differentiation mechanism with a PF scheduling mechanism. The classical PF scheme ($\frac{r_{i,j}}{\overline{\overline{R_i}}}$) was extended with packet loss and packet delays dependent components. α_i used to differentiate two flows that consist of the identical HOL delay. Its verdict is based on valid requirements of packet expiry deadlines and acceptable PLR and. In the MAC queue, packets that are associated with RT services and have not been transmitted by the time of their expiry date shall be removed from the queue. This is performed to avoid the consumption of bandwidth.

2.2.1.2. Exponential/Proportional Fairness (EXP/PF)

EXP/PF was proposed to support both RT services with different QoS necessities and NRT data services in an AMC/TDM (Adaptive Modulation and Coding and Time Division Multiplexing) system [34]. It integrates PF and adds an exponential term. EXP properties improve the RT flow's priority prior to the association of NRT flows and provide maximum throughput, while PF properties maintain a minimum service level for NRT to ensure that services are fair. The scheduling metric is:

$$w_{i,j} = \exp\left(\frac{\alpha_i D_{HOL,i} - x}{1 + \sqrt{x}}\right)\frac{r_{i,j}}{\overline{\overline{R_i}}} \tag{2.4}$$

$$x = \frac{1}{N_{rt}}\sum_{i=1}^{N_{rt}} \alpha_i D_{HOL,i} \tag{2.5}$$

Where:

- N_{rt} the number of active downlink real-time flows
- x the weight factor (average value of Head of Line delays)

EXP-PF algorithm categorizes users based on service type, RT and NRT. The NRT services use the PF rule to maximize system throughput while maintaining fairness and users with RT services are served using the EXP term aim to guarantee delay bound. To maintain a chance for NRT packet traffics to be scheduled, EXP-PF uses the PF method, while keeping low delay limits on certain RT flows by using an exponential function of HoL delay. Nevertheless, the algorithm cannot guarantee delay requirement between RT and NRT traffic flows, and it emphasizes mainly on maximizing the throughput.

2.2.1.3. Exponential Rule (Exp-Rule)

Exp-Rule is a channel-aware/QoS- aware throughput-oriented scheduling algorithm [35]. It takes into consideration both the channel quality and the states of queues while making scheduling decisions. And also this algorithm highly prioritizes flows on the basis of their achieved throughput. For decision making, it uses the following formula:

$$w_{i,j} = b_i exp\left(\frac{a_i D_{HOL,i}}{c+\sqrt{\left({}^{1}/{}_{N_{rt}}\right)\sum_i D_{HOL,i}}}\right).\Gamma_j^i \qquad (2.6)$$

Where

- a, b & c are tunable parameters (according to [36], optimal value is [5/(0.99τ*i*), 10/(0.99τ*i*)], 1/E[Γ_j^i] and 1, respectively)
- Γ_j^i spectral efficiency of the *i*th UE on the *j*th RB

This scheme prioritizes real-time traffic over non-real-time traffic. EXP-Rule tries to balance the weighted queue size of all the flow queues. If one queue is larger than others, the EXP term becomes larger, allowing the flow to be prioritized according to archived system throughput. In contrast, a flow with a smaller queue size will have a smaller EXP value that is near to one; in this case, the rule behavior will be toward keeping fairness for the flow. For NRT flows, the simple PF metric will be used. Similar to M-LWDF, packets belonging to a real-time flow that is not served before their expiration date shall be erased from the MAC queue. Both EXP-Rule and MLWDF are characterized as bounded delay schemes. Basically, the EXP-Rule is an improvisation of the PF/EXP scheduler discussed before. Due to its growth and to the fact that it monitors the whole network, the EXP rule has proven to be more robust [37].

2.2.1.4. Logarithmic Rule (LOG-Rule)

LOG-Rule is an opportunistic delay-based scheme [36]. In contrast with the EXP-Rule algorithm, the log-rule algorithm prioritizes flows by disregarding the balance of unequal queue sizes in favor of building a tradeoff between low delay amount and a good level of throughput. Its priority metric is:

$$w_{i,j} = b_i \log\left(c + a_i D_{HOL,i}\right) . \Gamma_j^i \tag{2.7}$$

To some extent, this scheme's approach in assigning resources is similar to the EXP-Rule. Arithmetically, the EXP and logarithm functionality is somewhat similar. The variance is that in which the logarithmic function implements the inverse performance of the EXP function. The scheduling approach of LOG-Rule prioritizes RT services and optimality constants (a, b, and c) have similar values as those of the EXP-Rule algorithm. LOG-Rule destresses queue balancing to enable more delay-based behavior decisions, however at the cost of system throughput.

2.2.1.5. Frame Level Scheduling (FLS)

It is a two-level scheduling scheme in which two levels (the highest level and the lowest level) cooperate to dynamically distribute resource blocks among UEs [38]. At the highest level, an innovative less complex algorithm, called FLS, has been implemented using discrete-time linear control theory. At the start of each frame, FLS specifies the amount of data that each real-time source should transmit within a single frame, to satisfy its delay constraint of RT services. Then, the lowest level scheme, to guarantee a good fairness level among multimedia flows, RBs are allocated according to the PF algorithm as per the constraint imposed by FLS. Radio resources left free by RT flows can be used to provide best-effort service using the PF algorithm, which also enforces fairness for such kinds of flows. The equation to calculate the quota of data to be transmitted during the kth frame is:

$$u_i(k) = h_i(k) * q_i(k) \tag{2.8}$$

Where

- $q_i(k)$ is the queue level
- $h_i(k)$ is pulse response and $*$ operator is the discrete-time convolution.

From Equation 2.8 the amount of data to be transfer by the i^{th} flow over the k^{th} LTE frame is found by filtering the signal $q_i(k)$ through a time-invariant linear filter $h_i(k)$.

3. System Modeling and Simulation

This Chapter presents descriptions of the simulation tool, the LTE system model developed to analyze the overall performance of scheduling algorithms, and the evaluation metrics.

3.1. Simulation Tool

Through computer simulation, a large and complex cellular network system can be modeled. To do this LTE-Sim, an open-source framework is used in this thesis to simulate system-level LTE networks. It was developed using C++ following the object-oriented paradigm as an event-driven simulator [39]. It incorporates several elements of LTE networks, including both the EPS and E-UTRAN. In particular, it supports both single-cell and multicell environments, multiuser environments with user mobility, QoS management, handover actions, and packet scheduling. A comprehensive and detailed framework tool, LTE-Sim models the entire stack of LTE protocol functions, with more focus on the MAC layer functionalities. Thus, it supports both time and frequency domains resources allocation [40]. The four main modules of LTE-Sim are shown in Table **3.1**.

***Table 3.1** Main Components of the LTE-Sim* [39].

Component	Functionalities	Important Methods
Simulator	• Creates/Handles/Ends an event	Schedule()
		RunOneEvent()
		Run() /Stop()
FrameManager	• Defines LTE frame structure • Schedules frames and sub-frames	StartFrame() and StopFrame()
		StartSubFrame() and StopSubFrame()
FlowsManager	• Handles applications	CreateApplication()
NetworkManager	• Creates devices • Handles UE position • Manages the handover • Implements frequency reuse techniques	CreateUserEquipment()
		CreateCell()
		UpdateUserPosition()
		HandOverProcedure()
		RunFrequecyReuse()

LTE-Sim operates on a Linux machine and for this particular thesis, it is run over Ubuntu with a 2.1-GHz Core i7 CPU and 4 GB of RAM on a VMware workstation. This simulator was chosen due to its versatility, validity in the scientific community, and free availability to students performing research work.

3.2. Simulation Scenario

An urban macro cell of radius equal to 1km with an interference scenario is modeled to evaluate the performances of the considered scheduling schemes as shown in Figure 3.1. A more realistic LTE cellular network simulation environment is prepared that considers nearly all possible effects that can be generated from neighboring cells as well as external interference. Several users ranging from 10 up to 100 are randomly spread throughout the cell and moving in a random direction. LTE network is developed to perform well under a range of diverse user speeds and for this thesis, two user speeds are selected to realize the effect on the scheduling, 3km/hr which is a typical average pedestrian speed, and 120km/hr as highway driving speed. The performance of the schedulers has been analyzed by varying the user speed [3, 120 km/hr] and the number of users. By choosing a random speed direction that remains constant throughout the simulation, the user moves towards the simulation boundary area. Once the simulation boundary area is reached, the UE chooses a new speed direction.

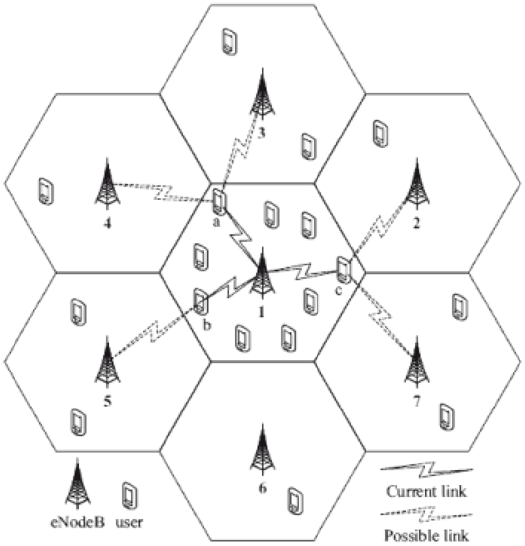


Figure 3.1 System Model of the Simulation Scenario.

The physical layer for downlink channels is modeled with a 2.1 GHz carrier frequency band. It consists of a number of sub-carriers each with 15 kHz spacing. The power transmission rate at eNodeB is configured to 43 dBm and it is equally distributed among subchannels. To cope with LTE standards, in this work propagation loss of the channel is implemented on a macro–cell urban area model in which it operates by combining four different modules (multipath, shadowing, path loss, and penetration loss). The path loss is calculated based on [41] as follows:

$$\rho_L = 128.1 + 37.6 \, log \, d \tag{3.1}$$

Where

- d is the distance in meters between eNodeB and UE.

In a multipath module, Rayleigh fast fading is implemented using Jakes' model [39], and a multiple paths number is uniformly selected from the set {6, 8, 10, 12}. In addition, the penetration loss is set to a default value, 10 dB while shadowing is modeled by lognormal distribution (standard deviation = 8dB, with mean of 0dB).

When the $i - th$ UE receives packets, it performs the following procedures:

1) The PHY layer computes, for each subchannel, the SINR for the received signal considering the received power, the noise, and the interference as follows [39]:

$$SINR_{i,j} = \frac{P_{RX_{i,j}}}{(FN_0B) + I} \tag{3.2}$$

Where

- $\mathrm{P}_{\mathrm{RX}_{\mathrm{i,j}}}$ Received Power
- F Noise Figure (with a default value of 2.5)
- N_0 Noise Spectral Density (with a default value of −174 dBm)
- B Bandwidth of a Resource Block
- I Interference

We remark that the interference is the total power received from the eNodeBs sharing the same frequency resources. The propagation loss of the interfering power is calculated by the NetworkManager through the ComputePathLossForInterference () method, which selects the proper propagation loss model, depending on the cell scenario.

2) According to the SINR, the UE creates CQI feedback to send to the eNodeB.

When the UE obtains packets in the downlink, it calculates the SINR for every downlink subchannel. Then, according to the CQI reporting rules, it creates CQI feedback to send to the eNodeB at which it is registered. The CQI is used by the UE to report to the eNodeB the highest data rate that can be achieved over a given subchannel while guaranteeing a BLER that is at least equal to a certain BLER target (the default value is 10%). In particular, the CQI value is obtained as a quantized version of the estimated SINR. The mapping procedure between the SINR and the CQI is performed through the BLER–SINR curves. LTE-Sim keeps various sets of BLER-SINR curves, which are selected based on a set of physical parameters.

During the resource allocation process, the eNodeB AMC module can select the most suitable MCS by using the mapping table for each scheduled flow according to the reported CQI from UE.

3) The PHY layer determines if packets have been properly received.

To this aim, for each subchannel used to transmit that packet, the BLER is estimated, that is, the ratio between the number of erroneously received blocks and the total number of sent blocks [42]. According to the proper BLER–SINR curve (depending on the used MCS), the simulator estimates if the packet has correctly been received or not. In the latter case, the packet is considered erroneous and discarded. If the packet has been correctly received, it is forwarded to the upper layers.

Telecom traffics can be classified into two main types: RT and NRT services. Depending on the traffic flow type RT services can be categorized as loss-sensitive (e.g. Buffered Video), delay-sensitive (e.g. voice over IP), or both delay and loss-sensitive (eg. video conferencing). An example of an NRT service with no tight requirements is best-effort traffic. They are allocated by spare resources.

In this work, the load of the traffic sources is applied to the network as 40% of the users receives H.264 video flow (encoded at 128 kb/s), 40% VoIP flow (encoded at the rate of 8.4kbps using the G.729 codec which has been declared as an ITU standard), and the rest of 20% receives BE flow modeled with the infinite-buffer application. The trace-based traffic generator at the application layer transmits packets based on realistic video trace files, which are available in [43]. The VoIP application in the simulator generates G.729 voice flows, an audio data compression scheme [39]. The VoIP flow, in particular, has been demonstrated with an ON/OFF Markov chain, in which the ON period has an exponential distribution with a mean of 3s, and the OFF period has a truncated exponential probability density function with an average value of 3s and an upper limit of 6.9s. The source sends a packet of 20 bytes every 20 milliseconds during the ON period (i.e., the source data rate is 8 kbps), but during the OFF period, the rate is zero since a voice activity detector is assumed. The infinite buffer application is modeled as an ideal greedy source that always has packets to send. The simulation parameters are summarized below in Table 3.2.

Table 3.2 *Simulation Parameters.*

Parameters	**Value**
Simulation duration	120 sec/ with 3 repeated iteration
Cell radius	1 km, Urban Macro cells
Bandwidth/Frame Length	10 Mhz/ 10 ms
Users	10-100
User speed	3 km/h & 120 km/h
Mobility	eNodeB: Constant position; UE: Random direction
Frame structure	FDD
Maximum delay	0.1 sec
Transmission power	43dBm (at eNodeB)
Scheduler Type	MLWDF, EXP-PF, EXP-Rule, Log-Rule & FLS
Traffic	RT (Video and VoIP); NRT (Best Effort)
Metrics	Throughput, PLR, Fairness & Energy

3.3. Evaluation Metrics

When running the LTE-Sim, it carries out simulations in a pre-defined condition, taking into account both signaling and data traffic. In its traces, however, it displays only the data traffic. These data traffic traces are then used to measure QoS parameters (throughput, packet loss rates (PLR), fairness among users), and energy consumption. These are in turn used to assess the performance of the five scheduling algorithms in this thesis.

- **Average Throughput**

Systems' average throughput is defined as the amount of successfully transmitted packets for all users per second over a physical channel. It is determined by dividing the size of transmitted packets by the time it takes to receive the packets per user [44].

$$Average\ throughput = \frac{1}{T}\sum_{i=1}^{K}\sum_{t=1}^{T} P_{transmit\ i}(t) \qquad (3.3)$$

Where

- $P_{transmit\ i}(t)$ denotes the size of transmitted packets

- **Packet Loss Ratio (PLR)**

Essentially, this metric measures the percentage of packets traveling across a physical channel that do not reach their destination. Additionally, there can be packet losses caused by buffer overflows. Improved PLR value is a critical issue since it affects performance significantly, especially when dealing with RT traffic such as video and voice communications. If a packet is not acknowledged within a certain delay threshold, it is considered lost. The packet transmission delay deadlines for RT and NRT traffic are different. A packet will be discarded if the HOL delay of the packet exceeds the user traffic delay deadline which is then counted as a packet loss. The formula is given by [44]:

$$PLR = \frac{\sum_{i=1}^{K}\sum_{t=1}^{T} P_{discard\ i}(t)}{\sum_{i=1}^{K}\sum_{t=1}^{T} P_{size\ i}(t)} \qquad (3.4)$$

Where

- $P_{size\ i}(t)$ denotes the total size of all received packet
- $P_{discard\ i}(t)$ is the total size of all discarded packets of user *i* at time *t*

- **Fairness**

It is used to determine whether the user is receiving a fair amount of resources or not. It is measured in terms of the fairness index, J, defined as [45]:

$$J = \frac{(\sum_{i=1}^{N} X_i)^2}{N \sum_{i=1}^{N} {X_i}^2} \tag{3.5}$$

Where

- N is the number of users
- $\mathrm{X_i}$ denotes the data rate of user *i*.

- **Energy Efficiency**

The energy savings are mainly dependent on the allocation of resources and load conditions. Various metrics are used in the literature to evaluate energy consumption but most of them use Energy Consumption Rate (ECR) [30].

ECR is given by:

$$ECR = \frac{P}{R} w/bps \tag{3.6}$$

Where

- P is required average transmit power
- R denote average data rate.

A higher ECR shows that more energy is consumed. An efficient system is therefore one that has a low ECR value, which implies less energy is used in data transfer.

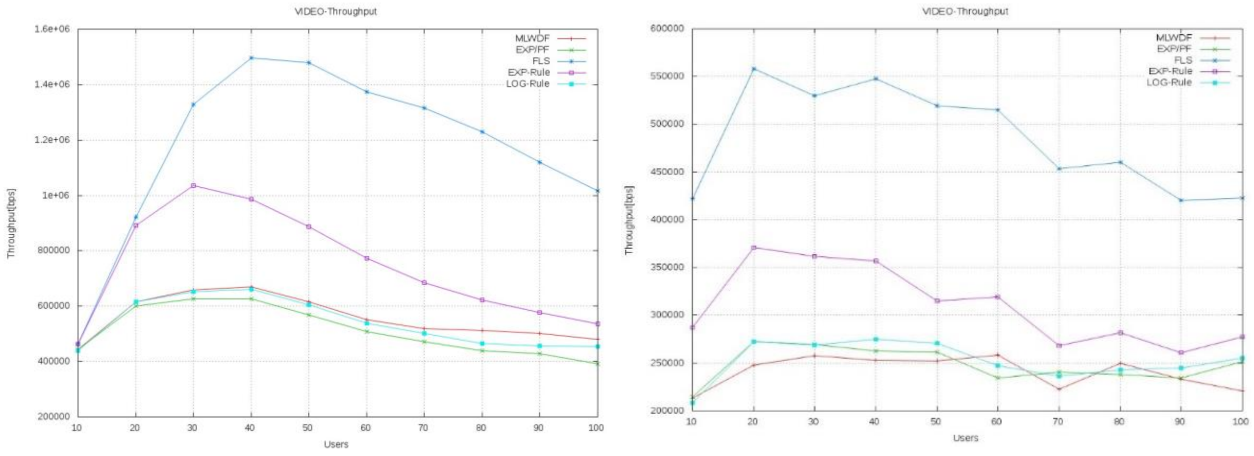
4. Results and Discussion

In the current version of the simulator, a detailed tracing feature is available. The traces are displayed directly during the simulation and saved as a text file in the workstation folder. This evaluation was then done by extracting the relevant value out of it. Simulations were run for three continuous iterations to get rid of randomness on the total result. Based on the simulation output, the result and analysis are divided into three parts: the first part deals with the video traffic, the second for VoIP, and the last one is for best-effort traffic data. The scheduling schemes' overall performance is then analyzed based on QoS and energy efficiency metrics separately.

4.1. QoS

a) Video Traffic

The aggregated throughput of video traffic is illustrated over the increased UE sets and speed variant in Figure 4.1. The average throughput for video flow appears to have a slight decrease with increasing users number and speed (the drop starts after 30 users at 3km/hr and after 20 users at 120km/hr). It is noticed that at higher user mobility, 120km/hr, there is a more rapid fluctuated reduction in average throughput while increasing the number of users unlike in the case of 3km/hr user speed.



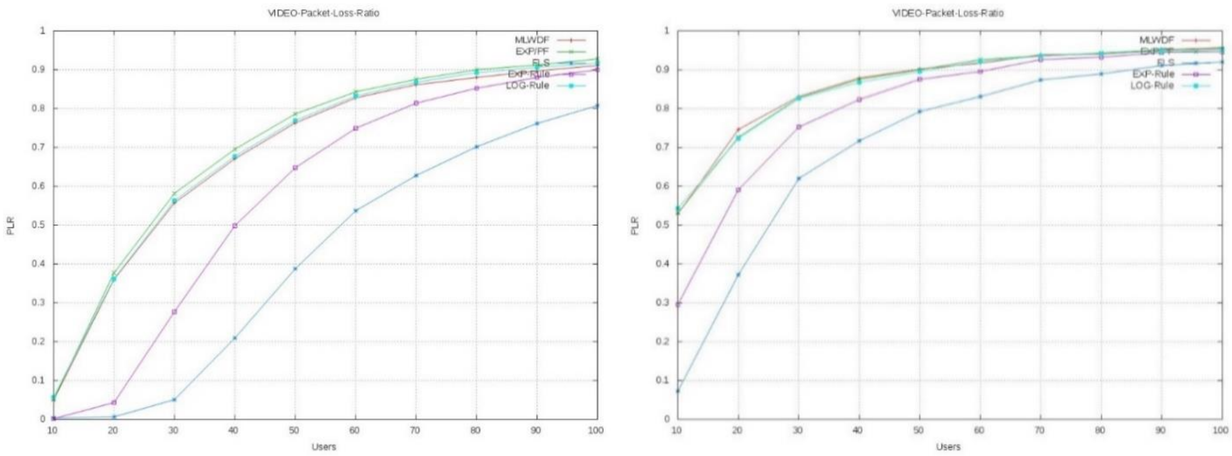
a)

b)

Figure 4.1 *Video Traffic Throughput a) 3km/h b) 120km/h*

The reason behind the throughput decrease as the user speed increases is due to the worse channel quality measured by the receiver UE which in turn affects the MCS selection. In both scenarios, FLS provides significantly better throughput than the others. EXP-Rule came at the second position since it's proposed as a throughput-optimal scheduler as discussed in Chapter 2. Others behave relatively the same.

The PLR measures how many packets are received at the destination relative to the number that is transmitted. It increases with the number of UEs, due to the higher network load, and in scenarios with a high number of concurrent RT flows, the probability of discarding packets for deadline expiration increases. It is important to note that, in this case, the PLR only counts for the PHY losses and that it cannot grant for bounded packet delays. Maintaining low PLR reveals the robustness of the scheduler to react toward high overload network states. Figure 4.2 PLR results for RT Video flows exhibit varied trends by the scheduling schemes. And as expected, the PLR increases with the user speed because the link adaptation procedure is impaired at high velocity. Since FLS imposes a bound on the maximum tolerable delay, it suffers the least packet loss unlike the others, and can greatly enhance multimedia services quality in an LTE system.

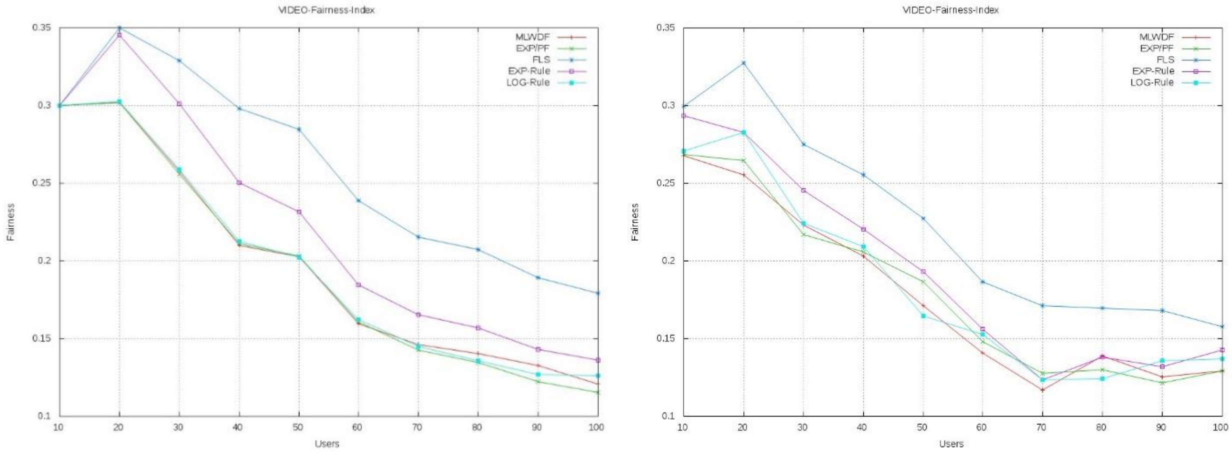


a)

b)

Figure 4.2 *Video Traffic PLR a) 3km/h b) 120km/h*

Fairness is used to determine whether the user is receiving a fair amount of resources or not. It has a value ranging from 0 to 1 and the closer to 1 the better. Figure 4.3 shows the fairness index of all scheduling algorithms for different numbers of UEs with different mobility speeds. All scheduling schemes' fairness decrease as the number of UEs increases. Increasing the speed also has an effect on the fairness level as well. FLS seems to exhibit better fairness. Sometimes reaching higher throughput has led to unfair allocations to users who are located far from the base station or who experience bad channel conditions. It's therefore essential to achieve a proper balance between fairness and throughput.

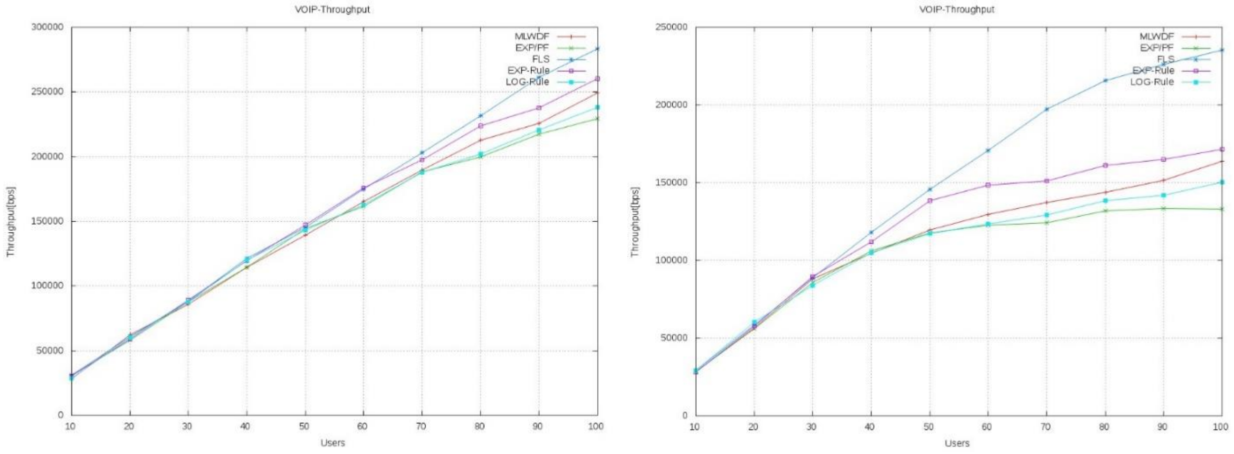


a) *b)*

Figure 4.3 *Video Traffic Fairness a) 3km/h b) 120km/h*

b) VoIP Traffic

All five schedulers' VoIP average throughputs were examined while increasing the number of voice users steadily. It is very difficult for VoIP packets to utilize all the available resources efficiently since they are very small. In general, being lightweight traffic, RT VoIP flows add no burden to be transmitted by the MAC scheduler. Nevertheless, as illustrated in Figure 4.4 it is evident that system throughput increased linearly as VoIP users grow, which implies that the resource utilization had improved. For the first half of users, all schedulers' performance is quite close with small differences. Moreover, we note that for the VoIP flows delivery there was no significant variation in throughput. This is mainly because the packets associated with voice traffic must be given very high priority and assigned to a guaranteed bandwidth channel in order to ensure that the packet delivery is within an acceptable delay limit. FLS scheduler performed better than the EXP rule scheduler which came second in both scenarios.

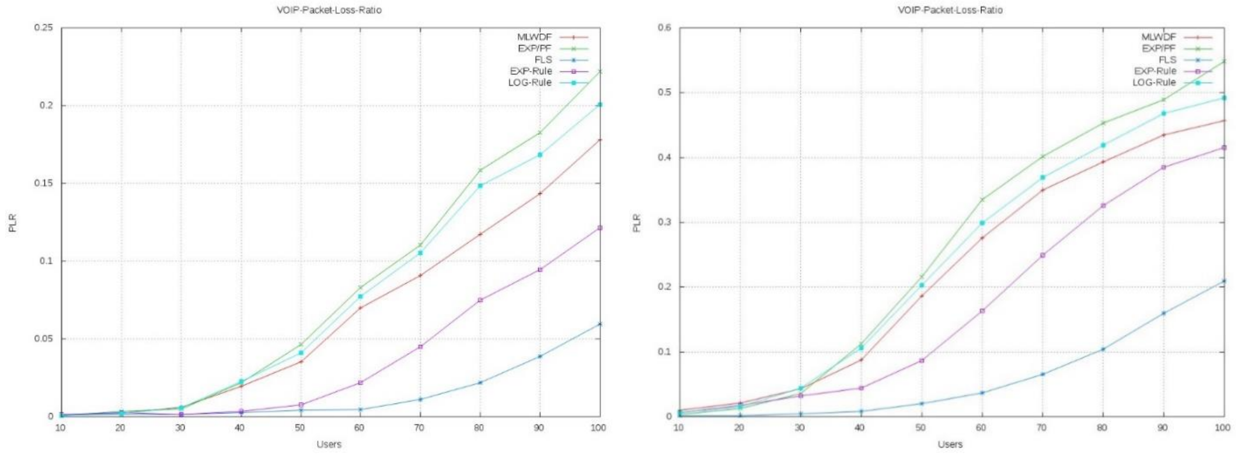


a) *b)*

Figure 4.4 *VoIP Traffic Throughput a) 3km/h b) 120km/h*

VoIP traffic is characterized by severe delay requirements with a low PLR. Figure 4.5 illustrates the achieved PLR of VoIP flows. The achieved PLR for VoIP flows is considerably lower compared to the video flows PLR. Furthermore, a network with 120km/h user speed attains a higher PLR relative to the one with 3km/h user mobility speed. This is due to the fact that the transmission channel quality varies faster with a higher mobility speed which leads to a higher slip in MCS selection by AMC module. Again, FLS provides the lowest PLR as compared to others.

Because traffic is always expected to come in bursts, packet loss may occur more frequently. Hence, due to small buffers and the fact that most RBs are allocated to burst RT video flows, VoIP flows have poor delivery rates. FLS and EXP–Rule attempt to keep a better balanced service for different flows so that small RT VoIP flows can be transmitted by compromising a certain level of throughput on RT burst video flows. Furthermore, PLR is measured on different traffic types. Unlike video streams, VoIP flows have a critical limit on packet loss and excessive dropping causes severe call quality degradation.

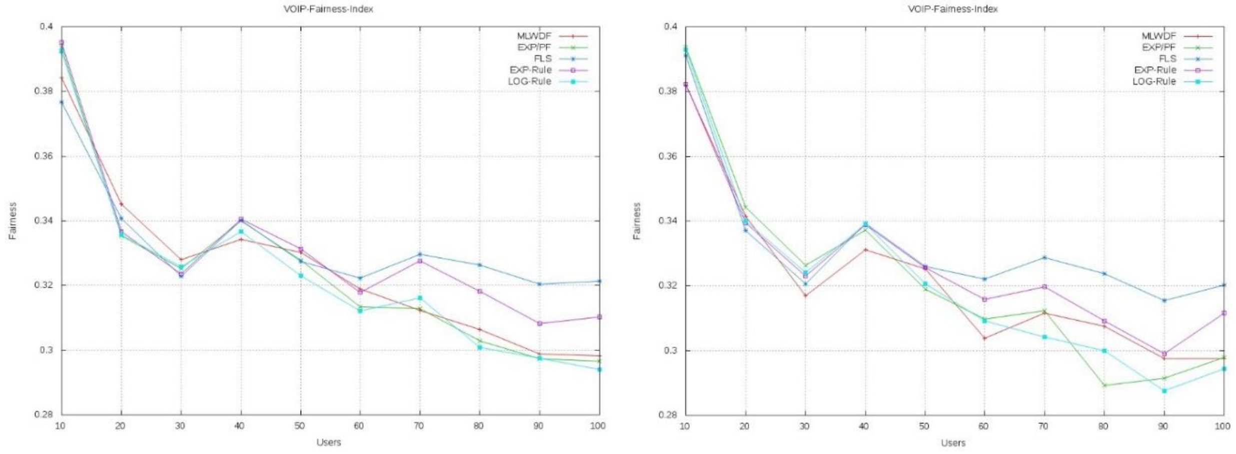


a)

b)

Figure 4.5 *VoIP Traffic PLR a) 3km/h b) 120km/h*

In Figure 4.6, the fairness index of VoIP data traffic is shown with an increasing number of users. As expected, increasing the number of users leads to a deterioration in the fairness index. There is little difference between the scheduling schemes examined here, but FLS and Exp-Rule appear to be slightly more fair than the others.



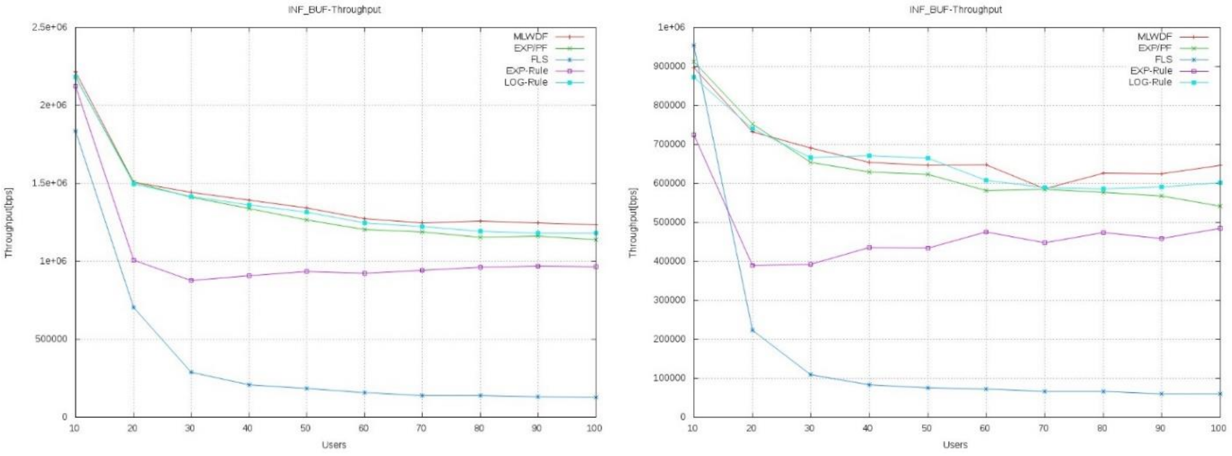
a)

b)

Figure 4.6 *VoIP Traffic Fairness a) 3km/h b) 120km/h*

c) Best-Effort Traffic (BE)

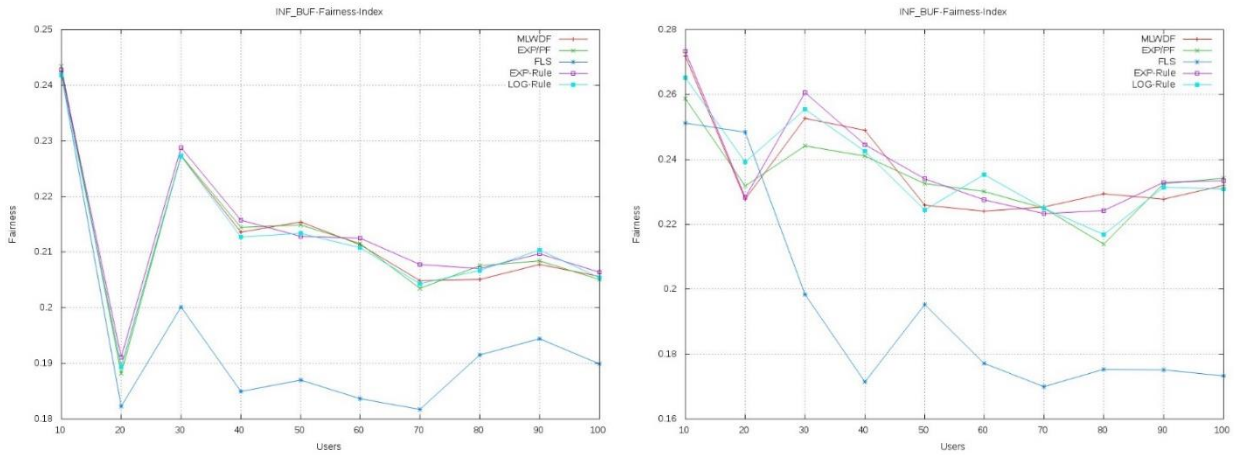
A network with BE traffic offers services with no guarantee of delivery time or bit rate. This means that users receive services according to the network traffic load. As NRT data flow, BE traffics do not have strict QoS specifications, only throughput and fairness index are considered here to compare the performance of those five scheduling algorithms.



a) *b)*

Figure 4.7 *BE Traffic Throughput a) 3km/h b) 120km/h*

As Figure 4.7 depicts, BE throughput decreases as the number of UEs increase for a while and then became stable. The FLS scheme shows the worst performance among the algorithms being considered and MLWDF is the better one. This result shows that FLS scheduler favored RT services rather than the NRT ones. The persistent increase in the number of active RT users can lead to the starvation of BE users in overloaded scenarios. It is also observed that average throughput decreases with increasing users' speed. Similarly, in Figure 4.8, all schemes show similar performance in Fairness except FLS. As discussed previously compared to FLS, the other algorithms perform poorly when handling multimedia flows, thus leaving more bandwidth available for best-effort flows.



a) *b)*

Figure 4.8 *BE Traffic Fairness at a) 3km/h b) 120km/h*

4.2. Energy Efficiency

Over the past few years, green communication has been a hot topic in wireless network research. The key issue is how to reduce energy consumption while maintaining good service quality. Commonly, the energy efficiency is expressed by the ECR. It is defined as the energy per delivered application bit. In general, between throughput and energy consumption, there is a trade-off. Hence, when the throughput is high, ECR will then decrease. FLS has the lowest ECR on both VoIP & Video but not on BE as shown in Figure 4.9. EXP-Rule has a relatively good ECR value than the remaining ones. And also note that ECR slightly increases when user speed increased.

a) *b)*

Figure 4.9 *Energy Consumption Rate at a) 3km/hr b) 120km/hr*

5. Conclusion and Future Work

5.1. Conclusion

Radio resource management algorithms in the LTE network are vital to optimize the system capacity and to enhance end-user performance. 3GPP does not standardize specific packet scheduling algorithms, hence network vendors and operators can design and tune the schemes to match their requirements. Based on network status and/or traffic patterns, the network provider is expected to select and apply an optimal packet scheduling algorithm. In this work, a comparative study on the performances of M-LWDF, EXP/PF, EXP Rule, LOG Rule, and FLS packet scheduling algorithms has been done from QoS and energy metrics perspective. The comparison aimed to show the behavior of the selected schemes for both RT & NRT traffics flows. The performance evaluation was done on different simulation scenarios while varying the number of users as well as users' mobility. The metrics used in this thesis are average throughput, PLR, fairness among users, and overall energy efficiency. LTE-Sim is used for the simulation of the LTE network. The thesis result shows that:

- All considered algorithms favor real-time services.
- The QoS is heavily influenced by the type of packet scheduling algorithm deployed at eNodeB, the number of active users from a particular class of application, and the speed of the user within the cell.
- With regard to throughput, PLR, and fairness, and energy efficiency FLS outperforms the other four algorithms considered herein for VoIP and video. However, it is the poorest performer for BE flows in all metrics. This is because the other algorithms provide poor service to multimedia flow as compared to FLS, thus leaving a higher quota of bandwidth for BE traffic flows.
- In general, the research indicates the importance of a suitable choice of scheduling algorithm at the LTE system.

5.2. Future Work

With the growth of the demand for telecom services, this type of study has great benefit for ethio telecom to improve network performance, fulfill user satisfaction and reduce energy consumption. Although various researches have been made regarding scheduling techniques for LTE, there still remain open-end issues. Almost all existing approaches have some limitations, as noted in Chapter 4. Thus, further studies should be continued on this topic.

In ethio telecom, we think this thesis could be somewhat a baseline to address LTE performance issues related to resource scheduling issues. Here some important aspects are highlighted to be considered for future work:

- This thesis focus on selected LTE existing downlink scheduling techniques. Extending this study to include uplink scheduling algorithms will have great importance for end-to-end system performance on the radio network.
- The design of the packet scheduler is a challenging optimization problem between increasing cell capacity (from operator perspective) versus user-related constraints, such as fairness. And recently energy has become one more constraint. Since there is no standard algorithm set by 3GPP, designing a novel optimized scheduling approach to improve the limitations of existing algorithms is still a hot research topic as it has a significant impact on the overall network performance.
- LTE-Advanced (LTE-A) is currently deployed in most parts of the country. Thus, it is better to extend this study to include this new technology as well.

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Appendix