3GPP LONG TERM EVOLUTION LTE SCHEDULING

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Future generation cellular networks are expected to deliver an omnipresent broadband access network for an endlessly increasing number of subscribers. Long term Evolution (LTE) represents a significant milestone towards wireless networks known as 4G cellular networks. A key feature of LTE is the implementation of enhanced Radio Resource Management (RRM) mechanism to improve the system performance. The structure of LTE networks was simplified by diminishing the number of the nodes of the core network. Also, the design of the radio protocol architecture is quite unique. In order to achieve high data rate in LTE, 3rd Generation Partnership Project (3GPP) has selected Orthogonal Frequency Division Multiplexing (OFDM) as an appropriate scheme in terms of downlinks. However, the proper scheme for an uplink is the Single-Carrier Frequency Domain Multiple Access due to the peak-to-average-power-ratio (PAPR) constraint. LTE packet scheduling plays a primary role as part of RRM to improve the system's data rate as well as supporting various QoS requirements of mobile services. The major function of the LTE packet scheduler is to assign Physical Resource Blocks (PRBs) to mobile User Equipment (UE). In our work, we formed a proposed packet scheduler algorithm. The proposed scheduler algorithm acts based on the number of UEs attached to the eNodeB. To evaluate the proposed scheduler algorithm, we assumed two different scenarios based on a number of UEs. When the number of UE is lower than the number of PRBs, the UEs with highest Channel Quality Indicator (CQI) will be assigned PRBs. Otherwise, the scheduler will assign PRBs based on a given proportional fairness metric. The eNodeB's throughput is increased when the proposed algorithm was implemented.

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LIST OF ACRONYMS

2G	Second generation wireless
3G	Third generation wireless
3GPP	Third Generation Partnership Project
4G	Fourth generation wireless
ADSL	Asynchronous digital subscriber line
ARP	Allocation retention priority
ARQ	Automatic repeat request
ATB	Adaptive transmission bandwidth
BFS	Breadth first search
BMTP	Block allocation for minimum total power
BS	Base station
BSR	Buffer status report
C-plane	Control plane
CAPEX	Capital expenses
CP	Cyclic prefix
CSI	Channel state information
CQI	Channel quality indicator
D-SR	Dedicated SR
DFDMA	Distributed FDMA
DFT	Discrete Fourier transform
DFT-S-OFDMA	DFT-spread-OFDMA
eNodeB	Evolved NodeB

EDGE	Enhanced data rates for global evolution
EPC	Evolved packet core
E-UTRAN	Evolved-Universal Terrestrial Radio Access Network
FDD	Frequency division duplexing
FDPS	Frequency domain packet scheduling
FME	First Maximum Expansion Algorithm
FTB	Fixed transmission bandwidth
GPRS	General Packet Radio Service
GSM	Global system for mobile communication
GBR	Guaranteed bit rate
HSDPA	High speed downlink packet access
HARQ	Hybrid automatic repeat request
HLGA	Heuristic Localized Gradient Algorithm
IP	Internet protocol
IPTV	IP television
ISI	Inter-symbol-interference
LCG	Logical channel group
LFDMA	Localized FDMA
LTE	Long term evolution
MAC	Medium access control
MAD	Minimum Area Difference Algorithm
MBR	Maximum bit rate
MME	Mobility management entity

MCS	Modulation and coding scheme
MMSE	Minimum mean squared error
MSC	Mobile switching center
OPEX	Operational expenses
OFDM	Orthogonal frequency division multiplexing
OFDMA	Orthogonal frequency division multiple access
PAPR	Peak-to-average-power-ratio
PDCCH	Physical Downlink Control Channel
PDCP	Packet Data Convergence Protocol
PDN	Packet Data Network
PHY	Physical layer
PRB	Physical resource block
PS	Packet scheduling
PUCCH	Physical uplink control channel
PUSCH	Physical uplink shared channel
QoS	Quality of service
QCI	QoS class identifier
RAC	Radio admission control
RA-SR	Random access-based SR
RB	Radio bearer
RBC	Radio bearer control
RC	Resource chunk
RLC	Radio link control

RNC	Radio network controller
RR	Round robin
RRC	Radio resource control
RRM	Radio resource management
SAE	System architecture evolution
SC-FDMA	Single carrier frequency division multiple access
SDF	Service data flow
SFN	Sequence frame number
SIMO	Single input multiple output
SINR	Signal to interference and noise ratio
SR	Scheduling request
SRS	Sounding reference signal
TB	Transport block
TDD	Time division duplexing
TDPS	Time domain packet scheduling
TTI	Transmission time interval
UE	User equipment
WCDMA	Wideband code division multiple access
UMTS	Universal mobile telecommunications system
U-plane	User plane

CHAPTER 1

INTRODUCTION

1.1 Introduction

From the very beginning of the radio communication experiments carried out by Guglielmo Marconi in the 1890s, until the current moment of IP-based mobile broadband networks, the path of wireless communication development has been long and full of success stories. The cellular access network, throughout its time line, has been improved from being very expensive, with a limited number of subscribers, to being widely accessible with a number of subscribers that equals nearly half of the current global population now (Dahlman, Parkvall, Skold, & Beming, 2008). The extraordinary growth of wireless communication systems, especially in the last two decades, compels us to seek to understand and explore the technologies that have governed this evolution. The beginning of the third millennium was the convergence point of the mobile broadband success story, and it was heralded by the emergence of Third Generation (3G) mobile broadband. Since then, this revolutionary mobile broadband has become available, and it has been declared by experts that mobile broadband networks are now widely used.

“The Third-Generation Partnership Project (3GPP) is a partnership project formed by the standards bodies ETSI, ARIB, TTC, TTA, CCSA, and ATIS. 3GPP consists of several Technical Specifications Groups (TSGs)” (Dahlman et al., 2008). Its goal is to take the telecom industry into the 2020s.

The 3GPP has introduced the 3G Universal Mobile Terrestrial System (UMTS) standard as 3GPP Release 5, as an extension of its successive accomplishment in the Second Generation (2G). Global System for Mobile Communication (GSM) technology was recognized in 2G before it was replaced by Enhanced Data Rates for Global Evolution (EDGE) technology, in what is known as “2.5G.” On another hand, the UMTS was able to provide up to 2 Mbps in terms of download speed, so this was a noteworthy enhancement compared to EDGE download speed.

The innovative improvements did not pause, and the 3GPP Release 6 of UMTS, known as high Speed Packet Access (HSPA), was able to be a successful alternative. In fact, the download speed was able reach up to 14 Mbps down, and 5.8 Mbps was achieved in upload speed. Because of this enhancement, the number of subscribers has started to increase exponentially, due to the support of Internet applications and services over the 3G radio interface, as well as the system’s capability to support Quality of Service (QoS) systems. In addition to that, media streaming and video calling are supported as smartphone devices have emerged with wireless communication networks as a response to the progression of 3G HSPA. Figure 1.1 illustrates the time line of the development of mobile broadband.

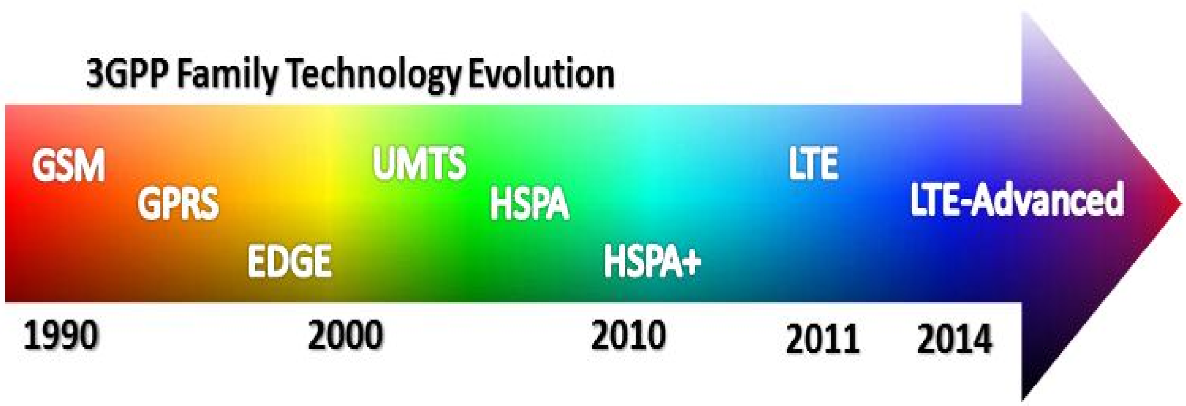

Figure 1.1 Time line for mobile broadband improvement (www.4gamerica.com)

The 3GPP observed that applications like live streaming, online gaming, and mobile TV require higher data rates than the HSPA can provide, due to the exponential growth of mobile data usage, which has been accompanied by an increased demand for 3G mobile broadband subscriptions. Since that time, the 3GPP has started moving its attention toward forming a revolutionary standard that can meet subscribers’ demands. Standardizing the new era of mobile broadband technology would be promising this to the next generation, once it is constituted, in terms of objectives such as delivering high data rates with improved QoS, which is one of the critical goals of next generation mobile broadband, and this would be finalized by the 3GPP. Henceforth, the 3GPP will design high-level requirements in order to come up with a revolutionary new era of mobile broadband. For example, it is moving toward founding a full IP-based packet switched network, as well as diminishing the complexity of the network protocols and network architecture.

The 3GPP started to finalize its Release 8, known as 3G-Beyond, in 2004. This standard was later named long term evolution (LTE). LTE is considered to be a very noteworthy mobile broadband standard due to its enhanced mechanisms and to the high level requirements that could be met by LTE. In addition to that, LTE competes surprisingly well with wired broadband networks (e.g., ADSL).

December 2008 was the year when LTE Release 8 was finalized by the 3GPP, and this was done by designing the final constitution of the system architecture. Afterward, exactly twelve months was an adequate period of time to finalize LTE Release 9, an improved version of LTE Release 8. The significant contribution of Release 9 that was not found in Release 8 was highlighted in the supportive femtocells by Release 9. Despite the fact that LTE is an essential enhanced standard, LTE performance and mechanisms still need more examination if it is to fulfill its full potential.

In terms of LTE structure, the architecture of the mobile broadband network differs from the preceding architectures of 2G and 3G. For example, some access network units such as the mobile switching controller (MSC) and the radio network controller (RNC) are disposed of in the LTE access network, in contrast to 2G and 3G mobile broadband networks, in order to meet the lesser complexity requirement. The LTE network involves the marvelously functional base station (BS), named “evolved NodeB” (eNodeB). Therefore, eNodeB has become responsible for radio resource management (RRM) and mobility management, which were RNC’s tasks.

As long as the RRM is managed efficiently, the high data rate target becomes attainable. Packet scheduling PS is one of RRM’s important tasks, and it is where we wish to focus our attention in this work. The idea behind the packet scheduler includes dedicating the available radio resources among UEs connected to the network. The packet scheduler’s decision is quite critical, so the system performance of LTE might be influenced either positively or negatively. Therefore, the packet scheduler set in eNodeB must take into account numerous factors due to its sensitive task.

The channel quality of each UE must be considered by the LTE packet scheduler to achieve capable adaptation for the transmission rate. The use of the orthogonal frequency division multiplexing (OFDM) transmission scheme facilitates the channel quality exploration, which includes the channel conditions in both time and frequency. As a result, frequency subchannels would be allocated to those UEs which have worthy channel quality and value.

Any traffic flow that runs over the LTE radio interface has to be taken into account by the LTE packet scheduler with its QoS requirements. Furthermore, the contiguity constraint of resource allocation must be adhered to while designing an uplink packet scheduler.

1.2 Thesis Scope

In the remainder of the thesis, chapter 2 provides background information and concepts related to LTE. In chapter 3, the mechanism of the scheduling in LTE is provided as well as a brief description of radio resource management. In chapter 4, the scheduling algorithms and literature review are presented, and an algorithm scheduling is proposed. The results of the simulation are provided in chapter 5. Finally, I conclude the thesis in chapter 6.

CHAPTER 2

LTE CONCEPTS

2.1 LTE Performance Goals

The variety of the applications that were developed coincidently with improved 3G networks and enhanced smartphones requires a high level of features, such as high peak data rates, in order to meet their needs and for them to be applicable for end users. The LTE network was produced with a high level of aspirant requirements that can overcome 3G's features and can meet durable and ambitious requirements (Author, Year).

In the 3GPP's document (2009), the set of targets and requirements for LTE included the following:

- Reduced latency**—**"Latency requirements cover both the control plane (C-plane) and the user plane (U-plane) latencies" (3GPP, 2010). Both the C-plane and the U-plane will be subsequently defined. The latency of the C-plane can be defined as the time that a user takes to transition from an idle state to an active state. LTE requires a maximum of 100 milliseconds in terms of the C-plane.

- Peak data rate**—**The goal of peak data rate in LTE at a bandwidth of 20 MHz is one that can be up to 100 Mbps and 50 Mbps in the downlink and uplink, respectively. Therefore, it is noticeable that the peak data rate is ten times higher than the peak data rate of Release 6 HSPA. This requirement can be recognized as the most promising target for future services.

- Bandwidth flexibility**—**Due to the use of OFDM modulation, which will be later described, the number of bandwidth sizes could be expanded in LTE. For example, the bandwidth can be 1.4 MHz, 5 MHz, 10 MHz, 15 MHz, or 20 MHz.

- Reinforcement for heterogeneous network deployment—Preceding 3GPP technologies, like GSM and HSPA, and LTE technology are harmonious with each other; accordingly, this meets the compatibility target set for LTE. The deployment of LTE in 3GPP and non-3GPP networks, such as Wi-Fi and WiMAX covered areas, is one of the accomplished targets of the LTE providers. Hence, LTE is an efficient and low cost deploying network; consequently, reinforcement of heterogeneous deployment of LTE with 3GPP and non-3GPP networks will provide seamless mobility for users among diverse wireless platforms.

- Architecture simplification—In LTE, the access nodes were diminished between the UE and the core network. Consequently, the COPEX, OPEX, and latency will be reduced as well. Furthermore, the choice of IP-only support gives the capability of running all services over LTE. As an alternative of set detached circuit switched and packet switched networks compare to HSPA.

- Improved QoS—QoS support is considered to be enhanced in LTE due to the transfer to a fully IP-based network. As a result, LTE supports various services with a diversity of QoS requirements.

2.2 LTE Architecture

Figure 2.1 shows an overview of the LTE network access architecture. “The system architecture evolution (SAE) is an all-IP network, consisting of a user plane (U-plane), the evolved UTRAN (E-UTRAN), and a control plane (C-plane), the evolved packet core (EPC)” (Safa & Tohme, 2012). As illustrated in the figure, E-UTRAN comprises a single type of access level component, the eNodeB. An eNodeB handles the functionalities of both NodeB and RNC nodes, as defined in HSPA. Furthermore, it systematizes the flow of the packet between the EPC network and a radio connection. The UE is the end user.

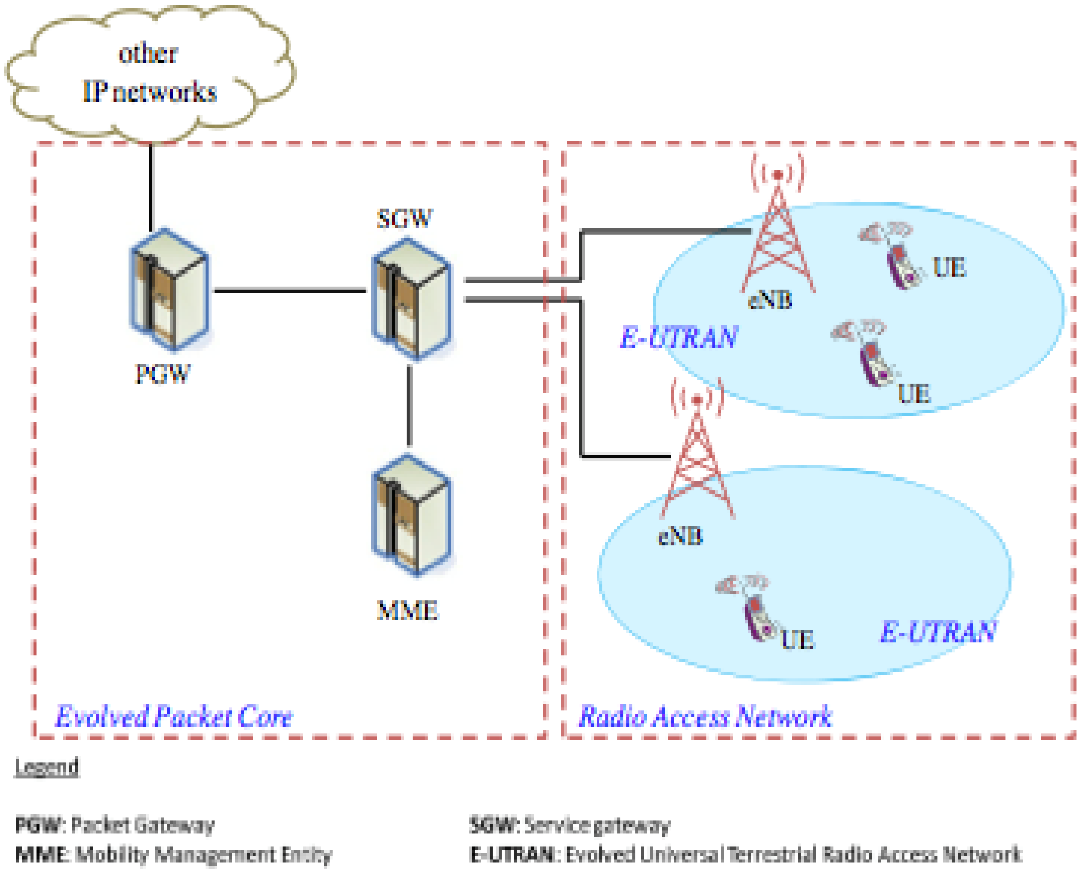

Figure 2.1 LTE architecture (Capozzi, Piro, Grieco, Boggia, & Camarda, 2013)

EPC is a single IP-based core network that supports multi access networks, so that multiple 3GPP radio access technologies, like HSPA and LTE, can be accessed and deployed within the same network. EPC is primarily responsible for mobility management, policy management, and security. It is also the internet gateway. The eNodeB is connected to the EPC through two separate entities, the mobility management entity (MME) and the serving gateway (S-GW). The X2 interfaces are logical interfaces that bring together and coordinate the neighboring eNodeBs.

2.2.1 Evolved UTRAN E-UTRAN

The eNodeB, distributed throughout the coverage region, is recognized as the primariy component of E-TRAN. It is responsible for multiple functions, and it is the physical bridge between the UE radio channel and the EPC, so it can be considered the termination point of the radio protocols for the UE. Likewise, it acts as the data relay from the radio channel toward the corresponding IP-based connection in the EPC. In addition, it executes the ciphering/deciphering as well as the IP header compression/decompression.

The number of nodes is diminished in E-UTRAN architecture to reduce the complexity of the core network architecture. As a result, numerous functions are set at the eNodeB. The essential functions that the eNodeB delivers are as follows:

- Radio interface transmission and reception—In receiving and transmitting radio propagation, the coding/decoding and modulation/demodulation radio channel function are the responsibility of eNodeB.
- Uplink/downlink dynamic RRM and packet scheduling—The eNodeB must overcome challenges that are associated with this function, such as user priority and requested QoS, in order to deliver multiplex various data flow over the radio channel and to efficiently use the available resources.
- Radio bearer management—This task revolves around the RRM functionalities and radio bearer set up, so that eNodeB can accept or reject connection requests according to the network polices.
- Network signaling security—Exchanging the messages from eNodeB toward UE and MME, and vice versa, requires protection against alteration and eavesdropping, so eNodeB contributes to the providing of secure connections.

- Mobility management—The UE mobility is a critical event for eNodeB, so the determination of targeted cell and the mobility decisions, which are critical tasks, is actually coordinated by eNodeB toward MME, paced in EPC. Typical mobility management procedures include location updates and paging. The movement of the UE is updated and provided by the UE itself, so the location update procedure assists the UE to report the new location to the network (Liou, Lin, & Tsai, 2013).

- IP header compression—IP header compression provides a more efficient link by diminishing the overhead of the protocol header and controlling the transparency from end-to-end (Naidu & Tapadiya, 2009).

Note that the eNodeB's functional capabilities are derived from its connection to two major units at EPC, MME, and S-GW. Also, multiple UEs can be served by a single eNodeB. However, a single UE is linked to a single eNodeB at actual particular time. Also, the eNodeB is in charge of performing a handover between neighboring eNodeBs during UE mobility. The UE actually refers to the handheld device, used by the end user for communication purposes. The UE contains a universal integrated circuit card (UICC) and involves a programmed application called USIM, which is used to identify and authenticate the end user. The UE is categorized and classed as shown in Table 2.1 according to Dahlman, et al. (2008).

Table 2.1 LTE UE Categories, reproduced from Dahlman, et al. (2008).

UE Classes	**Peak Data Rate (Mbps)**		**Soft Buffer size (Gbits)**	**Number of MIMO stream**	**Max. DL modulation**	**Max. UL modulation**
	DL	**UL**				
1	10	5	0.25	1	64 QAM	16 QAM
2	50	25	1.24	2		
3	100	50	1.24	2		
4	150	50	1.83	2		
5	300	75	3.67	4		64 QAM

2.2.2 The Evolved Packet Core (EPC)

The evolved packet core (EPC) corresponds to the core network in GSM/UMTS system, in terms of its functions and responsibilities. Several functions are performed at the EPC, such as MME, S-GW, HSS, P-GW, and PCRF.

2.2.2.1 The Mobility Management Entity (MME)

The MME is the central control entity set in EPC. It performs only in the C-plane by creating a logical connection between MME and the C-plane. It authenticates UEs once they are registered to the network for the first time. Additionally, the authentication procedure might be repeated periodically or when needed for different reasons. The UE's ciphering and integrity protection keys are collected and produced from the master key, released by the home network as well as the MME, which dedicates to each UE a temporary identity. These procedures are performed by the MME in order to deliver a secure connection for the authenticated UE.

Also, the MME tracks the UE's location in its dedicated area so that it can signal the UE's location to HSS once the UE has been registered to the network. Additionally, the MME handles the handover between multiple eNodeBs by controls signaling among eNodeBs. While the MME is serving a UE, the network wants to figure out what packet data network connections will be allocated to the UE. Therefore, the MME stores subscription profile information in order to retrieve this information and regulates the UE to an appropriate packet data network connection.

2.2.2.2 The Serving Gateway (S-GW)

The serving gateway (S-GW) is one of the most significant elements incorporated in the LTE network infrastructure (Holma & Toskala (Eds.), 2009). The S-GW is in charge of its own resources, and it acts once it gets a request from entities like P-GW or MME. These entities request the S-GW's resources in order to clear or establish bearers for the UE. Besides, the S-GW receives demands from MME to shift the tunnel from eNodeB to another throughout mobility between two neighboring eNodeBs. However, MME performs handover from S-GW to S-GW, once it is needed, by eliminating tunnels from the previous S-GW and establishing tunnels to the new S-GW. In addition, the S-GW is responsible for relaying data between the P-GW element and the eNodeB in case all data flows are UEs in active mode. In addition, S-GW connections are one-to-many, so a particular S-GW would serve areas in a restricted number of eNodeBs as well as a limited number of MMEs.

2.2.2.3 The Home Subscription Server (HSS)

The momentary data of all UEs associated with the LTE networks are saved at the home subscription server (HSS). "It is a database server maintained centrally in the home operator's premise" (Holma & Toskala, 2009). Essential information required for mapping proper services to correct UEs is part of the subscriber profile stored in the HSS. Similarly, keys used for authentication, as well as to protect the integrity and encryption, are stored and retrieved from the HSS. In order to deliver capability that allows UEs to move, HSS must be able to reach each MME in the entire system.

2.2.2.4 The Packet Data Network Gateway (P-GW)

The packet data network gateway (P-GW) actually acts as an entity that coordinates the mobility between non-3GPP and 3GPP technologies. In fact, an IP address is dedicated to each UE by means of a P-GW so that other host external networks can be accessed by the UE. When the UE requests a PDN connection, an IP address is dedicated to the UE immediately. Dedication of the IP to the UE is accomplished by dynamic host configuration protocol (DHCP) functionality. Lawful interception is one of practical functions that the P-GW performs.

2.2.2.5 Policy and Charging Resource Function (PCRF)

Policy and charging control (PCC) is a primary task that the PCRF performs. PCRF is a server where a service handling decision is made according to given QoS parameters. Applicable bearers and policing are set up efficiently by means of the PCRF's communicating with the P-GW element through PCEF and communicating with the S-GW element through BBERF.

2.3 LTE Radio Protocol Architecture

Figure 2.2 shows a diagram of the protocol architecture for the evolved-universal terrestrial radio access network (E-UTRAN level). As illustrated, the PHY layer constitutes layer 1 TCP/IP in LTE while layer 2 is composed of three sub-layers.

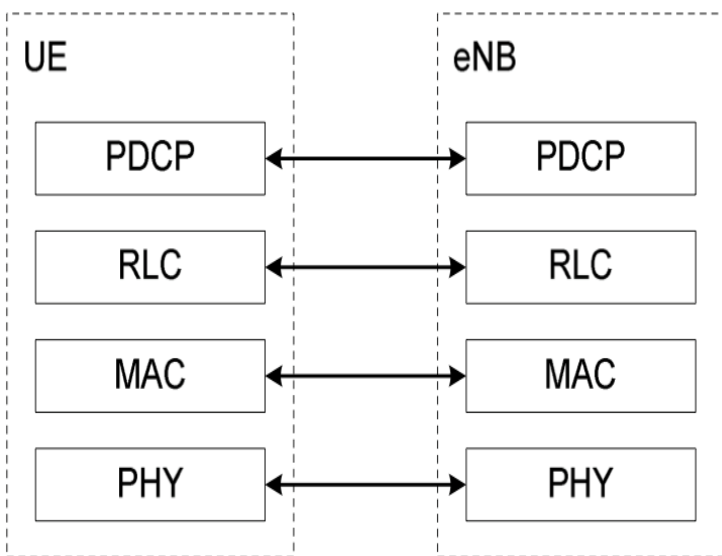

Figure 2.2 LTE E-UTRAN protocol architecture (3GPP, 2010)

- Layer 2 (L2)
    - Packet data convergence protocol (PDCP)
    - Radio link control (RLC)
    - Medium access control (MAC)
- Layer 1 (L1)
    - Physical layer (PHY)

2.3.1 The PDCP Layer

The PDCP layer is responsible for the following functions:

- Header compression/decompression for all U-plane data packets
- Handover management
- Encryption/decryption data
- Integrity protection and verification of C-plane data

The header compression is significant due to a decrease in the overhead of transmitted/received data over the radio interface. As a result, the spectral efficiency of the system is increased. In addition, PDCP is responsible for checking the status of data packets, whether they are delivered or not, in both directions, up to the IP layer or down to the RLC layer. Also, PDCP senses when packets are missed in order to establish a retransmission or duplication of the packets in case those packets are to be discarded. In addition, it accomplishes packet ciphering and it provides secure packets over a radio interface.

2.3.2 The RLC Layer

The radio link control (RLC) layer utilizes the service access point (SAP) in order to communicate with the packet data convergence protocol (PDCP) layer, and utilizes the logical channels in order to communicate with the medium access control (MAC) layer, so it is designed to be in the middle between the PDCP and MAC layers (Telesystem Innovation, 2010). RLC executes functions like those in the PDCP. In addition, the RLC utilizes the window-based automatic repeat reQuest (ARQ) procedure to carry out error correction for data packets received from the MAC layer. Also, segmentation and reassembly of data are critical tasks done by RLC. radio bearers (RB) data buffers facilitate those tasks for RLC.

The data can be transmitted by RLC through three different modes:

- The transparent mode**—**this mode is utilized for some control signaling, e.g., paging messages.
- Unacknowledged mode**—**Delaying sensitive traffic, such as VoIP, is an example in which this mode would be utilized.
- Acknowledge mode**—**Delay tolerance is supported by utilizing this mode (Telesystem Innovation, 2010).

2.3.3 The MAC Layer

The medium access control (MAC) layer is empowered to perform numerous significant duties, and the most significant function the MAC performs is assigning the bandwidth provided by the network among the UEs, which is known as scheduling (Telesystem Innovation, 2010). In addition, logical channels and physical channels are mapped by the MAC layer. The logical channels are classified into two major types, data traffic channels and control channels, which will be detailed later in this section. A particular RB is inspected in RLC according to its QoS requirement in order to provide suitable RB priority. The MAC layer has a function that allows

UEs to access and synchronize with the network, which is a random access procedure control. Due to the fact that the UE's transmissions might be overlapped at eNodeB, the MAC layer executes an uplink timing alignment function in order to avoid such transmission overlap.

HARQ operation is implemented in the MAC layer in order to retransmit or generate ACK/NACK signaling. In addition, if the transmission has an error, the HARQ tries to correct the data by means of combining multiple transmissions of the data.

The MAC layer transmits/receives data to/from the RLC layer and transmits/receives data to/from physical layer (Telesystem Innovation, 2010).

The set of physical channels is specified in LTE standard:

- Physical Broadcast Channel (PBCH)
    - This broadcast channel is coded and defined by four sub-frames
- Physical Control Format Indicator Channel (PCFICH)
    - Provides the number of OFDM symbols defined for PDCCH to the UEs
    - Each 1 millisecond, it is transmitted
- Physical Downlink Control Channel (PDCCH)
    - Conveying the grant scheduling from eNodeB to UE
    - Provides information to UE, i.e., the information about the Hybrid ARQ of the DL-SCH
- Physical Hybrid ARQ Indicator Channel (PHICH)
    - Replies ACK/NACK to the uplink transmission
- Physical Downlink Shared Channel (PDSCH)
    - Supports both PCH and DL-SCH
- Physical Multicast Channel (PMCH)

- Handles the multicast channel

- Physical Uplink Control Channel (PUCCH)
    - Replies ACK/NACK to downlink transmission
    - Conveys CQI report
    - The request for the PRBs is carried by PUCCH
- Physical Uplink Shared Channel (PUSCH)
    - Responsible for uplink shared channel UL-SCH
- Physical Random Access Channel (PRACH)

Figure 2.3 shows the actual mapping among the LTE channels in the uplink and figure 2.4 shows the actual mapping among the LTE channels in the downlink. Table 2.2 illustrates the transport and logical channels. The transport channels are set between the physical layer and the RLC layer, while the logical channels are set between the RLC layer and the PDCP layer.

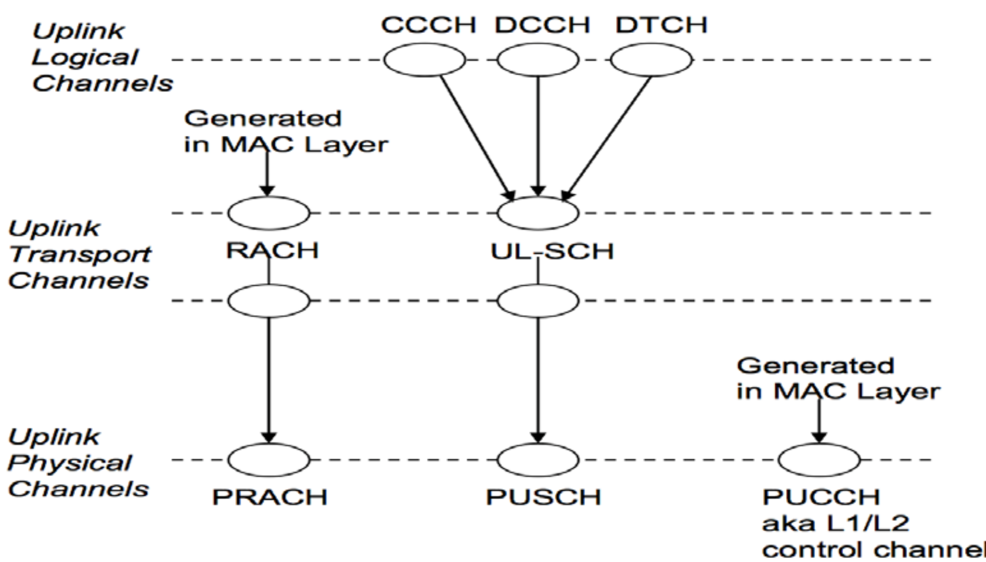

Figure 2.3 Mapping among LTE channels in the uplink (freescale, 2008).

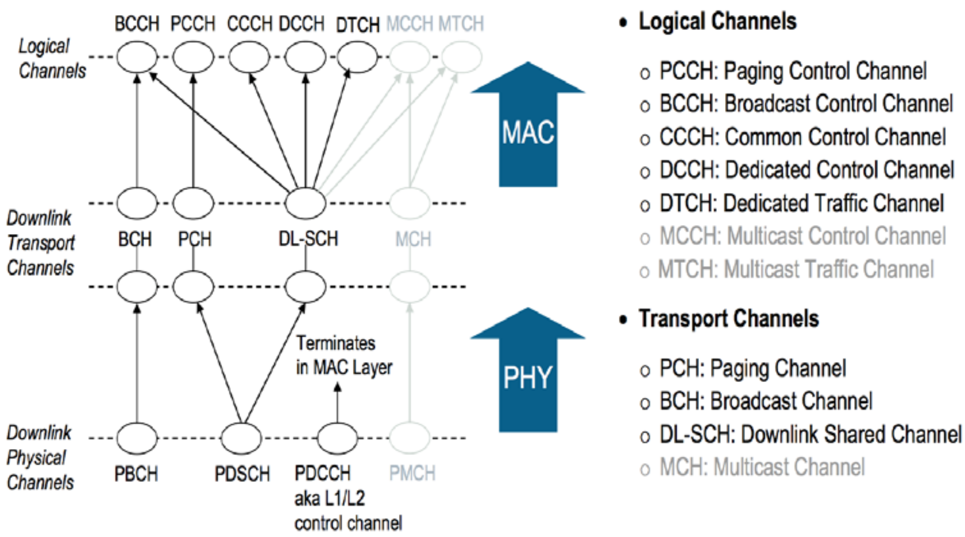

Figure 2.4 Mapping among LTE channels in the downlink (freescale, 2008)

Table 2.2 Logical and Transport Channels (Telesystem Innovation, 2010).

Channel Type		**Description**
Control Logical Channels		
BCCH	Broadcast Control Channel	Downlink channel used to broadcast system information.
PCCH	Paging Control Channel	Downlink channel used to notify UE of incoming call or change in system configuration.
CCCH	Common Control Channel	Downlink and uplink channel used to deliver control information during connection establishment when no confirmed association between the UE and eNodeB B has been established.
MCCH	Multicast Control Channel	Downlink channel used to transmit MBMS service control information.
DCCH	Dedicated Control Channel	Downlink and uplink channel used to transmit dedicated control information to a specific UE.
Traffic Logical Channels		
DTCH	Dedicated Traffic Channel	Downlink and uplink channel used to transmit dedicated user data.
MTCH	Multicast Traffic Channel	Downlink channel used to transmit user data for MBMS services.
Transport Channels: Downlink Transport Channels		
BCH	Broadcast Channel	Used for part of the system information essential to access the DL-SCH.
DL-SCH	Downlink Shared Channel	Used to transport downlink user data or control messages and system information not transported over the BCH.
PCH	Paging Channel	Used to transport paging information.
MCH	Multicast Channel	Used to transport user data or control messages requiring MBSFN combining.
Transport Channels: Uplink Transport Channels		
UL-SCH	Uplink Shared Channel	Used to transport uplink user data or control messages.
RACH	Random Access Channel	Used to access the network when UE does not have allocated uplink transmission resources or when it has no accurate uplink timing synchronization.

2.4 The Physical Layer

Wideband code division multiple access (WCDMA) is employed as a transmission scheme in HSPA. It represents the physical wireless channel with a 5 MHz spectrum. However, WCDMA is not a worthy choice when it comes to high data rates that meet the LTE standard's requirements. For example, WCDMA delivers a high signal-to-noise ratio (SINR) and it involves more complicated design issues such as the need to design complex equalization at the receiver side. Accordingly, WCDMA is ineffectively schemed in terms of supporting scalable bandwidth as compared to the supporting of scalable bandwidth up to 20 MHz in LTE. Therefore, the 3GPP changed its attention toward multiple carrier transmission instead of using single carrier transmission, so that it could achieve a high data rate with a reasonable SINR.

Hence, the "OFDM modulation scheme was a more appropriate choice for LTE due to the multicarrier nature of OFDM that provides significant advantages in terms of high data rate support" (Ciochina & Sari, 2010).

Accordingly, the 3GPP has chosen orthogonal frequency multiple access (OFDMA) as the downlink transmission scheme for LTE. Also, single carrier frequency division multiple access SC-FDMA was defined as an uplink transmission scheme in the LTE standard.

2.4.1 Orthogonal Frequency Division Multiplexing (OFDM)

Orthogonal frequency division multiplexing (OFDM) is a technique that is utilized in order to encode data over multiple carrier frequencies. It is industrialized for transmitting digital data for wireless or wired wideband digital communications, and it is implemented in numerous applications such as LTE and DSL internet access. In this section, an introduction of OFDM is provided. Then concepts related to CP are described and an explanation is given regarding how this scheme becomes orthogonal. Also, the generation of OFDM signals is discussed.

2.4.1.1 Introduction

Orthogonal frequency division multiplexing (OFDM) was considered by the 3G partnership project (3GPP) organization as an appropriate transmission scheme for LTE downlink transmissions. OFDM can be defined as a multicarrier modulation scheme. “The main principle behind OFDMA is breaking the radio spectrum into multiple orthogonal, narrowband subcarriers” (Berardinelli, Ruiz de Temino, Frattasi, Rahman, & Mogensen, 2008). OFDM generates numerous closely-spaced orthogonal sub-carriers. Each particular sub-carrier is modulated, i.e., by 16QAM at a low symbol rate. The primary difference between single-carrier schemes and OFDM is the capability of OFDM to overcome sever channel conditions with no need for complicated equalization filters placed at the receiver. It can also handle the inter-symbol interference (ISI). “The OFDM modulation scheme was a more appropriate choice for LTE due to the multicarrier nature of OFDM that provides significant advantages in terms of high data rate support” (Ciochina & Sari, 2010). Hence, the OFDM scheme is widely used, e.g. IEEE 802.11a/g and IEEE 802.16 (WiMAX). OFDM might be preferable due to some of its advantages, as follows:

- High spectral efficiency
- Sever channel conditions can be adapted with no need for complex equalization
- Less sensitivity to sample timing offset
- Elimination of ISI by means of cyclic prefix
- Effectual implementation while suing FFT

Thinking about hundreds or thousands of sub-carriers, the question of how users are multiplexed on the radio interface is arises. Figure 2.5 illustrates the implementation of multiplexing on both the time domain (TDM) and the frequency domain (FDM).

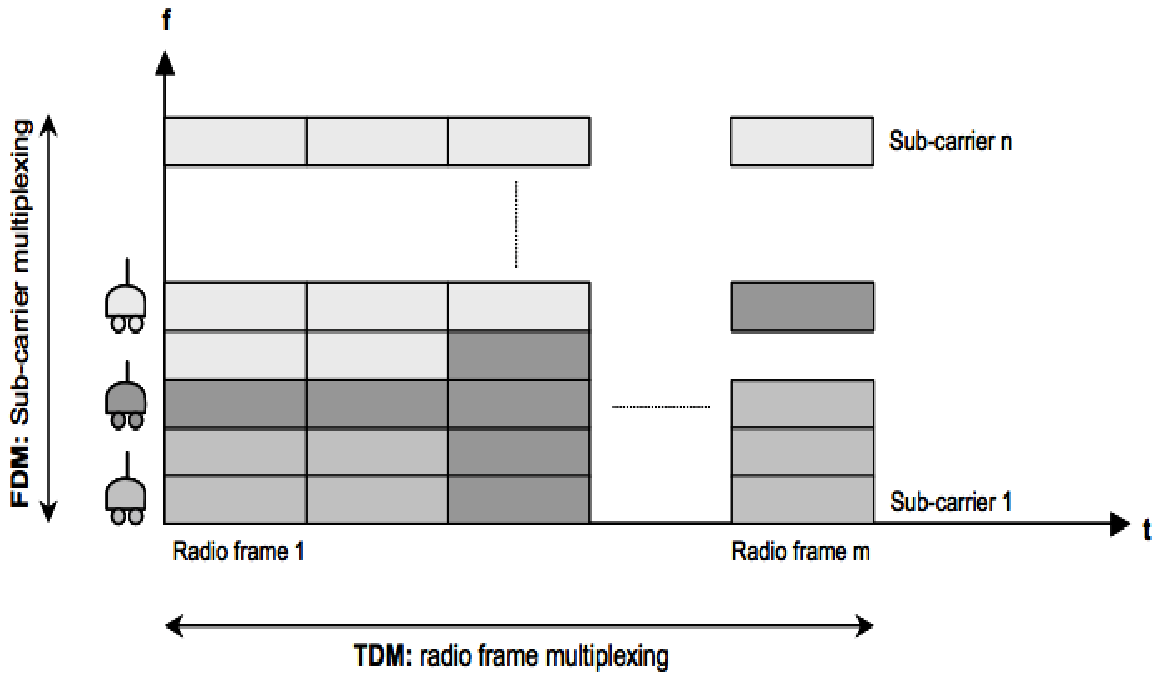

Figure 2.5 OFDM multiplexing using both FDM and TDM (Apis Technical Training, 2007)

2.4.1.2 Orthogonality

The frequencies of the subcarrier are set orthogonally to avoid interference with each other. Consequently, increased spectrum efficiency can be achieved. A particular user is granted a set of parallel subcarriers. However, the complexity that is caused by modulating/demodulating a massive number of subcarriers can be overcome by implementing discrete fourier transform (DFT) and fast fourier transform (FFT) techniques.

A precise frequency spacing must be included to ensure the orthogonality, e.g., the frequency spacing or carrier spacing defined in LTE is 15 kHz, as shown in Figure 2.6.

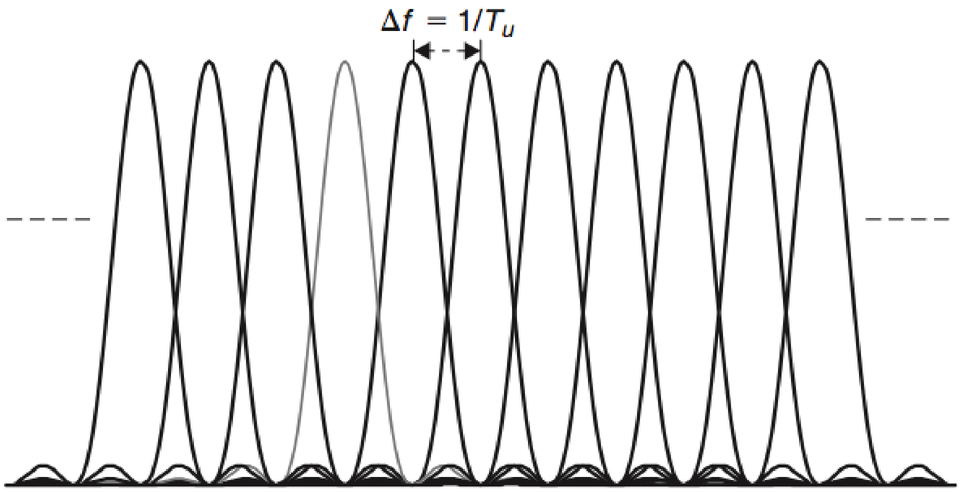

Figure 2.6 OFDM subcarrier spacing (Dahlman et al., 2008)

2.4.1.3 Cyclic Prefix Insertion

OFDM manages the multipath fading because the duration of its symbol is quite long. However, ISI might be experienced in OFDM, so including the cyclic prefix can resolve multipath echoes caused by ISI. Figure 2.7 shows the insertion of the cyclic prefix.

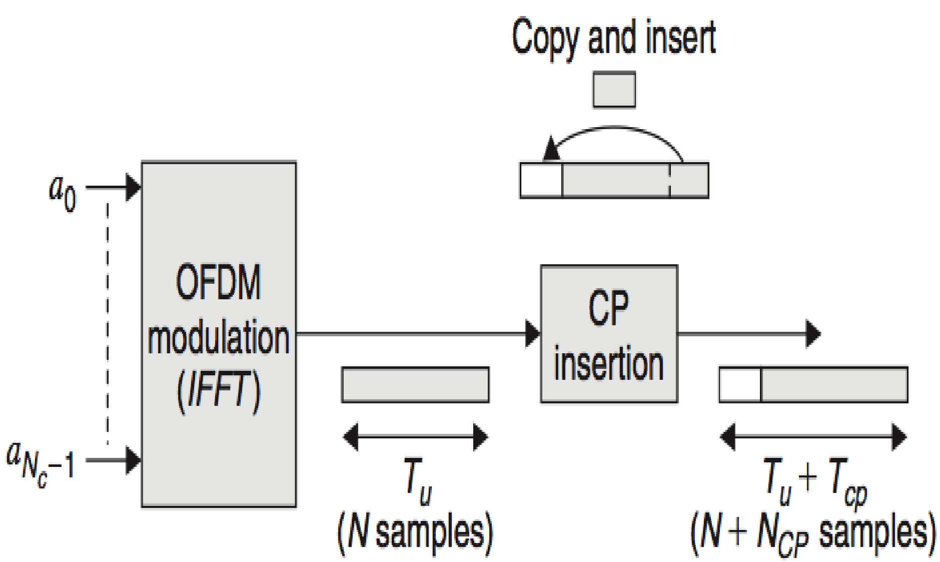

Figure 2.7 Cyclic prefix insertion (Dahlman et al., 2008)

As shown in the figure, the cyclic prefix is a copy of the last part of the OFDM symbol that is inserted in front of the symbol. However, this cyclic prefix (CP) will be removed at the receiver prior to demodulation of the information.

2.4.1.4 Generation of OFDM Signal

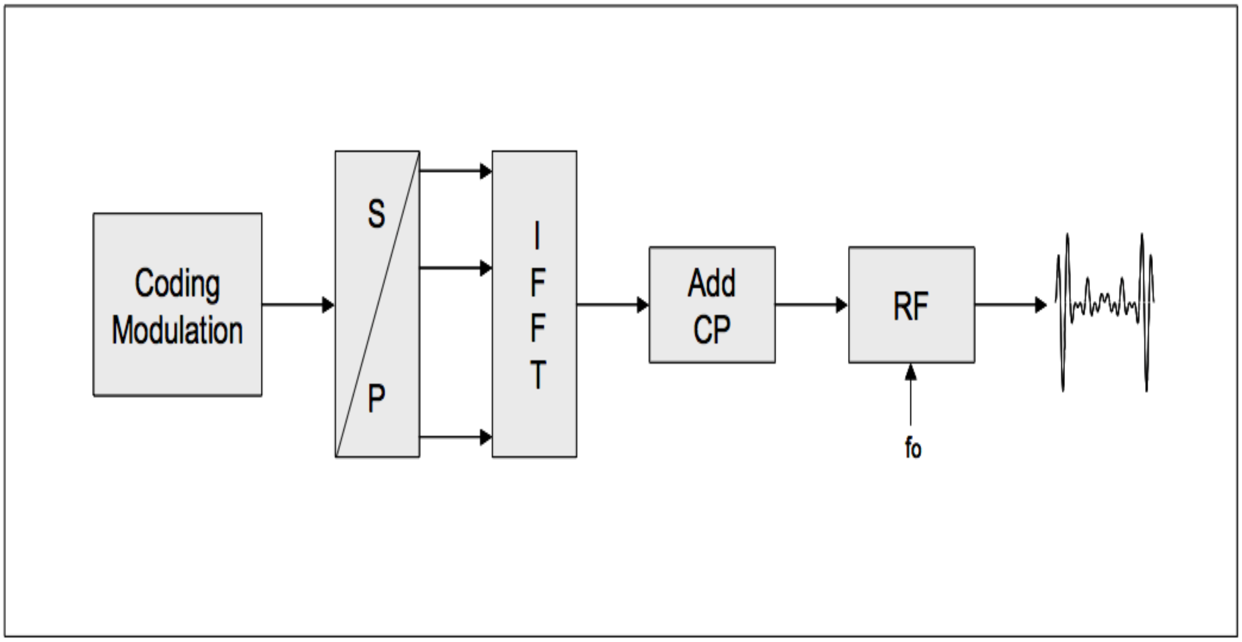

Figure 2.8 OFDM transmitter using IFFT (Apis Technical Training, 2007)

Figure 2.8 illustrates the implementation of different procedures for the OFDM transmission. At the first stage, step coding and modulation are implemented. Any traditional modulation scheme, e.g., QPSK or 64QAM, can be used in order to modulate the transmission.

Then the group of modulation symbols is converted from serial state into parallel state so that they are ready for the application of IFFT.

Inverse Fast Fourier Transform (IFFT) is applied in order to produce an OFDM single symbol that contains congregated and modulated subcarriers.

The cyclic prefix is appended to the output of IFFT implementation, which is a single symbol. The reason for the appended CP is to overcome the ISI effects.

Pulse shaping or filtering mechanisms may be implemented for RF processing purposes.

Note that those processing procedures are applied inversely by the receiver side. Therefore, FFT is applied instead of IFFT in order to recover the content of the symbol blocks.

2.4.2 Single Carrier-Frequency Domain Multiple Access (SC-FDMA)

The OFDM delivers high peak-to-average-power-ratio (PAPR). The OFDM, actually, is an inadequate transmission scheme in consideration of uplink transmission (Berardinelli, Ruiz de Temino, Frattasi, Rahman, & Mogensen, 2008). The OFDM transmission delivers high peak power compared to the transmission power average. Consequently, power inadequacy will occur while the UE terminal is transmitting to the uplink channel. Therefore, SC-FDMA was found to be a superior substitute for the LTE uplink transmission scheme. Figure 2.9 illustrates the process of SC-FDMA transmission.

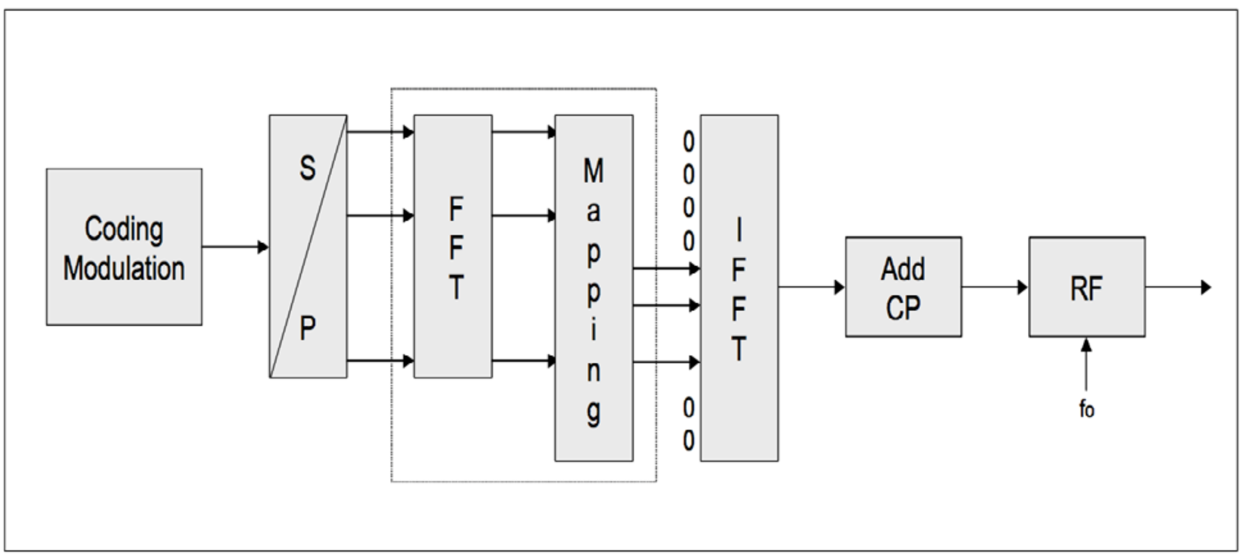

Figure 2.9 The SC-FDMA transmitter using FFT spreading (Apis Technical Training, 2007)

SC-FDMA is alternatively known as DFT-Spread-OFDMA (DFT-S-OFDMA). Compare SC-FDMA transmission processing, illustrated in Figure 2.9, to OFDM transmission processing, illustrated in Figure 2.8. SC-FDMA applies two more steps in its transmission for FFT and subcarrier mapping.

In the FFT procedure, each modulation symbol is spread over all subcarriers/bandwidth. Then those FFT outputs are divided into subsets and mapped into IFFT as inputs. The cyclic prefix will be appended to the SC-FDMA symbol afterward.

On the receiver side, the operations are basically the reverse of those for signal generation at the transmitter. Additionally, there are techniques to identify which subcarriers should be contained in a specific chunk for a certain user:

- Localized SC-FDMA**—**Where a group of consecutive subcarriers is selected, if we have 1-100 subcarriers, a consecutive set is from 10-20, not 10-15 and 20-25, for example.
- Distributed SC-FDMA**—**The subcarriers are distributed equally.
- Randomized SC-FDMA**—**The subcarriers are selected according to a specific pattern.

Accordingly, the SC-FDMA transmission scheme is different from the OFDM transmission scheme because of an additional DFT step with the SC-FDMA transmission scheme. However, the SC-FDMA transmission scheme and the OFDM transmission scheme are similar in most of their characteristics with lower-PAPR advantages of the SC-FDMA transmission scheme. Therefore, battery life in the UE is aided by this advantage. Furthermore, data rates can be increased while power efficiency increases as well, so that can be counted positively for UE uplink transmission.

Despite the fact that SC-FDMA lowers the PAPR, the SC-FDMA transmission scheme requires restriction, while subcarriers are ready to be allocated. The set of subcarriers must be contiguous to each other, and that triggers an obstacle for allocating resources to scheduled UEs.

2.4.2.1 Frame Structure

Figure 2.0 illustrates the frame structure for the LTE downlink scheme and the uplink scheme. Therefore, the downlink/uplink frame structure is the same even though the schemes are different.

The LTE downlink/uplink frame equals a 10 milliseconds long radio frame in terms of time domain. The System Frame Number (SFN) identifies and classifies frames so that diverse transmission cycles can be controlled.

Each LTE downlink/uplink frame is divided into ten sub-frames, and each one of them equals one millisecond time duration. A sub-frame contains two slots, each of which is 0.5 milliseconds long. Eventually, the 0.5 millisecond slot comprises a number of OFDM/SC-FDMA symbols. The number of OFDM/SC-FDMA symbols is set according to the CP mode that is considered for the networks. Actually, two types of CP mode are defined in LTE, normal CP mode and extended mode. In the case of normal CP mode, default mode, the number of OFDM/SC-FDMA symbols involved in the 0.5 millisecond slot is set to seven symbols. In other words, if the CP mode is extended, the number of OFDM/SC-FDMA symbols involved in 0.5 millisecond slot is six symbols. According to the modulation and coding scheme (MCS) utilized in uplink transmission, the number of data bits conveyed by a particular OFDM/SC-FDMA symbol can be calculated.

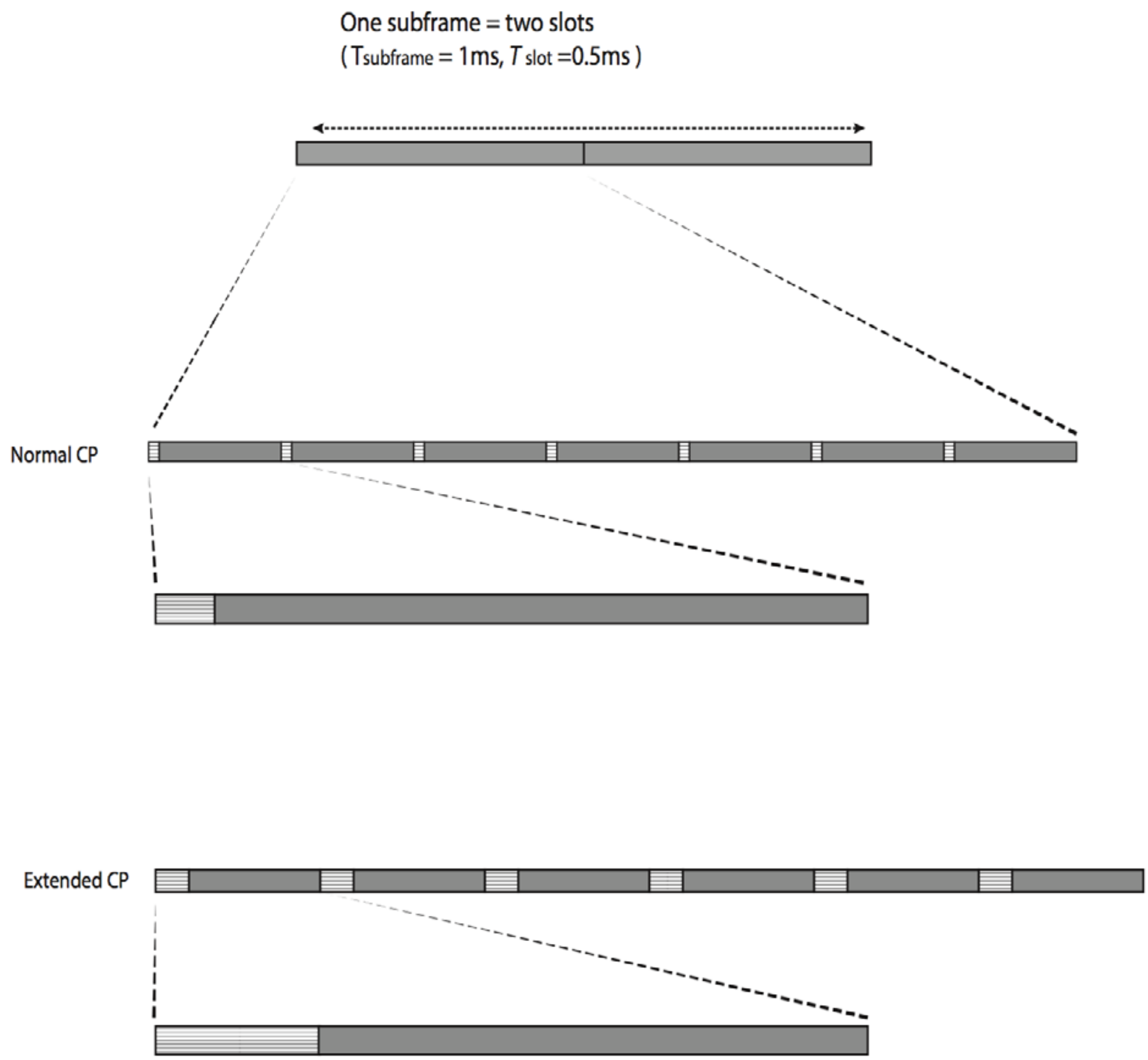

Figure 2.10 Frame structure of an OFDM and SC-FDMA radio interface, reproduced from Zyren & McCoy (2007)

Figure 2.11 illustrates the frequency resource grid structure of an LTE frame in the 0.5 millisecond time slot. As is demonstrated, the frequency domain of the OFDM/SC-FDMA time slot contains numerous sections, and each one of them equals 180 kHz. Accordingly, each section is comprised of twelve adjacent OFDM/SC-FDMA subcarriers. The particular radio resource unit known as physical resource block (PRB) is formed by 180 kHz X 0.5 millisecond frequency-time blocks as shown in Figure 2.11. The PRB comprises a set of twelve OFDM/SC-FDMA subcarriers.

Seven OFDM/SC-FDMA symbols are included in each subcarrier in the normal CP case or six in the extended CP case.

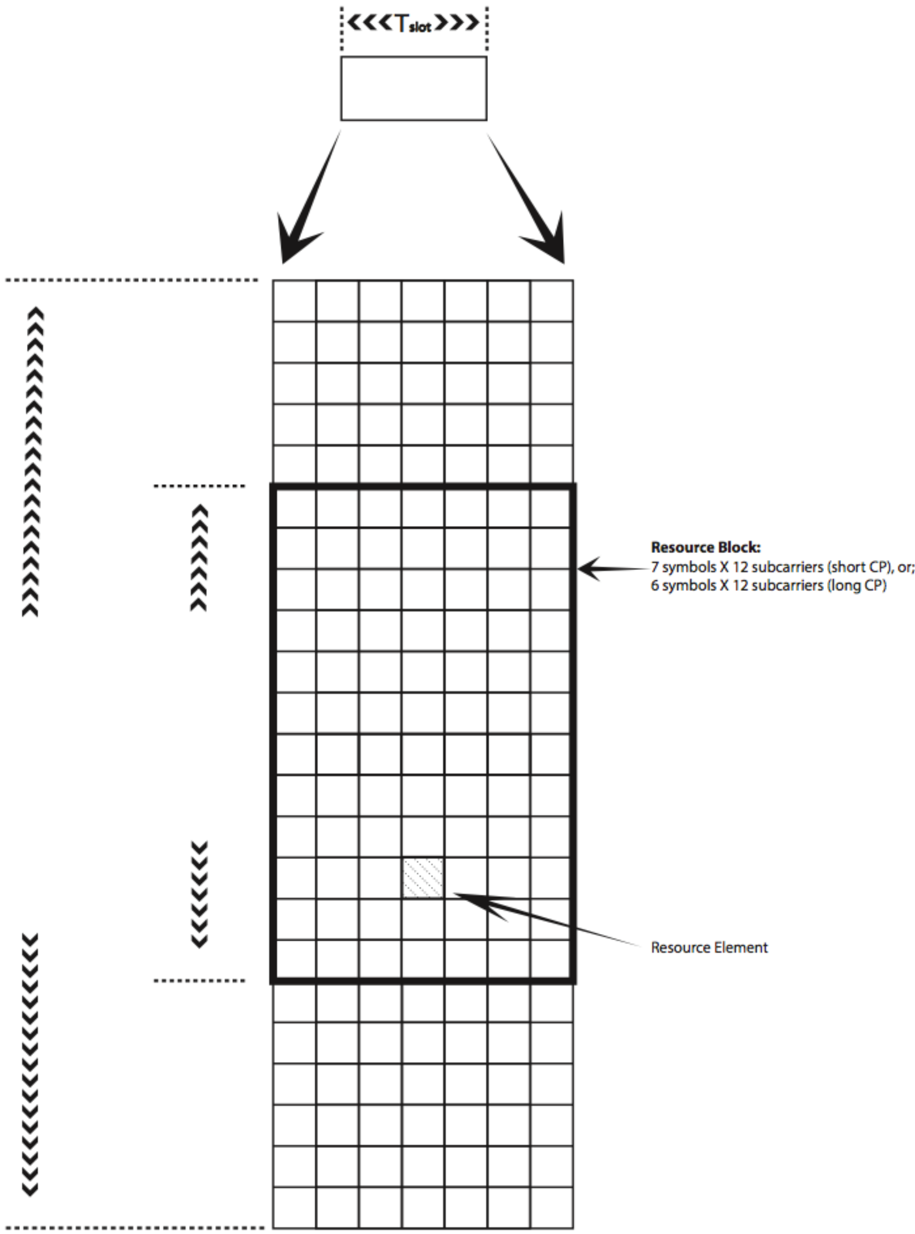

Figure 2.11 The frequency resource grid structure of an OFDM/SC-FDMA 0.5 millisecond time slot, reproduced from Zyren & McCoy (2007)

To dedicate LTE frames for both downlink and uplink directions, two duplexing modes are defined in LTE, time division duplexing (TDD) and frequency division multiplexing (FDD). In

TDD mode, uplink transmission and downlink transmission can be contained in a frame, and the distribution of subframes between uplink and downlink transmissions is influenced by the configuration of the TDD. Additionally, a particular subframe is used to distinguish between uplink and downlink transmissions. In the case of FDD, the uplink transmission and downlink transmission are detached into various frequency bands so that a single subframe can be defined as a full unit for each uplink or downlink transmission.

CHAPTER 3

RESOURCES MANAGEMENT AND PACKET SCHEDULING

This chapter focuses more on the management of the radio resources and on addressing the scheduling problem in LTE. First, we define the radio resource management (RRM) entity with its specifications and functions, according to 3GPP specifications. Then the packet scheduling will be taken into account as a major discussion element in this chapter. Thereafter, the discussion closely investigates the procedure of the packet scheduler in the LTE. The initiation of the scheduling request (SR) with two different methods, and how the UE interacts with target eNodeB, are among the packet scheduler duties. After that, the details of the packet scheduler procedure function are addressed. In order to produce a practical packet scheduler, the elements that influence the system's performance are given. Lastly, the factors that should be taken into account while building and designing the packet scheduler in LTE are addressed.

3.1 Radio Resource Management (RRM) in LTE

The significance of radio resource management RRM is manifested when it makes sure that the available radio resources are used efficiently. The main tasks that RRM performs are to take the network policies into account in order to build its decision for either accepting or rejecting the connection requests and make sure that the entire available bandwidth is utilized in an efficient manner (3GPP, 2010). In addition to that, RRM delivers effective mechanisms so that E-UTRAN can meet the LTE requirements.

3.1.1 RRM Functions

Functions of RRM potentially interact with each other in order for RRM accomplish its purposes. The most significant functions are the following:

- Connection mobility control (CMC)

  The major task that CMC performs is to manage the radio resources in connection with idle or connected mode mobility.

- Inter-cell interference coordination (ICIC)

  The inter-cell interference coordination (ICIC) is assigned the control of the inter-cell interference (3GPP, 2010).

- Load balancing (LB)

  When the traffic load over multiple cells is disparate, load balancing is tasked to balance the traffic load.

- Radio bearer control (RBC)

  RBC is responsible for the establishment, maintenance, and release of radio bearers.

- Radio admission control (RAC)

  RAC is the crucial function associated with RRM. RAC is tasked with inspecting the UE's request for establishing a new radio bearer RB connection for both directions, downlink and uplink. RAC takes into account the overall resource situation in E-UTRAN, such as QoS requirements, and based on that, RAC decides to admit or reject the establishment of an RB connection.

- Dynamic resource allocation (DRA)— packet scheduling (PS)

  The DRA/PS function is used in order to allocate and de-allocate available radio resources to a set of UEs.

3.2 Packet Scheduling

Packet scheduling means allocating the available physical resource block (PRB) for UEs associated with the network. Packet scheduling acts for a particular amount of time. The period of time in which packet scheduling can act is identified as a transmission time interval (TTI). TTI equals 1 millisecond, which is the period of one sub-frame.

The packet scheduler is responsible for choosing a group of UEs within its range, in order to schedule them each a TTI. Then, the packet scheduler maps between the available PRBs and the selected group of UEs in order to decide which group of PRBs will be applicable to valid UEs which have achieved the highest performance metric. The performance metric refers to the measuring of some UEs' properties, such as average packet delay or data rate, which is to be determined for each UE. The measurement of a given performance metric can have an effect on the system's performance, so the packet scheduler can maximize the desirable level system requirements.

The packet scheduler also does a task other than resources allocation, which is link adaptation (LA). The link adaptation task is significant in order to ensure that the data packets are transmitted to the correct target destination. The message exchanged between UE and eNodeB and the signaling control constitutes the actual mechanisms for requesting (from UE to eNodeB) or granting (from eNodeB to UE) resources. However, the LTE standard did not specify a particular way or algorithm for the packet scheduler. This is left open to the research field. Moreover, the scheduling request (SR) is an action performed by the UE and handled by eNodeB for uplink packet scheduling in LTE. Therefore, the SR must be described.

3.2.1 Scheduling Request

The uplink packet scheduler is activated when the UE transmits a scheduling request (SR) to the eNodeB asking for resources in order to upload its data. The SR is one bit of information that indicates that the uplink has data to upload. In Larmo, Lindstrom, Meyer, Pelletier, Torsner, & Wiemann (2009), the mechanism of the Scheduling Request (SR) was detailed as two different mechanisms that can be performed to send an SR. Those mechanisms are dedicated SR (D-SR) and random access-based SR (RA-SR).

- Dedicated SR (D-SR)

The D-SR mechanism is utilized when the resources are dedicated on the physical uplink control channel (PUCCH) for the UE. Hence, acquiring resources is much easier in this case, according to the UE preferable mechanism. The UE will then send one bit flag on the PUCCH in order to demand its dedicated resources. The eNodeB will respond sequentially and deliver the scheduling grant over the physical downlink control channel (PDCCH) to its associated UE.

- Random access-based (RA-SR)

Once there are no dedicated resources to the UE on the PUCCH, the RA-SR mechanism will become an appropriate mechanism for sending SR. In addition, the RA-SR is utilized when the uplink of UE is not time aligned. Accordingly, the RA-SR is used to reestablish time aligned with the target eNodeB in order to acquire radio resources on the uplink. At that time, the one bit of information is sent by the UE toward the target eNodeB. The eNodeB responds according to that request by sending a scheduling grant over the PDCCH to the UE in order to allow the UE to upload its uplink data.

3.2.2 LTE Packet Scheduling Procedure

To obtain efficient downlink packet scheduling, the UE might provide a report about the channel status to eNodeB. According to the measurement of the channel status report, the downlink scheduling can make a wise decision to allocate proper PRBs to the right UE.

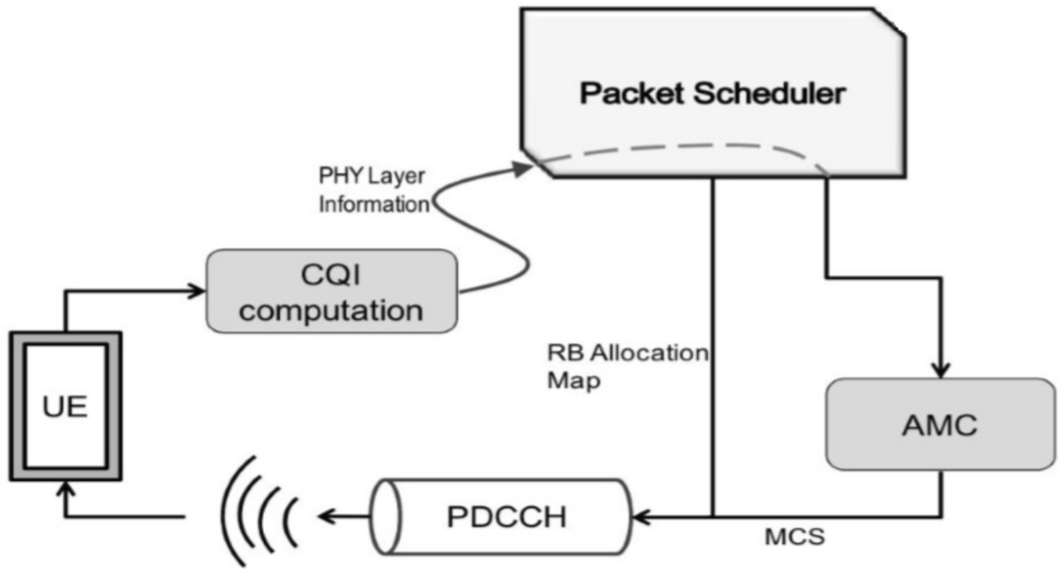

Figure 3.1 Simple model of paacket scheduler (Capozzi, Piro, Grieco, Boggia & Camarda, 2013)

Figure 3.1 depicts the interaction between the RRM functions and the downlink scheduler. The eNodeB first transmits a reference signal to the UE. Then, the UE decodes it, calculates the CQI, and sends it back to the eNodeB. The CQI is calculated as a quantized and scaled measure according to the signal to interference plus noise ratio (SINR). This CQI information is used by the eNodeB to make a decision about PRBs scheduling. Accordingly, the best MCS will be selected by the AMC module. Afterword, the PDCCH takes place and sends information about the assigned PRBs and a selected MCS. Eventually, each UE reads the PDCCH and will access an appropriate PDSCH payload in case it is scheduled.

In LTE uplink packet scheduling, due to utilization of the SC-FDMA transmission scheme, the allocation of resources must be contiguous. Therefore, during the assigning of resources to the UEs, each UE will be assigned consecutive PRBs.

At the very beginning of the scheduling process, the UEs' buffer size is not attainable for the uplink scheduler. As mentioned before, the UE will notify the eNodeB that it has data that it wants to upload by sending an SR. Because it is the first transmission, the scheduler is set at the eNodeB initial transmission and sends an uplink scheduling grant toward the UE. Once the UE receives the grant, the unloadable data will be uploaded to eNodeB. Figure 3.2 illustrates the process.

Note that a scheduling request provides only limited knowledge about buffer situations at the terminal. When the terminal is scheduled to transmit on an uplink shared channel (UL-SCH), more information about the buffer situation will be provided (Dahlman, Parkvall, Skold, 2011).

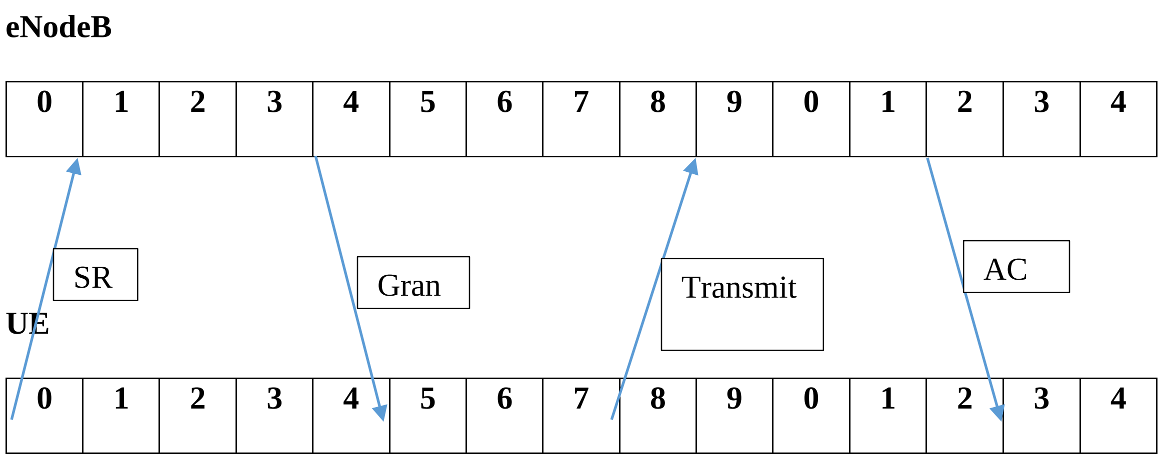

Figure 3.22 Interaction between UE and eNodeB

Every periodic TTI time, which is 1 milliseconds, the scheduler decides which PRBs are obtained, to which UEs, with what transport format. The transport format selection (TFS) is one of the link adaptation (LA) responsibilities. TFS refers to the modulation and coding scheme (MCS) selection. The determination is made based on the measurement of SINR, according to the uplink demodulation reference signal.

After the scheduling grant is received, the UE is able to transmit its data on assigned uplink resources. The scheduler decision must be made according to accurate factors such as information about the buffer situation, and the first uploaded transmission data will be transmitted to eNodeB with information about the buffer report. Therefore, the scheduler will be able to make an efficient decision in terms of subsequent sub-frame transmissions.

3.2.3 Design and Modeling Packet Scheduler

Forecasting the UE's needs is a potential feature that is anticipated through a constructed scheduler. For example, it should be possible to enable the UE to meet the QoS requirements of its traffic and make sure that the UE occupies allocated PRBs in an efficient manner. A set of factors that can influence the scheduler mechanism are as follows:

- Channel state information (CSI) reports**—**This is support information about the channel conditions for each UE to the packet scheduler, in order to come up with an efficient scheduling priority according to a given value.

- Hybrid automatic repeat request (H-ARQ) retransmission**—**This assists the packet scheduler to distinguish between PRBs that should be either retransmitted or dedicated as a new transmission.

- The history of UE's transmission, such as the previous average throughput informed by UE.

- Allowed number of UEs that can be accepted in each TTI.

- Adjacent PRB allocation constraints in terms of uplink scheduling**.** Due to the SC-FDMA, the PRBs assigned to a particular UE must be contiguous in the frequency domain.

- The power is inadequate when it comes to the UE due to the limited battery life for the UE's portable devices**.** Accordingly, the mentioned factors are significant due to their contribution toward getting the best out of the system objectives.

The system objectives refer to the term that the scheduler will maximize. The desirable objectives can be among the following:

- Achievable fairness: Fairness determines how much the packet scheduler can deliver fair PRBs and allocate them among the available UE.
- Power utilization: Reducing the power that is utilized by the UE can be an objective for the system that is considered by the packet scheduler.
- QoS satisfaction: In QoS terms, the packet scheduler tries to take full advantage of the optimistic QoS experienced per UE.
- Maximizing throughput: Once the packet scheduler is configured to maximize the throughput, the packet scheduler attempts to make sure that the entire bandwidth is utilized resourcefully, which means that the maximum number of the resources are sufficiently occupied and utilized for transmission.

Designing a packet scheduler is a somewhat complicated problem, because there are some factors that must be taken into account. However, designing a reasonable packet scheduler can be done in two phases:

1. Delimiting the Utility Function

The utility function is expressed mathematically and is used in order to measure the system's performance, which needs to meet target requirements. The preferable performance metrics will express the desired target requirement. For example, it can be data throughput, fair resource allocation, and so on. The utility function will be measured periodically every TTI, due to the way that the packet scheduler assigns resources every TTI.

2. Design PRBs Allocation Mechanism

The packet scheduler performs a search-based algorithm in order to constitute an efficient allocation mechanism by mapping between PRBs and UEs. In addition to that, the packet scheduler is built according to a chosen utility function. In fact, one TTI is the time that the search-based algorithm takes, so the search-based algorithm must be as simple as possible.

As soon as those two phases are completed, the implementation is taken into account. For example, in Pokhariyal et al. (2007), the authors presented the most utilized model in order to implement an LTE uplink scheduling proposal and solution. This model is broken down into two domains, a time domain packet scheduling (TDPS) and a frequency domain packet scheduling (FDPS).

In the TDPS case, the packet scheduler investigates the priority of the associated UEs in order to schedule them in upcoming TTIs. The prioritizing is according to which UE has the highest metric and whether its chance to be scheduled becomes high. Henceforth, the FDPS constitutes appropriate mapping between PRBs and UEs which have high metric value, and allocates the PRBs in a frequency domain. Figure 3.3 shows the TDPS/FDPS model for LTE uplink scheduling according to Pokhariyal et al. (2007).

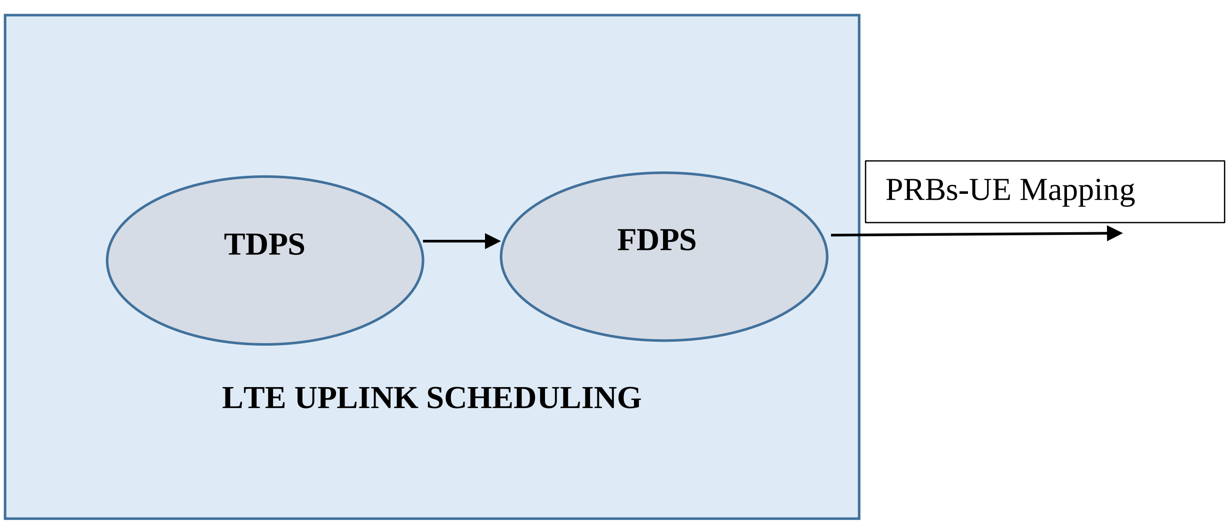

Figure 3.3 Block diagram of LTE uplink scheduling

TDPS scheduling generates a performance metric for each user, and this metric will determine the prioritizing for UEs. Accordingly, a UE which has a high metric value, or in other cases, low metric value, will have chance to be placed in the schedulable UE list that will be assigned PRBs in upcoming TTIs.

Accordingly, the FDPS allocates PRBs to UEs whose metric value has been calculated, and for which it has been proved that that value is adequately high and qualified in order to map PRBs-UE in a frequency domain.

CHAPTER 4

PACKET SCHEDULING ALGORITHMS

4.1 Literature Review

This section provides a survey of LTE scheduler proposals from the literature. Most of the material on proposed LTE scheduling emphasizes maximizing the fairness and data throughput, in terms of performance metrics. In the Best-CQI algorithm, for example, PRBs will be assigned to the UE with the highest CQI. Also, some algorithms assign PRBs to UEs with maximum throughput in order to maximize the overall system's throughput.

In Iosif and Banica (2011), the authors went through the basic scheduling method, which is the round robin Scheduler (RR). The round robin scheduler is used to maximize fairness objectives among the UEs. The number of UEs which have a chance to be scheduled is constrained by the number of physical downlink control channels (PDCCH). That is because the PRBs are signaled to the UEs through the available PDCCH. Moreover, the throughput of the system is degraded.

The round robin scheduler was recognized based on two different domains, which are the time domain (TD) and the frequency domain (FD). In the time domain, the scheduler will allocate the available PRBs to one UE each TTI. The UE is picked up from a scheduled list of UEs, which contains the number of available UEs. However, multiple users can be served in one TTI.

Four greedy heuristic algorithms are proposed in Lee, Pefkianakis, Meyerson, Xu, & Lu (2009). The carrier-by-carrier, in turn, was one of the algorithms they proposed. In this algorithm, the available RBs were ordered from RB1 to RB m to meet the constraint of assigning contiguous RBs for each UE that has the highest metric value. Additionally, proportional fairness is the performance metric that is measured by the algorithm, which then starts assigning the set of contiguous RBs.

Also, the Largest-Metric-Value-RB-First algorithm was proposed in the same article (Lee et al., 2009). In this algorithm, the authors attempted to solve the contiguity constraint slightly. The algorithm attempts to enforce non-candidate RBs to be assigned to a scheduled user while these non-candidate RBs are placed between two different candidate RBs to fulfill the contiguity constraint.

Additionally, the opportunistic scheduling algorithm, termed the Heuristic Localized Gradient Algorithm (HLGA), was proposed and discussed in Al-Rawi, Jantti, Torsner, & Sagfors (2007). Accordingly, the HLGA is able to manage the retransmission request and resource allocation concurrently. When PRBs are assigned to a particular UE, the PRBs must meet the contiguity constraint. If two PRBs, which are not adjacent to each other, are assigned to the same UE, the algorithm imposes additional PRBs that are placed between those PRBs and are to be allocated to same UE. The same concept is implemented on the ARQ-blocks by the algorithm in case of a transmission failure. Then, a pruning phase will be taken into account. The pruning phase refers to when the algorithm makes sure that no PRBs are left. When some PRBs are remaining, however, the remaining PRBs are assigned and distributed among unsatisfied UEs. However, the HLGA demands high memory resources while it is allocating the PRBs among the UEs.

4.2 The Proposed Packet Scheduler Algorithm

The round robin scheduler algorithm is the standard and is used for comparison with other proposed algorithms. The round robin scheduler algorithm delivers a high level of fairness among the UEs. However, the throughput of the system is degraded. We need to define an algorithm in order to increase the throughput of the system. Therefore, the proposed algorithm performs based on the number of PRBs and the number of UEs. The number of PRBs is related to the bandwidth of the system. Therefore, if the bandwidth is known, the number of PRBs can be distinguished as well. Table 4.1 shows the relationship between the bandwidth and the number of PRBs.

Table 4.1 Relationship between the Number of PRBs and the Bandwidth.

BW	1.4 MHz	3 MHz	5 MHz	10 MHz	20 MHz
Number of PRBs	6	15	20	50	100

As long as the number of attached UEs to eNodeB is increased, the overall throughput will be severely degraded when the round robin algorithm is employed. However, the Best-CQI Algorithm can deliver a good overall throughput, but it performs unfair resource sharing since UEs with low CQI might suffer starvation.

In the proposed algorithm we try to produce a proper solution to this quandary considering the probability of increased numbers of UEs, so we build the algorithm to perform based on the number of UEs attached to the eNodeB in a particular TTI.

In case the number of UEs is larger than the number of available PRBs, the proposed scheduler algorithm performs in order to maximize the following metric:

$$m\,(i,j) = D_j^i(t)/T^i(t-1) \tag{4.1}$$

where $D_j^i(t)$ is the expected data-rate for $i-th$ UE at time t on the $j-th$ PRB, and $T^i(t-1)$ is the past average throughput experienced by $i-th$ UE.

Accordingly, the percentage of allocation of UEs with poor channel conditions can be increased (Capozzi, Piro, Grieco, Boggia, & Camarda, 2013).

In case the number of UEs is lower than the number of available PRBs, the proposed scheduler algorithm schedules the UE with the highest CQI. Figure 4.1 depicts the pseudo-code of the proposed scheduler algorithm, while figure 4.2 depicts the flow chart of the proposed scheduler algorithm.

Algorithm 1 PROPOSED ALGORITHM FOR LTE SCHEDULING

```
Let N be the number of UE and R be the number of PRB
Let X be the expected data rate and Y be the past average throughput for
each UE
Let M = X / Y
for all UE do
  if N >= R then
    assign RB to UE with highest value of M
  else
    assign RB to UE with best CQI
  end if
end for
```

Figure 4.1 The pseudo-code of the proposed algorithm

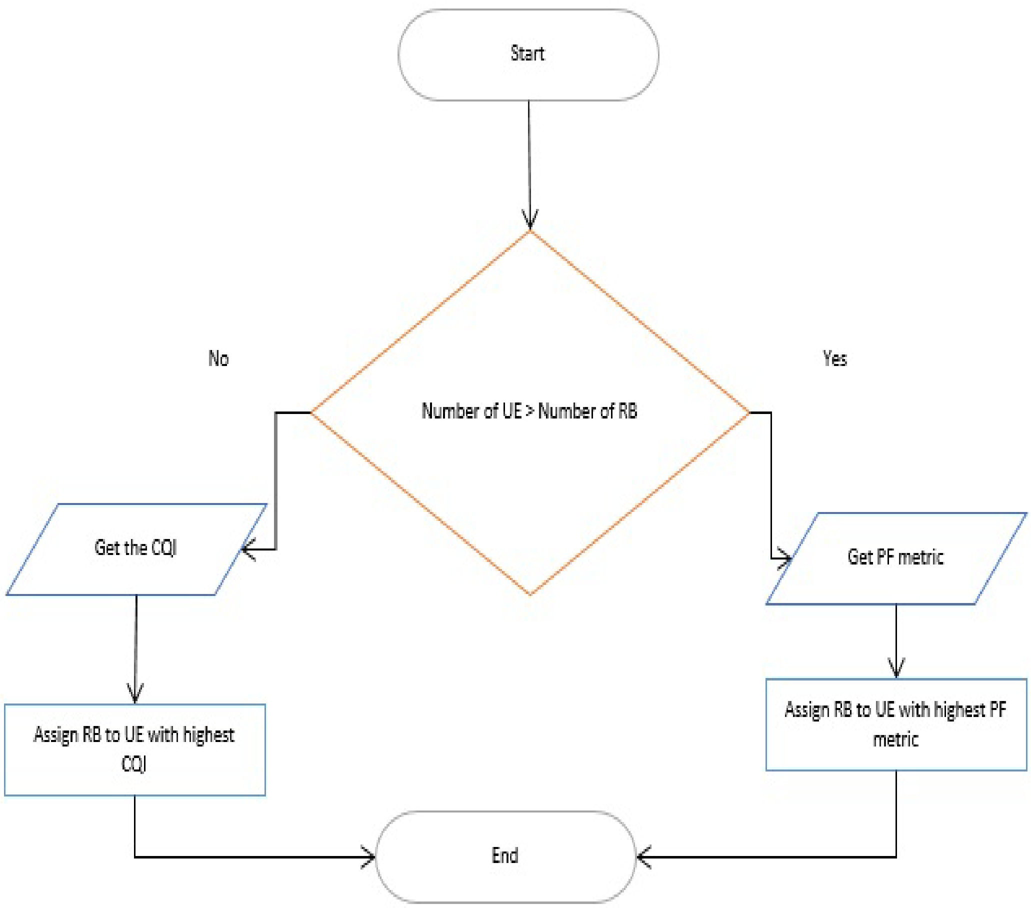

Figure 4.2 The flow chart of the proposed scheduler algorithm

CHAPTER 5

SIMULATION RESULTS

In this chapter, the results for implementing the proposed algorithm are given and compared with the results of the round robin scheduler algorithm. We consider two scenarios: one with 3 UEs and the other with 8 UEs; the scenarios, with 1.4 MHz bandwidth, consist of 6 PRBs. The reason is to test how the proposed algorithm performs when the number of UEs becomes either higher or lower than the number of RBs as compared with the results from the round robin scheduler algorithm.

The implementation of the LTE system level simulator is in order to provide an advanced level of flexibility due to the use of the object-oriented programming (OOP) capabilities of Matlab R2012a (J. C. Ikuno et al (2010)). Thus, the simulation of radio connection between UEs and eNodeB is a major task in the simulation. The throughput and block error ratio (BLER) for both the UEs and the eNodeB are captured and measured. The simulator will run every TTI (50 TTIs in this experiment). Each UE transmits feedback information about SINR and MCS according to the received transmission pilot from the eNodeB. Then the eNodeB receives the feedback from each attached UE, and the scheduler decides the allocation of PRBs based on the scheduler's criteria. The channel model is based on the zero forcing (ZF) receiver with two transmit antennas.

In this experiment two scenarios were assumed. The first scenario is to let the number of UEs be 3 UEs below the number of PRBs in order to investigate the performance of the proposed algorithm under this condition. The second scenario assumed is to let the number of UEs (8 UEs in this case) be larger than the number of PRBs. The simulation parameters are depicted in Table 5.1.

Table 5.1 Simulation Parameters

Frequency	2 GHz
Bandwidth	1.4 MHz
Number of UE	3/8
Number of transmit antenna	2
Number of receive antenna	2
Transmission mode	Spatial Multiplexing
Simulation Time	50 TTIs
eNodeB Transmission Power	43 dBm
Channel Model Type	PedB
Scheduler	RR Algorithm/Proposed Algorithm
Cyclic Prefix Type	Normal

5.1 The Three UEs Scenario

Throughput and BLER will be depicted for all three UEs attached to the target eNodeB. In this scenario, the proposed algorithm will assign PRBs to the UEs with the highest CQI while the round robin algorithm is fairly assigning the PRBs among the UEs.

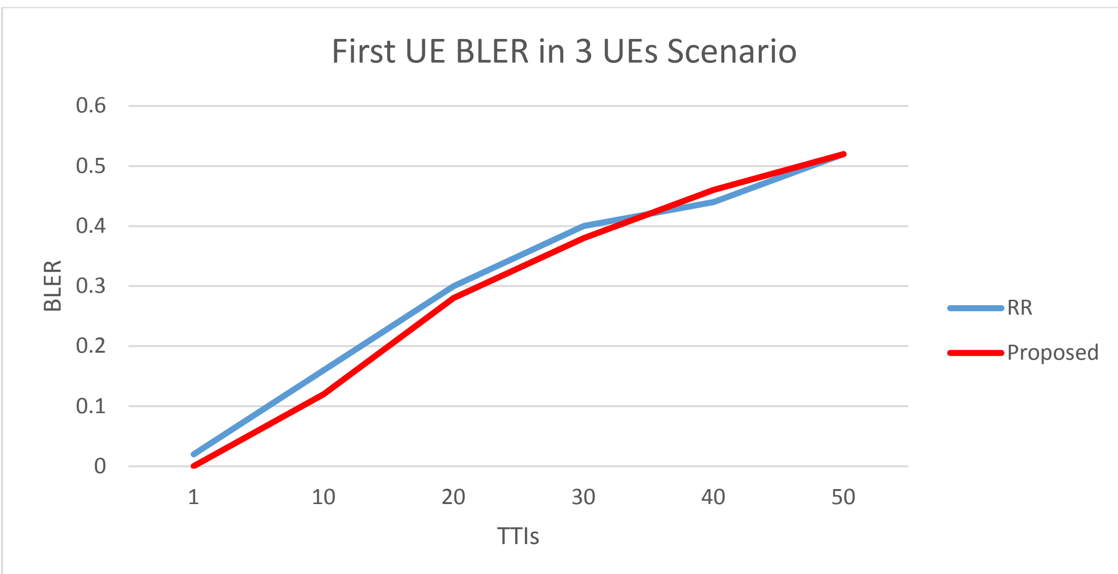

Figure 5.1UE number 1 BLER in the 3 UEs scenario

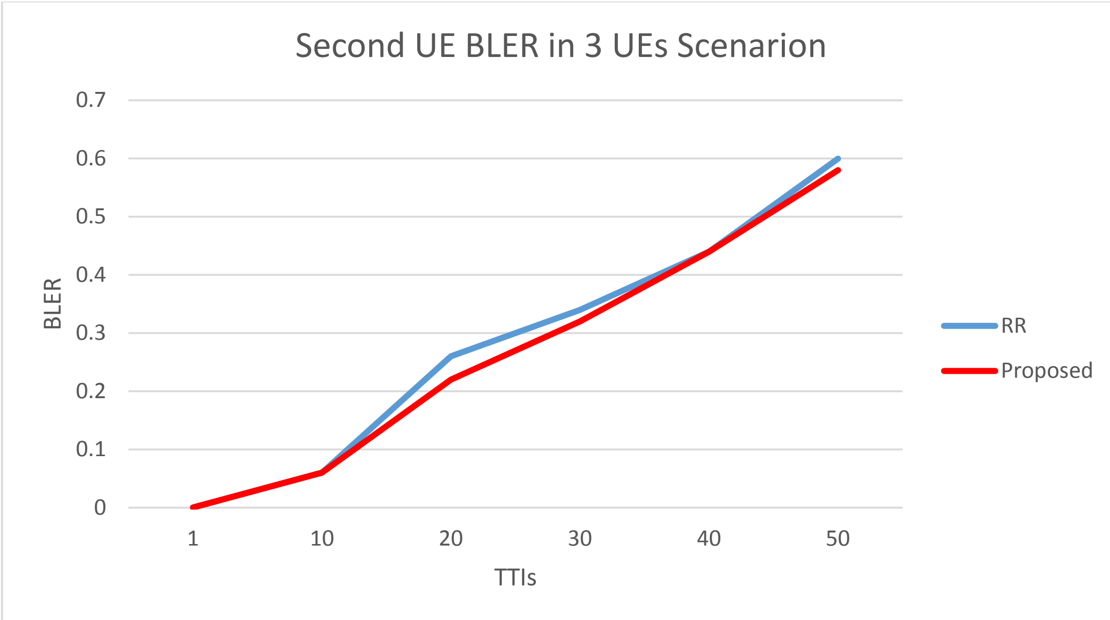

Figure 5.2 UE number 2 BLER in the 3 UEs scenario

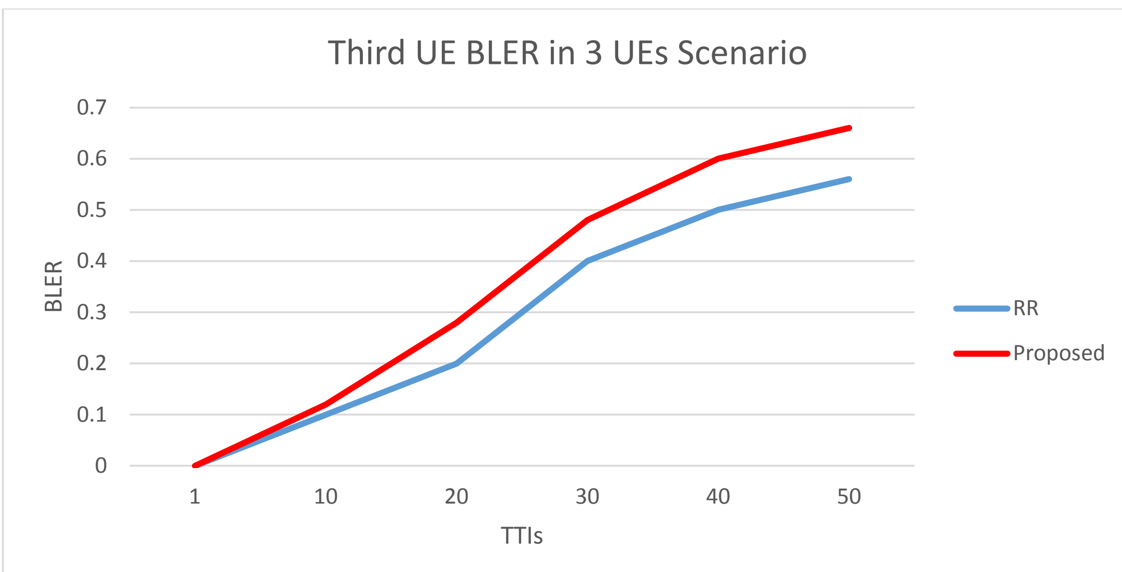

Figure 5.3 UE number 3 BLER in the 3 UEs scenario

From Figure 5.1 to Figure 5.3, the plots depict the BLER for the three attached UEs for both schedulers, the round robin algorithm and the proposed algorithm. The BLER in LTE is given as the following form:

$$BLER = \frac{erronous\ Blocks}{total\ of\ recieved\ Blocks} \qquad (5.1)$$

The BLER is measured after the data are extracted from the transport block specially after the decoding. The first two UEs were too close to each other, and as is shown in Figure 5.3, the third UE gains higher BLER in the proposed algorithm.

From Figure 5.4 to Figure 5.6, the gain throughput for the three UEs is depicted for both the round robin algorithm and the proposed algorithm. The throughput is given in Mbps.

In Figure 5.4, the first UE with the proposed algorithm gains throughput better than the first UE with RR. When we compare the three UEs with the proposed algorithm, we find that the first two UEs gain throughput better than the third UE because of the poor channel condition of the third UE. Also, through implementation of the proposed algorithm, the overall eNodeB throughput is increased and becomes higher than the throughput delivered by the round robin algorithm as shown in Figure 5.7.

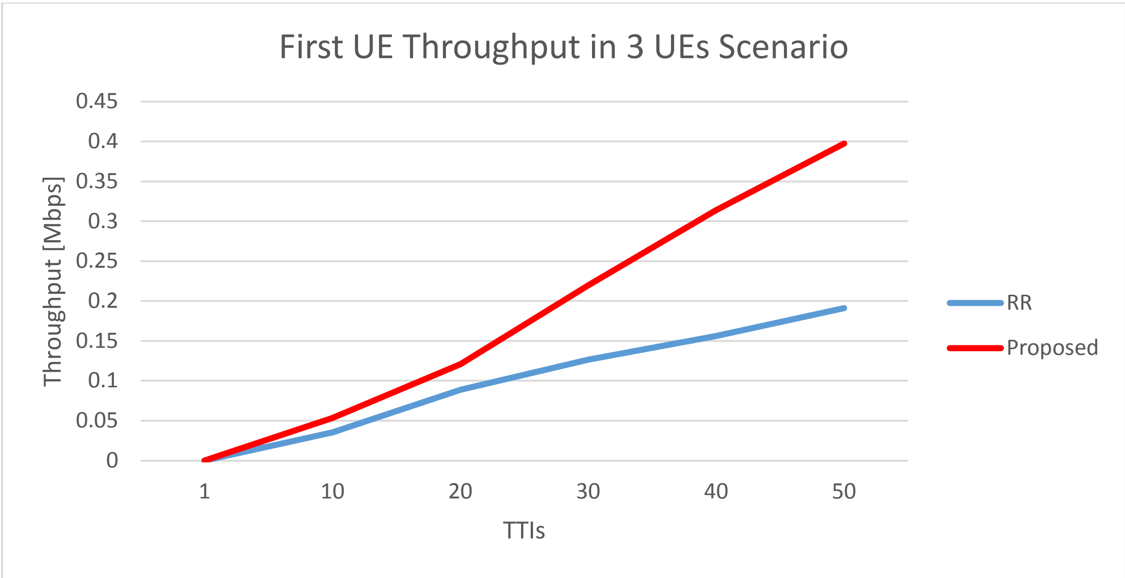

Figure 5.4 UE number 1 throughput in the 3 UEs scenario

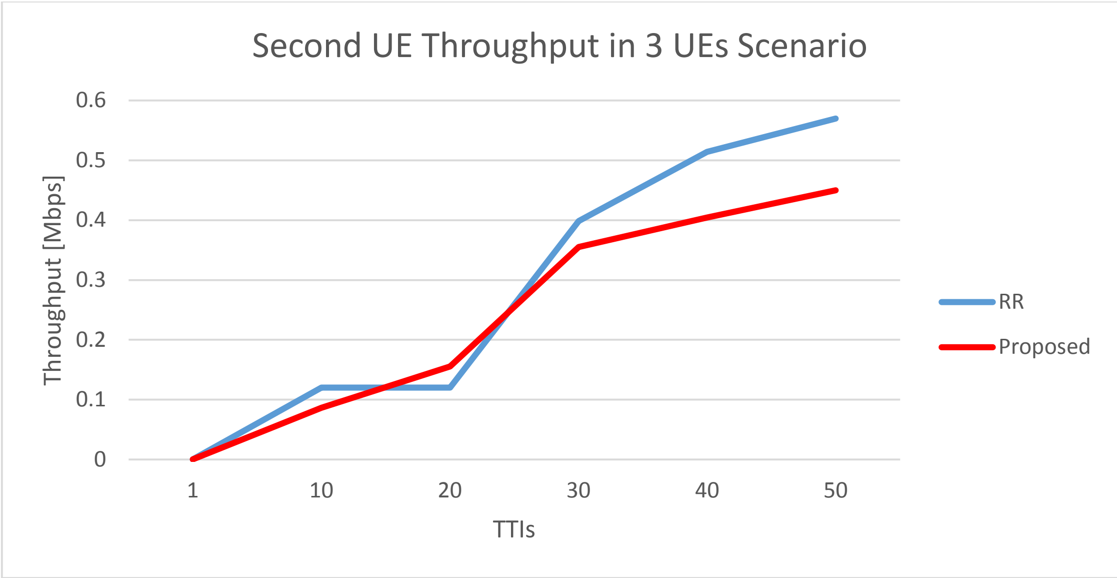

Figure 5.5 UE number 2 throughput in the 3 UEs scenario

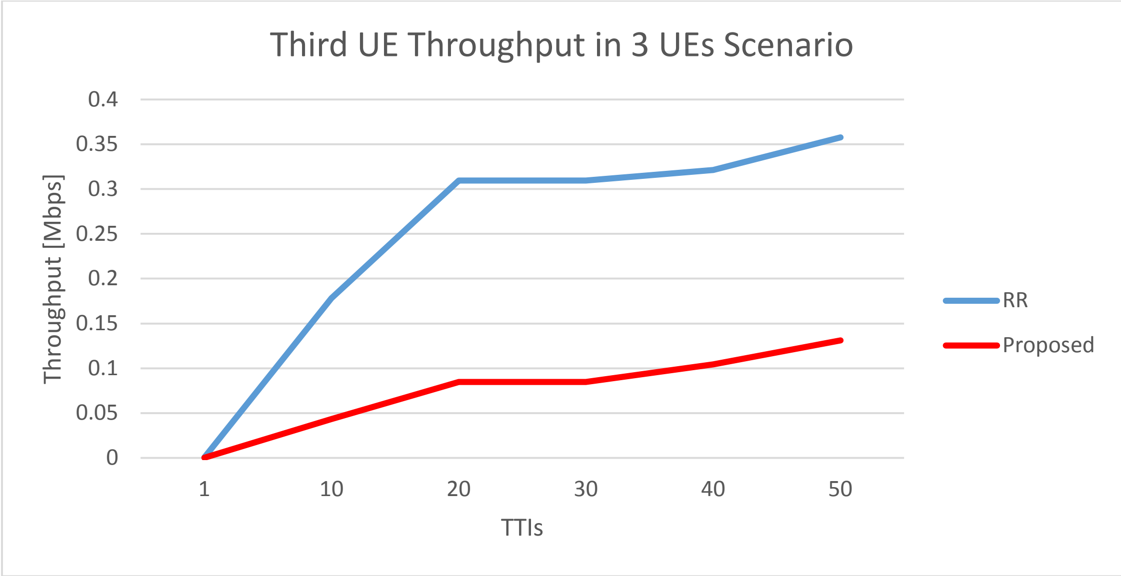

Figure 5.6 UE number 3 throughput in the 3 UEs scenario

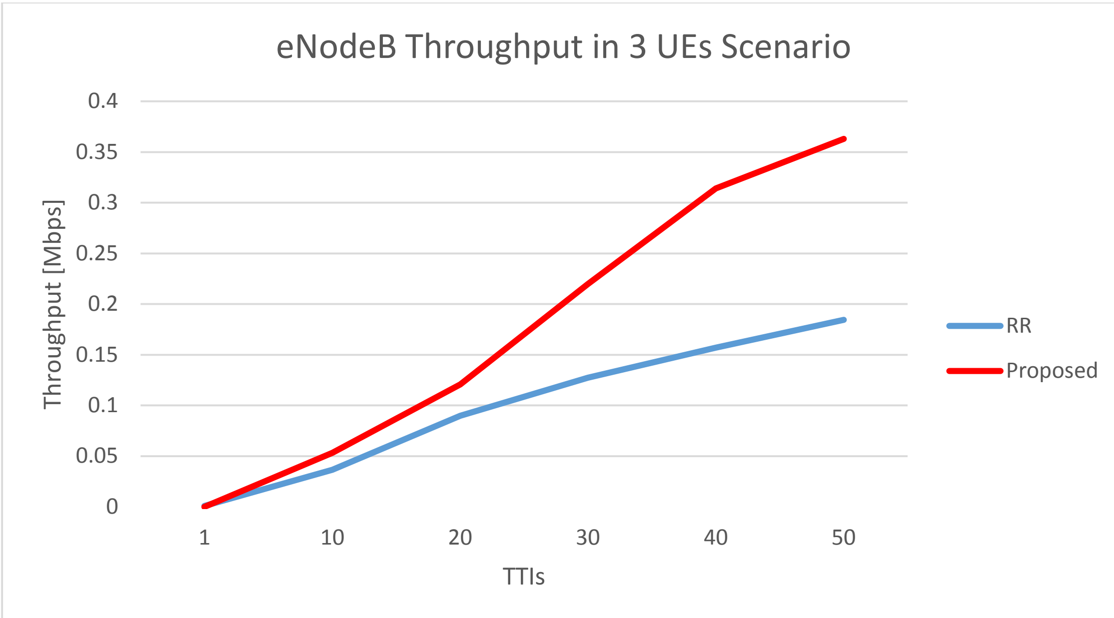

Figure 5.7 eNodeB throughput in the 3 UEs scenario

5.2 The Eight UEs Scenario

In this scenario, the number of UEs attached to the eNodeB is increased to eight in order to meet the second condition in the proposed algorithm (Number of UEs > Number of PRBs). First we show each UE BLER with both the round robin algorithm and the proposed algorithm. In the case of the proposed algorithm, the lowest BLER was for the fifth UE while the highest BLER was for the third UE, so we can observe the difference in the channel conditions between UE number five and UE number three. As shown in Figures 5.8 to figure 5.15, the UEs gain more BLER when the scheduler performed the RR Algorithm. When the round robin algorithm was implemented, the PRBs was assigned to all UEs and the channel conditions were not taken into account. As a result, the BLER increased for some UEs.

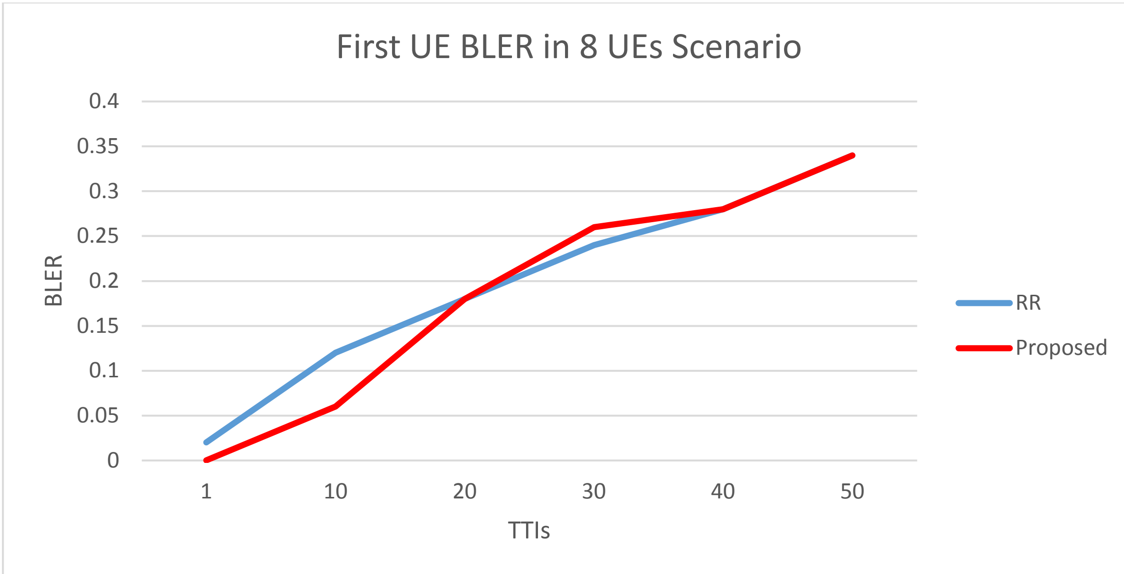

Figure 5.8 UE number 1 BLER in the 8 UEs scenario

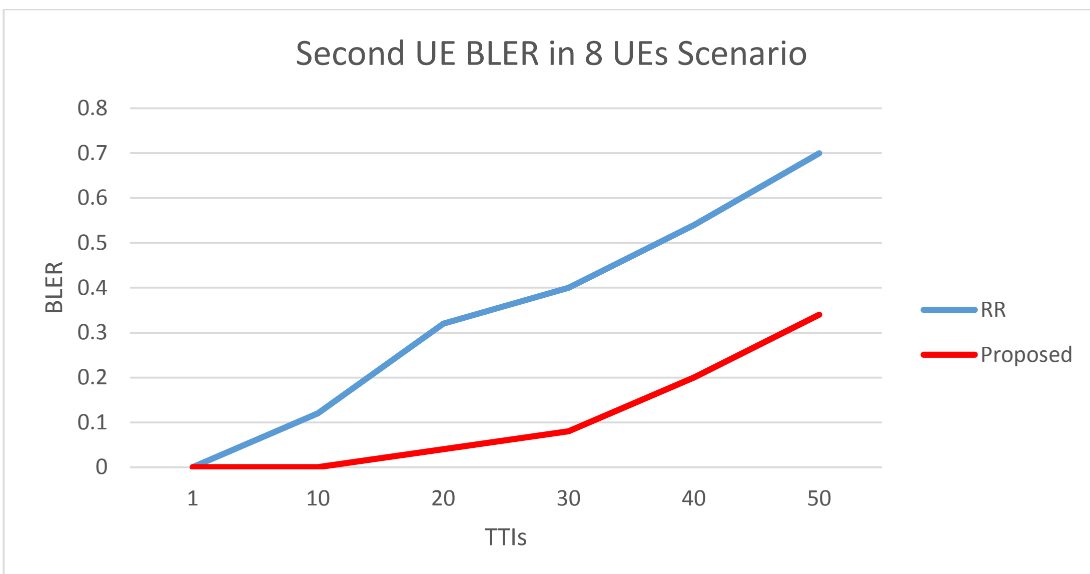

Figure 5.9 UE number 2 BLER in the 8 UEs scenario

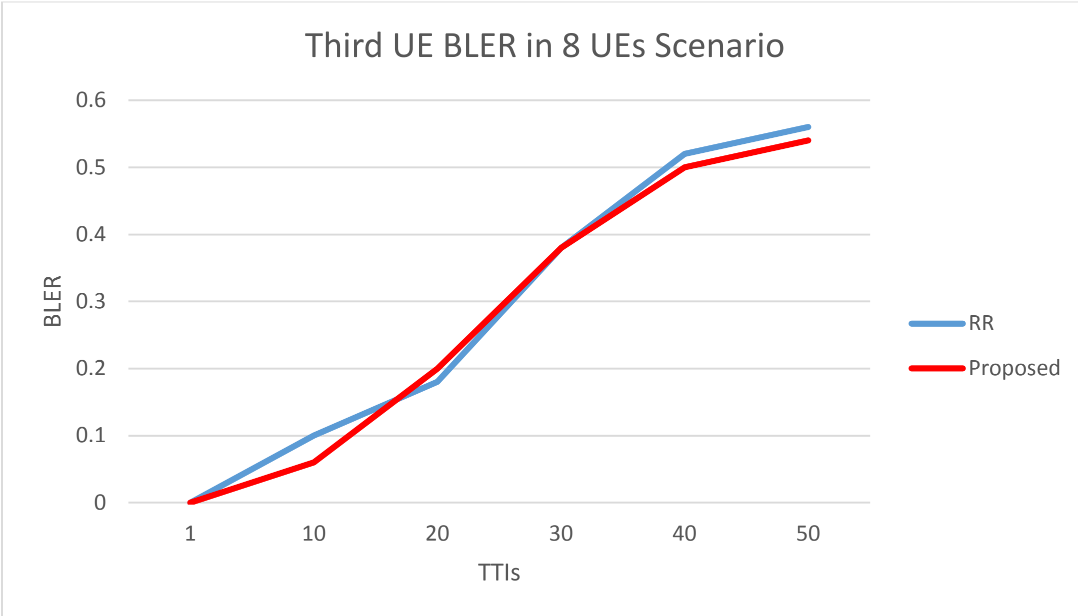

Figure 5.10 UE number 3 BLER in the 8 UEs scenario

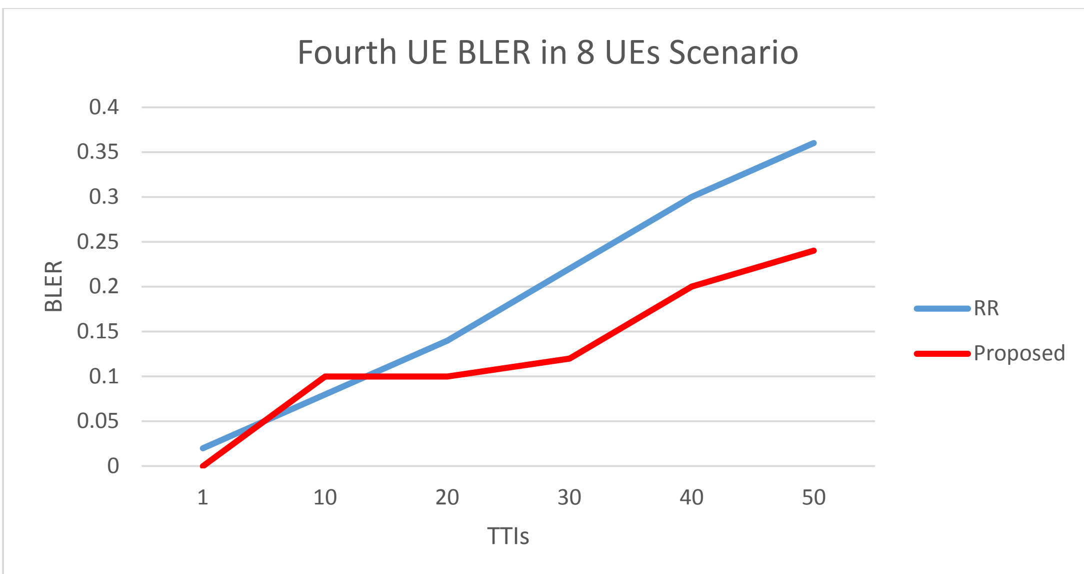

Figure 5.11 UE number 4 BLER in the 8 UEs scenario

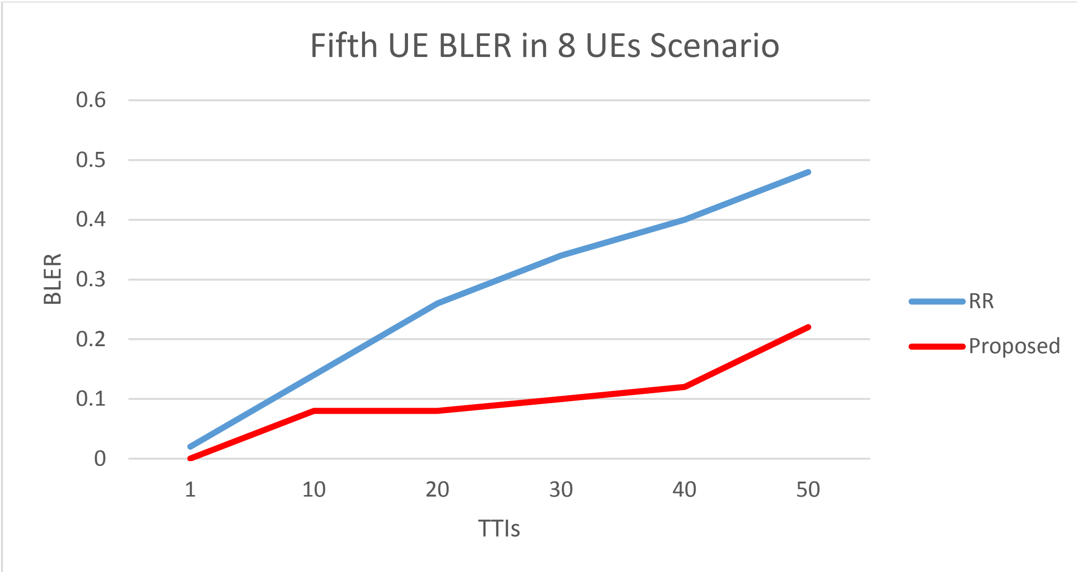

Figure 5.12 UE number 5 BLER in the 8 UEs scenario

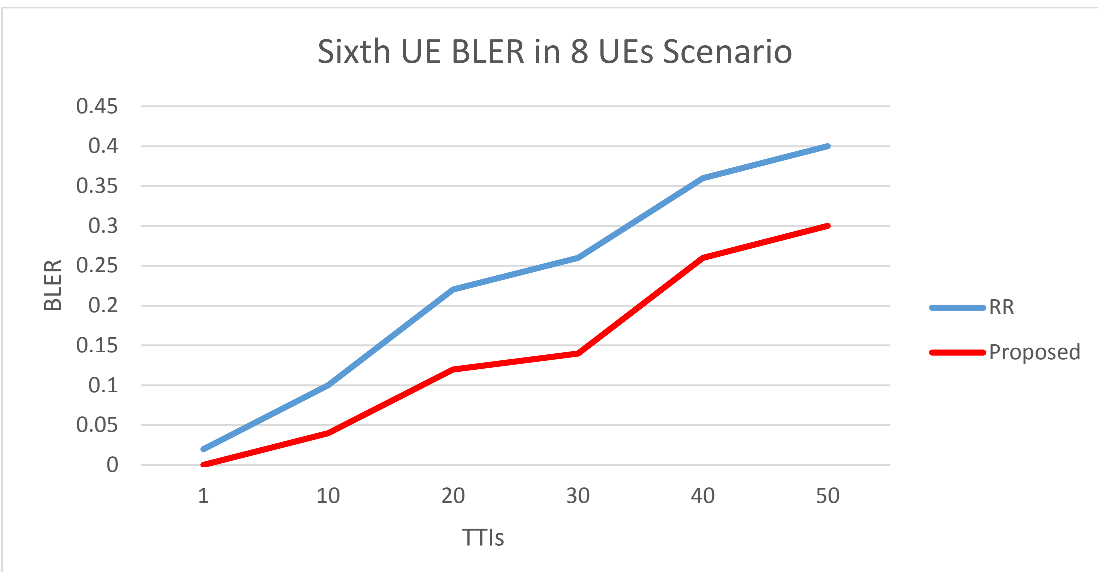

Figure 5.13 UE number 6 BLER in the 8 UEs scenario

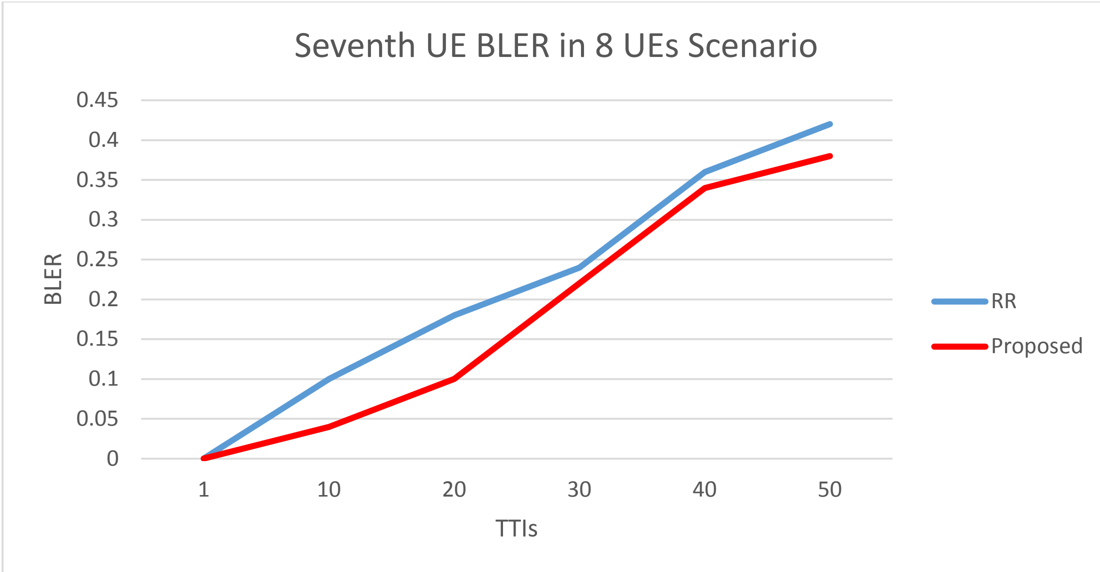

Figure 5.14 UE number 7 BLER in the 8 UEs scenario

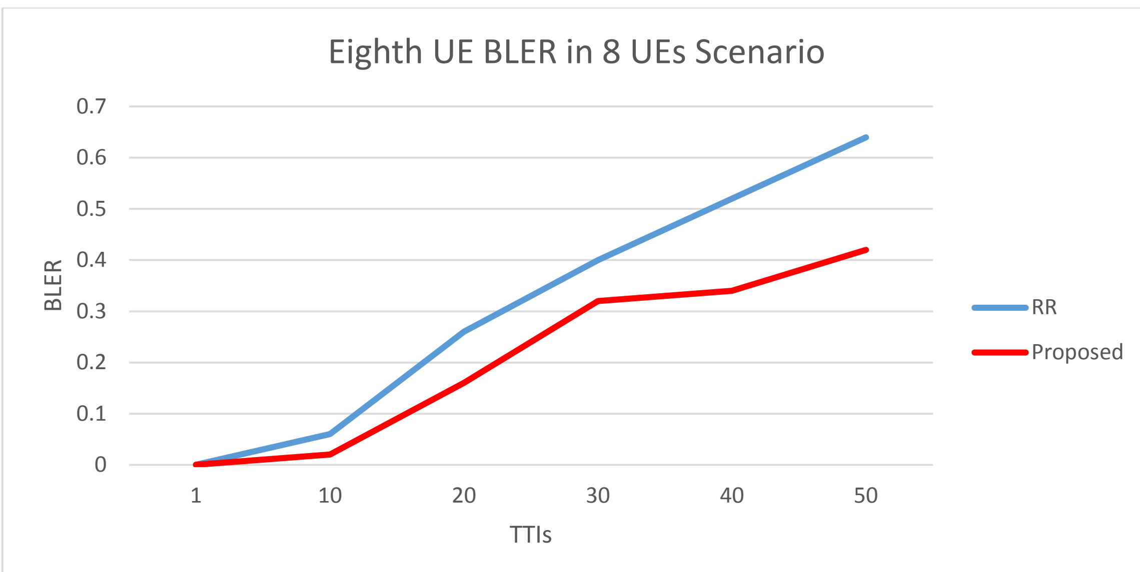

Figure 5.15 UE number 8 BLER in the 8 UEs scenario

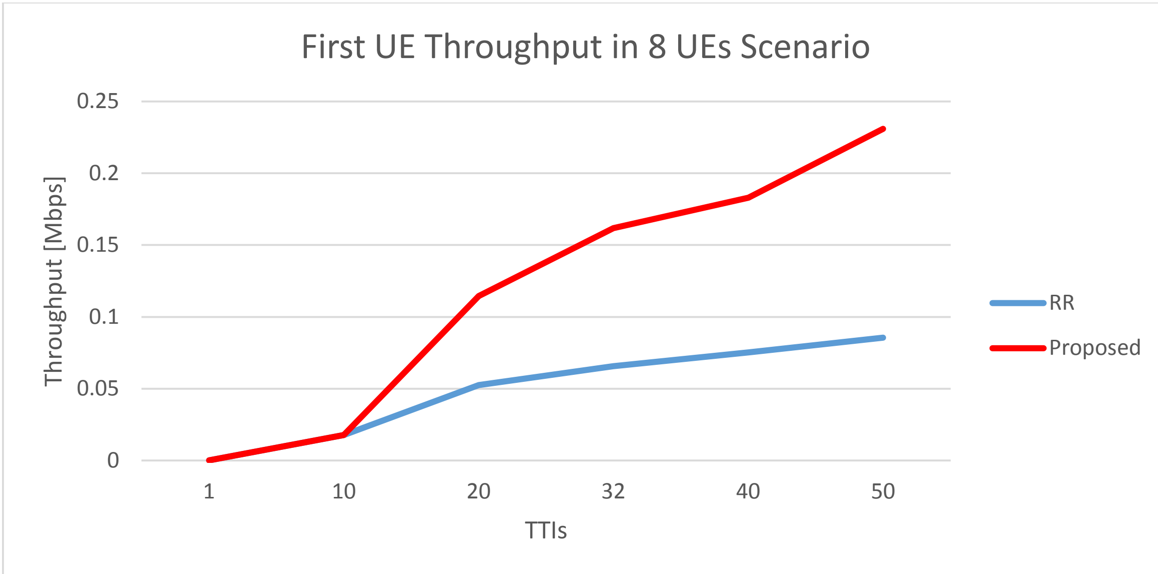

Figure 5.16 UE number 1 throughput in the 8 UEs scenario

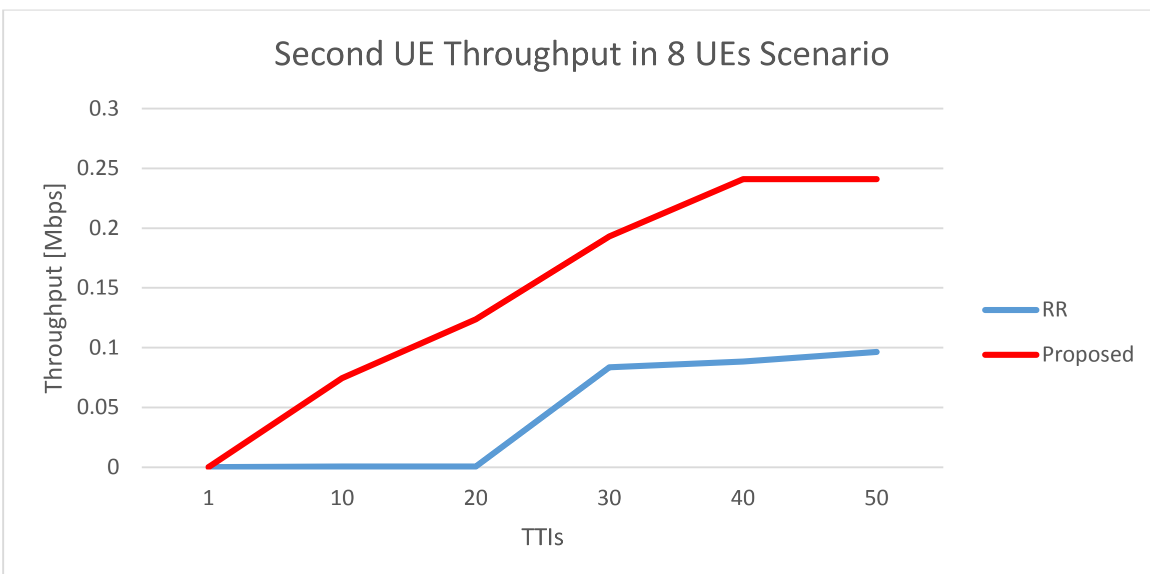

Figure 5.17 UE number 2 throughput in the 8 UEs scenario

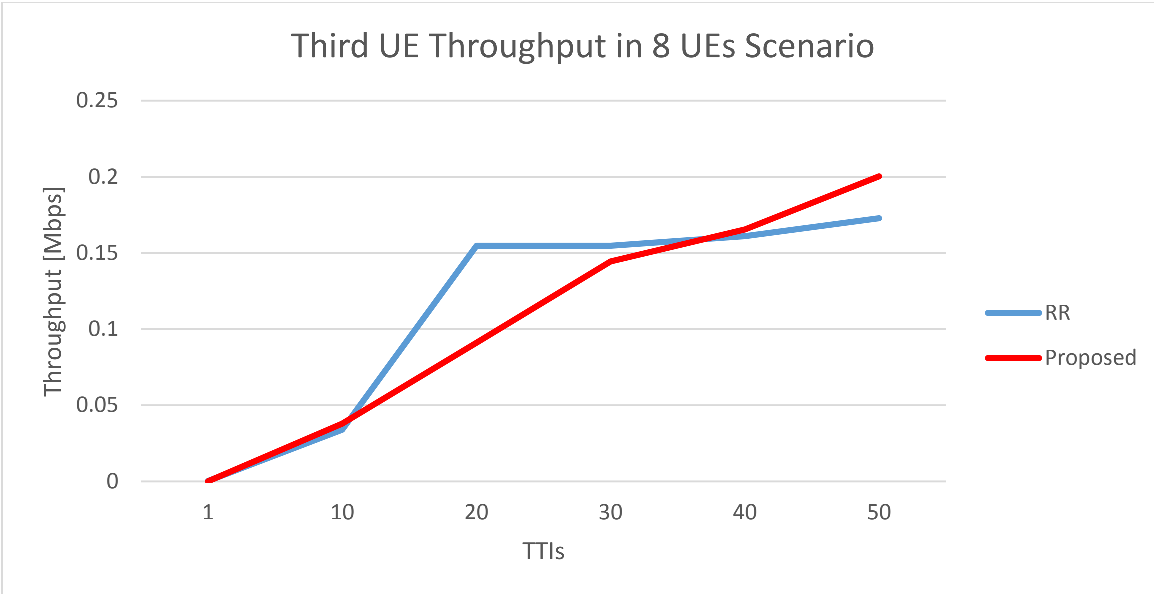

Figure 5.18 UE number 3 throughput in the 8 UEs scenario

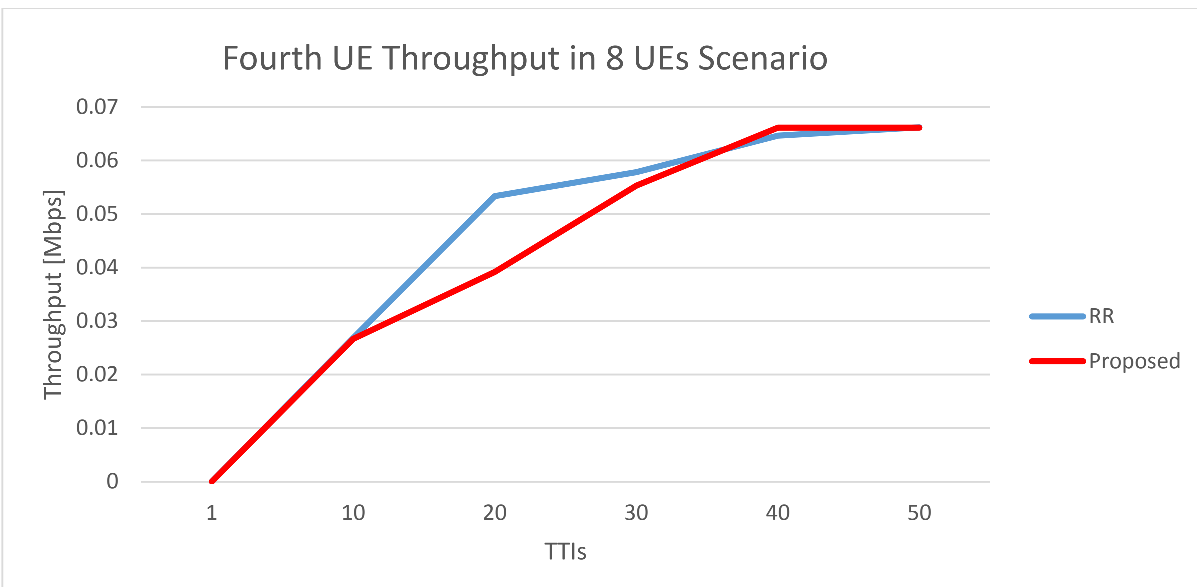

Figure 5.19 UE number 4 throughput in the 8 UEs scenario

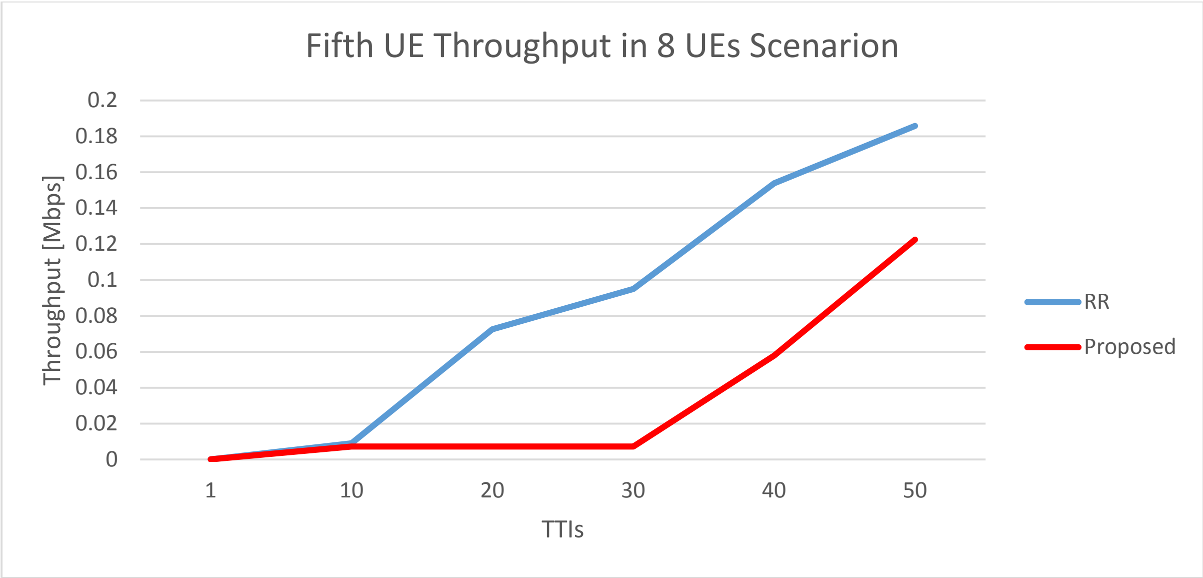

Figure 5.20 UE number 5 throughput in the 8 UEs scenario

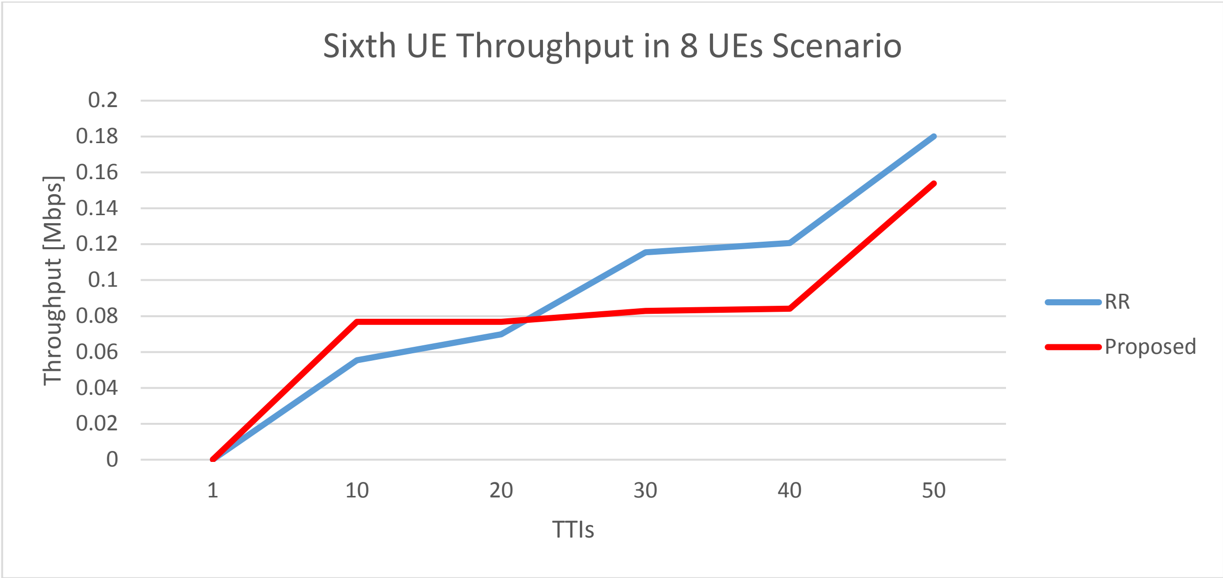

Figure 5.21 UE number 6 throughput in the 8 UEs scenario

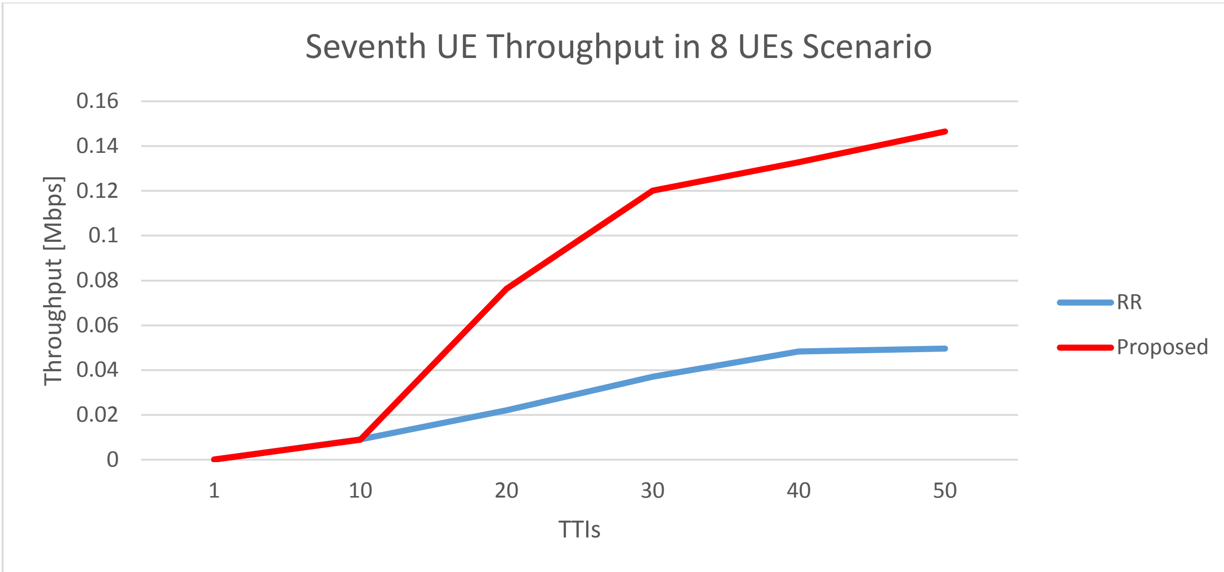

Figure 5.22 UE number 7 throughput in the 8 UEs scenario

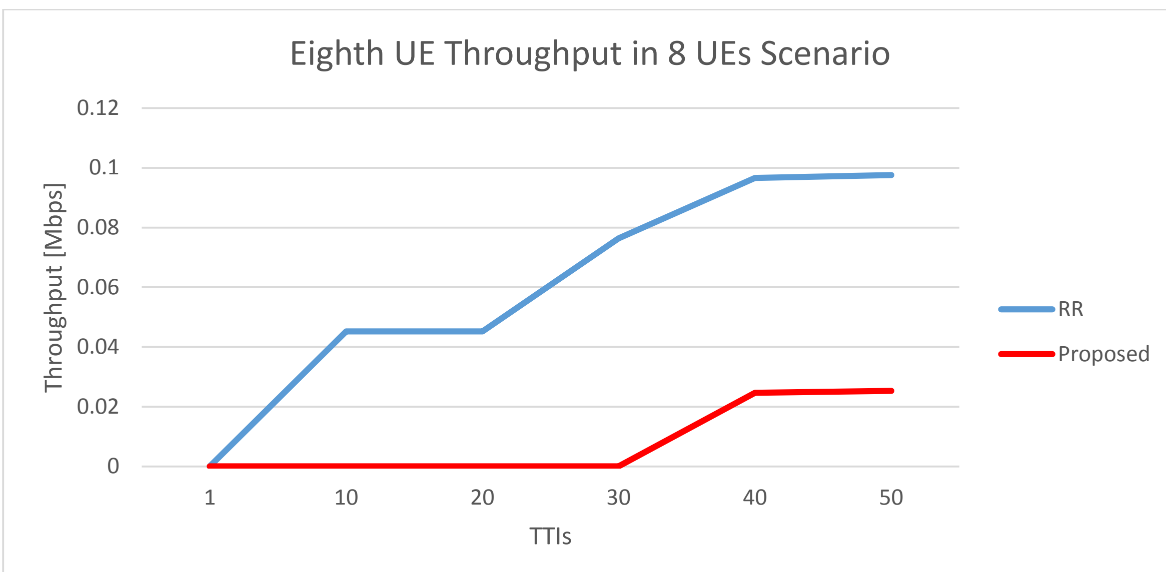

Figure 5.23 UE number 8 throughput in the 8 UEs scenario

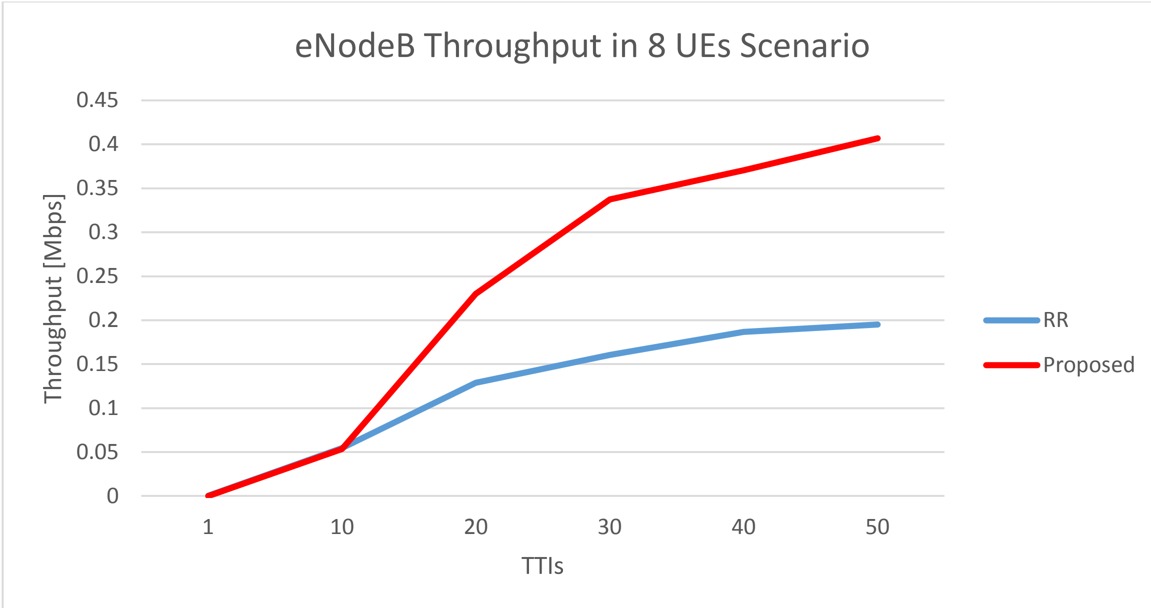

Figure 5.24 eNodeB throughput in the 8 UEs scenario

From Figure 5.16 to Figure 5.23, the throughput of the attached UEs is depicted. From the results above, we can observe that the first three UEs gained more throughput compared to the remaining five UEs.

Also, UEs number 5, 6, and 8 were not scheduled in some TTIs when proposed algorithm was implemented. The proposed algorithm assigned PRBs based on a given metric above, so PRBs were not assigned to some UEs because they did meet the minimum value of proportional fairness metric. Figure 5.23 depicts the throughput for UE number eight. This UE suffered from very poor channel condition, it was idle for a long time when proposed algorithm was implemented. Also, when the round robin Algorithm was implemented, the throughput of the same UE was low.

Figure 5.24 depicts the eNodeB throughput compared between the round robin algorithm and the proposed algorithm; the gap between them is quite long, and it can be observed. Also, the proposed algorithm delivered better throughput in 8 UEs scenario than 3 UEs scenario.

CHAPTER 6

CONCLUSION

The success of HSPA deployment has led to more enhanced mobile hardware and networks as well as the incorporation of Internet services. 3GPP has introduced LTE, which offers higher data rate networks with low cost, to deliver a competitive alternative in the future mobile market. High throughput, lower latency, and simple architecture are promised features accomplished in LTE.

The LTE architecture is an all-IP network. The significant elements in LTE are EPC and E-UTRAN and the number of nodes were diminished in order to reduce the complexity in the architecture. The EPC supports multi access networks and performs tasks such as security, policy management, and mobility management. The E-UTRAN consists of eNodeB which is the primary and unique component. The eNodeB is the termination point of the radio protocols for UEs. The packet scheduling is placed in eNodeB, so that gives eNodeB more signification. Most of the LTE protocols tasks are performed in eNodeB.

The LTE protocol architecture is formed in four layers: the physical layer, the PDCP layer, the RLC layer, and the MAC layer. In terms of the physical layer, OFDM has been chosen to be a downlink scheme, while SC-FDMA was chosen to be an uplink scheme due to the PAPR consideration. The OFDM/SC-FDMA frame consists of ten twenty sub-frame and each sub-frame consists of two slots each one is 0.5 millisecond long in time domain and 180 KHz in frequency domain, which constitutes the actual PRB. The PDCP layer performed functions such as encryption/decryption, integrity protection, and IP header compression/decompression. The

RLC layer is placed in between PDCP layer and MAC layer, so it coordinates the communication between PDCP layer and MAC layer. The most important function of MAC layer is to assign the PRBs among UEs. In addition, MAC layer is responsible for mapping among logical channels and physical channels.

The packet scheduler in LTE refers to the mechanism used to allocate the available PRBs among the UEs attached to eNodeB. The scheduler makes a decision every TTI period of time. The scheduler makes its decision according to given criteria. It might maximize the throughput or allocate PRBs fairly among the UEs, for example. In terms of uplink, before the packet scheduler makes its decision, the UE must interact with the eNodeB by sending a scheduling request. The designing of packet scheduler is broken into two phases. First utility function must be defined. Then the mechanism of allocating PRBs is designed according to the designing of the utility function.

We have proposed an algorithm for packet scheduling in LTE. The proposed algorithm is based on the number of the UEs attached to the eNodeB. It acts differently according to the number of UEs, so when the number of UEs is larger than the number of PRBs, it tends to allocate the PRBs to the UEs with fairness and with maximum possible throughput. However, when the number of UEs is low, the scheduler allocates the PRBs to the UE with the highest CQI.

The results were depicted in chapter 5, and the simulation was considered in two different scenarios. The proposed algorithm was compared with the round robin algorithm. Accordingly, the scheduler with the proposed algorithm could deliver reasonable overall throughput as compared to the round robin algorithm in both scenarios with a relative fairness in the second scenario. All UEs got a chance to be scheduled when round robin scheduler algorithm was implemented. However, the throughput of some UEs was very low due to the poor channel conditions. On another hand, some UEs did not get chance to be scheduled and styed idle when the proposed algorithm was implemented due to they did not meet the satisfying value of proportional fairness metric.

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