Efficient Resource Allocation Algorithms for 4G-LTE Networks

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A Dissertation submitted to

The Faculty of
The School of Engineering and Applied Science
of The George Washington University
in partial fulfillment of the requirements
for the degree of Doctor of Philosophy

May 20th 2018

Dissertation directed by

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The School of Engineering and Applied Science of The George Washington University certifies that Mahir Ayhan has passed the Final Examination for the degree of Doctor of Philosophy as of March 28th, 2018. This is the final and approved form of the dissertation.

**Efficient Resource Allocation Algorithms for 4G-LTE Networks**

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To my loved ones
Abstract

Efficient Resource Allocation Algorithms for 4G-LTE Networks

The growing demand for mobile applications, such as voice telephony, web browsing, interactive gaming and video streaming with delay and bandwidth requirements, poses new challenges in the design of the future generation cellular networks. As a response to this need, 3rd Generation Partnership Project (3GPP) introduced the Long Term Evolution (LTE) [1]. LTE defines all-IP architectures for the radio access and the core networks and aims at ambitious performance goals.

With radio resource management in LTE air interface being the focus this dissertation is divided into three parts. In the first part, a channel-aware scheduler is designed for commercial LTE networks in which fairness and system throughput challenges were addressed. The convergence proof of the algorithm and simulation results in terms of throughput, fairness, and delays are presented. The second part outlines the challenges of scheduling packets in LTE based public safety broadband networks (PSBNs), which are private networks with very strict performance constraints. The algorithm proposed in this section focuses on quality of service (QoS) and priority provisioning. Simulation results of different deployment scenarios are presented to support our claims. It is believed that, this is the first scheduler that considers all the QoS parameters, namely packet delay budget (PDB), packet error loss rate (PELR), guaranteed bit rate (GBR) and priority. It is also the first algorithm specifically designed for PSBN. In the third section, both a channel and QoS aware scheduler is
proposed, which is based on the algorithm described in the first part. The algorithm outperforms the state-of-art scheduler in terms of QoS provisioning.

The contributions of the research are QoS and priority provisioning and enhancement in fairness and spectral efficiency in the area of radio resource management. Key challenge is trade-offs between conflicting performance parameters. The proposed solutions are novel and results illustrate that they effectively contribute in addressing the challenges caused by high demand, QoS requirements, and channel conditions.
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<td>2G</td>
<td>Second Generation</td>
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<td>3G</td>
<td>Third Generation</td>
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<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
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<tr>
<td>AMC</td>
<td>Adaptive Modulation and Coding</td>
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<td>ARP</td>
<td>Admission and Retention Priority</td>
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<td>BestCQI</td>
<td>Best Channel Quality Indicator</td>
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<td>BII</td>
<td>Bearer Importance Index</td>
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<td>BLER</td>
<td>Block Error Ratio</td>
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<td>CA</td>
<td>Carrier Aggregation</td>
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<td>Code Division Multiple Access</td>
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<td>CP</td>
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<td>CQI</td>
<td>Channel Quality Indicator</td>
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<td>CqaPf</td>
<td>Channel and QoS Aware scheduler with PF metric</td>
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<tr>
<td>CTL</td>
<td>Communications Technology Laboratory</td>
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<td>Downlink Shared Channel</td>
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<td>DPS</td>
<td>Delay Prioritized Scheduler</td>
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<td>EPC</td>
<td>Evolved Packet Core</td>
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<td>EPS</td>
<td>Evolved Packet System</td>
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<td>E-UTRAN</td>
<td>Evolved UMTS Terrestrial Radio Access Network</td>
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<td>eNB</td>
<td>Evolved NodeB</td>
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<td>FAHT</td>
<td>Fair Allocation High Throughput</td>
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<td>FCC</td>
<td>Federal Communications Commission</td>
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<td>FDMA</td>
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<td>FDS</td>
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<td>FRs</td>
<td>First Responders</td>
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<td>GBR</td>
<td>Guaranteed Bit Rate</td>
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<td>GDR</td>
<td>Guaranteed Data Rate</td>
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<td>GSM</td>
<td>Global System of Mobile Communications</td>
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<td>HARQ</td>
<td>Hybrid Automatic Retransmission Request</td>
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<td>HOL</td>
<td>Head-of-Line</td>
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<td>IoT</td>
<td>Internet of Things</td>
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<td>IATs</td>
<td>Inter-arrival Time</td>
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<td>LMR</td>
<td>Land Mobile Radio</td>
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<td>LTE</td>
<td>Long Term Evolution</td>
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<td>MAC</td>
<td>Medium Access Control</td>
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<td>MCPTT</td>
<td>Mission Critical Push-to-Talk</td>
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<td>MCS</td>
<td>Modulation and Coding Scheme</td>
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<td>MIMO</td>
<td>Multiple Input Multiple Output</td>
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<td>MME</td>
<td>Mobility Management Entity</td>
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<td>MU-MIMO</td>
<td>Multiple Users Multiple Input Multiple Output</td>
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<td>NIST</td>
<td>National Institute of Standards and Technology</td>
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<td>NPSBN</td>
<td>National Public Safety Broadband Network</td>
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<td>NPSTC</td>
<td>National Public Safety Telecommunications Council</td>
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<tr>
<td>ODE</td>
<td>Ordinary Differential Equation</td>
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<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Access</td>
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<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
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<td>PCC</td>
<td>Policy and Charging Control</td>
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<td>PCEF</td>
<td>Policy and Charging Enforcement Function</td>
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<td>Acronym</td>
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<td>PCRF</td>
<td>Policy and Charging Rules Function</td>
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<td>PDB</td>
<td>Packet Delay Budget</td>
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<td>PDSCH</td>
<td>Physical Downlink Shared Channel</td>
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<td>PDCCH</td>
<td>Physical Downlink Control Channel</td>
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<td>PDN</td>
<td>Packet Data Network</td>
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<td>Ped-B</td>
<td>Pedestrian-B</td>
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<td>PELR</td>
<td>Packet Error Loss Rate</td>
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<td>PF</td>
<td>Proportional Fair</td>
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<td>PFS</td>
<td>Proportional Fair Sharing</td>
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<td>P-GW</td>
<td>Packet Data Network Gateway</td>
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<td>PHY</td>
<td>Physical Layer</td>
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<td>PQA</td>
<td>Priority and QoS Aware</td>
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<td>PS</td>
<td>Public Safety</td>
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<td>PSBNs</td>
<td>Public Safety Broadband Networks</td>
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<tr>
<td>QCI</td>
<td>QoS Class Identifier</td>
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<td>QFAHT</td>
<td>Qos-Aware Fair Allocation High Throughput</td>
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<td>QoS</td>
<td>Quality of Service</td>
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<td>Description</td>
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<td>QPF</td>
<td>QoS-Aware PF</td>
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<td>RBs</td>
<td>Resource Blocks</td>
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<td>RE</td>
<td>Resource Element</td>
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<td>RLC</td>
<td>Radio Link Control</td>
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<td>RR</td>
<td>Round Robin</td>
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<td>RRM</td>
<td>Radio Resource Management</td>
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<tr>
<td>RT</td>
<td>Remaining Time</td>
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<td>SAE</td>
<td>System Architecture Evolution</td>
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<td>S-GW</td>
<td>Serving Gateway</td>
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<tr>
<td>SNR</td>
<td>Signal-To-Noise-Ratio</td>
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<tr>
<td>TB</td>
<td>Transport Block</td>
</tr>
<tr>
<td>TBR</td>
<td>Target Bit Rate</td>
</tr>
<tr>
<td>TCP</td>
<td>Transmission Control Protocol</td>
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<tr>
<td>TDMA</td>
<td>Time-Division Multiple Access</td>
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<td>TD-PSS</td>
<td>Time Domain Priority Set Scheduler</td>
</tr>
<tr>
<td>TDS</td>
<td>Time Domain Scheduler</td>
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<tr>
<td>TFTs</td>
<td>Traffic Flow Templates</td>
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<td>Abbreviation</td>
<td>Description</td>
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<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Uplink</td>
</tr>
<tr>
<td>WCDMA</td>
<td>Wideband Code Division Multiple Access</td>
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</table>
Chapter 1 - Introduction and Motivation

LTE has been adopted faster than any previous mobile technology generation. With 2.54 billion LTE subscribers globally and over 600 commercially launched LTE networks in 192 countries as of October 2017, LTE has been the most successful wireless network both commercially and technologically \[8\]. It has even been chosen as the future mobile broadband radio technology for public safety networks by authorities in U.S. and Europe. Consequently, the amount of mobile traffic worldwide has increased dramatically, and it is expected to grow even further. The design of competent resource allocation scheme is essential to meet the system performance targets and to satisfy user needs according to specific Quality of Service (QoS) requirements such as packet delay budget (PDB), packet error loss rate (PELR), and minimum data rate \[9\]. For these reasons, both research and industrial communities are making a considerable effort on the study of packet scheduling in the air interface of LTE, proposing new and innovative solutions in order to analyze and improve its performance.

LTE access network, based on Orthogonal Frequency Division Multiple Access (OFDMA), is expected to support a wide range of multimedia and Internet services such as voice, video, interactive gaming, and file transfer, etc. even in high mobility scenarios. It has been designed to provide higher data rates, lower latency, and improved spectral efficiency in comparison with previous generations. To achieve these goals, some Radio Resource Management (RRM) features such as, Channel Quality Indicator (CQI) reporting, link adaptation through Adaptive Modulation and Coding (AMC), and Hybrid Automatic Retransmission Request (HARQ), are utilized. QoS
and channel-aware solutions are more suited for OFDMA because they exploit channel quality variations by assigning higher priority to users experiencing better channel conditions and being aware of application needs. Solutions for packet scheduling in wireless network are in a mature stage as surveyed in [9]. Main problems with scheduling have been identified. The key design challenges of packet scheduling algorithms are feasibility of the solution, QoS provisioning, fairness and spectral efficiency which we will describe in details in the next chapter. In addition, practical limitations such as limited radio resources, the time-varying channel conditions, energy consumption and growing demand add up to the challenge.

The thesis introduces three novel packet scheduling algorithms: One for commercial LTE networks and one for LTE based PSBNs and one for both.
The 3\textsuperscript{rd} Generation Partnership Project (3GPP) initiated Long-Term Evolution (LTE) project as successor for Universal Mobile Telecommunications System (UMTS) and introduced it first in Release 8 \[1\] in 2008. The objectives were peak data rate, lower latency and other improvements \[10\]. These enhancements necessitate fundamental changes in the system architecture. The core network, which is called System architecture evolution (SAE), and the radio access network, which is called LTE, and mobile were designed as part of the work. Although, LTE refers only to the evolution of the air interface, official name for this new network is the evolved packet system (EPS). The term LTE is used when referring to the whole system throughout the dissertation. Figure 2.1 shows the overall network architecture of EPS. There are three main components, namely the user equipment (UE), the evolved UMTS terrestrial radio access network (E-UTRAN) and the evolved packet core (EPC). While the EPC consists of many logical nodes, the E-UTRAN is made up of just one node, the evolved Node B (eNB), which connects to the UEs. Figure 2.2 shows the functional split between E-UTRAN and EPC. Some of these functions will be covered next.

2.1 The Radio Access Network

The access of network of LTE, E-UTRAN, is just comprised of networks of eNBs, and it manages radio resource management and security of the data sent over the air interface.
2.2 The Evolved Packet Core

The EPC consists of many components and is responsible for the overall control of the bearer establishment. Bearers can be considered as bi-directional pipe, which carries information between the UE and the packet data network (PDN) gateway (P-GW) [10]. Some of the logical nodes of EPC and their functions are:

**Policy and Charging Rules Function (PCRF)** provides policy and charging control (PCC) rules (QoS identifier and bit rates) to P-GW for service data flows
either by referring to pre-defined rules or by composing one dynamically.

**P-GW** is the gate to outside world. Through SGi interface P-GW exchanges data with external servers and the Internet. The P-GW is responsible for IP address allocation for the UE and filtering of downlink user IP packets into different bearers. Filtering packets into different bearers is done based on downlink Traffic Flow Templates (TFTs). The TFTs use packet’s source and destination IP addresses and Transmission Control Protocol (TCP) port numbers to filter packets such as VoIP from file transfer traffic so that each can be transmitted with bearers equipped with appropriate QoS. QoS enforcement is also P-GW’s task. The policy and charging enforcement function (PCEF), which resides in P-GW, implements PCC rules obtained from PCRF.

**Serving Gateway (S-GW)** routes and forwards data between the eNB and P-GW. It also buffers downlink data temporarily while the mobility management entity (MME) starts paging of the UE to re-initiate the bearers.

**MME** processes signaling messages such as security and the management of data streams that are unrelated to radio communications between the UE and the EPC. It is responsible for idle mode UE paging and involved in the bearer activation/deactivation process.

### 2.3 Access Technologies in Wireless Mobile Networks

Various radio access technologies have been developed to enhance the resource allocation performance in mobile networks since wireless communication have entered our lives. Figure 2.3 shows access technologies used in different generations [2].
In Frequency-Division Multiple Access (FDMA), multiple users access sub-channels of frequency spectrum without significant interference from other users concurrently operating in the system. Yet, Time-Division Multiple Access (TDMA) divides the time axis into time slots and at each time slot a single user transmits data over the whole spectrum. Figure 2.4 and 2.5 show the FDMA and TDMA technologies respectively.

The second generation (2G), Global System of Mobile Communications (GSM), initiated in 1980s and it uses digital communication technique. GSM was the first fully specified system with international compatibility and transparency and that made the most commercially successful 2G system [11]. The GSM system applies TDMA. In TDMA, signals for different users are transmitted in the same frequency band at different times [12].

Increasing demand for higher data rates pave the way for developing the third Generation (3G) systems. 3G mobile cellular networks adopted Code Division Multiple Access (CDMA) (fig. 2.6) as the radio access technology [13]. In 1998, 3GPP
began to outline the specifications of the UMTS with a new air interface, Wideband Code Division Multiple Access (WCDMA), for 3G networks [14]. WCDMA allows a very flexible use of the available spectrum because of advanced power control and link adaptation techniques and UTRAN.

In CDMA, signals for different users are transmitted in the same frequency band
at the same time but using different codes. As all signals are transmitted at the same time and on the same band so the capacity is mainly constrained by the interference between signals of different users.

2.4 Orthogonal Frequency Division Multiplexing Access in LTE

The LTE air interface is based on OFDMA technology in the downlink. OFMDA is essentially the same as FDMA, but it has some advantages not included in FDMA. LTE selects OFDM for following reasons: robustness to the multipath fading channel, high spectral efficiency, low-complexity implementation, and the ability to provide flexible transmission bandwidths and support advanced features such as frequency-selective scheduling and Multiple Input Multiple Output (MIMO) transmission \textsuperscript{[3]}. Understanding of LTE transmission requires a good understanding of the time–frequency representation of data and how it maps data to what is known as the resource grid. In the time domain, LTE organizes the transmission as a sequence of radio frames
of length 10 ms. Each frame is divided into 10 subframes of length 1 ms and each subframe is composed of two slots of length 0.5 ms each. Finally, each slot consists of a number of OFDM symbols, either seven or six depending on the type of cyclic prefix is used. Fig 2.7 shows LTE time-domain structure when normal cycle prefix (CP) is used.

Figure 2.7: OFDM time domain structure. Source [3].

### 2.5 Time-Frequency Representation

The resource grid has time on the x-axis and frequency on the y-axis. Figure 2.8 illustrates the LTE downlink resource grid when a normal cyclic prefix (CP) is used.
A resource element is placed at the intersection of an OFDM symbol and a sub-carrier. A resource block is made of 12 sub-carriers in the frequency-domain and one 0.5 ms slot in the time domain. In the case of a normal CP where there are seven OFDM symbols per slot, each resource block contains 84 resource elements. In the case of an extended cyclic prefix, where there are six OFDM symbols per slot, the resource block is consist of 72 resource elements. Resource block (RB) represents the smallest unit of transmission. The sub-carrier spacing is 15 kHz and this in turn helps the OFDM to efficiently combat frequency-selective fading [3].

### 2.6 Resource Grid Content

Each resource element carries either modulated symbol of user data or a reference signal or control information. Figure 2.9 shows the relative locations of these symbols in a resource grid as defined for a unicast mode of operation.

In unicast mode the user data bear the information that each user wants to transmit and are carried from the Medium Access Control (MAC) layer to physical layer (PHY) as a transport block. Reference signals are used for channel estimation, channel measurement, and synchronization. Control data carry information that receiver requires for correct signal decoding.

### 2.7 EPS Bearers and Quality of Service

LTE transports data between different elements of E-UTRAN and EPC via bearers. Bearers have specific QoS requirements. The QoS defines how the data will be treated in terms of data rate, error rate, and delay. EPS bearer can carry one or more service
Figure 2.8: Resource grid, blocks, and elements

data flows [10]. IP packets that are mapped to the same EPS bearer receive the same bearer-level packet forwarding treatment (e.g. scheduling policy, queue management policy). There two types of EPS bearers; dedicated bearers and default bearers.

A dedicated bearer can be either a GBR type bearer or non-GBR (NGBR) type whereas no default EPS bearer can be GBR type. A GBR bearer is associated with a minimum bit rate, which is an average data rate that the mobile can expect to
receive. GBR bearers are suitable for real-time services such as voice and video.

A non-GBR bearer does not receive any minimum bit rate guarantee, so is suitable for non real-time services such as web browsing. UE receives one default bearer as soon as it registers with the EPC to provide UE with always-on IP connectivity to a default PDN such as the internet [4]. At the same time, the UE receives an IP address for it to use when communicating with that network. Later on, each time UE connects to other PDNs, it receives an additional default bearer for every network that it connects to, along with an additional IP address.

After establishing a default bearer, an UE can receive one or more dedicated
bearers that connect it to the same PDN. No new IP addresses are allocated for
dedicated bearers; instead, each dedicated bearer shares the same IP address with its
parent default bearer. A mobile can have a maximum of 11 EPS bearers [15]. The
EPS bearer has to cross multiple interfaces as shown in Figure 2.10. It is broken down
into three lower-level bearers: the S5/S8 interface from the P-GW to the S-GW, the
S1 interface from the S-GW to the eNB, and the radio interface from the eNB to the
UE.

Figure 2.10: LTE bearers across the different interfaces. Source [4].

Across each interface, the EPS bearer is mapped onto a lower layer bearer, each with
its own bearer identity. Each of these is also associated with a set of QoS parameters.
The overall EPS bearer service architecture is shown in 2.11.

The 3GPP has studied the needs of applications on LTE and identified their
attributes in [7]. Standardized combinations of these characteristics are called QoS
Class identifiers (QCIs). It is a scalar that acts as a pointer into a look-up table (Table
2.1) which describes four other quantities — bearer type, priority, packet delay budget
Figure 2.11: The overall EPS bearer service architecture. Source [4].

(PDB) and packet error loss rate (PELR). The PELR is an upper bound for a rate of non-congestion related packets losses. The PDB defines an upper bound, with 98% confidence, for the time that a packet may be delayed between the UE and the P-GW. Priority determines when packets should be sent to or received from the UEs [6] and is handled in the access network by eNB. High priorities are associated with low numbers. A QCI assigned to an application’s bearer may or may not be changed afterward. These values should be considered by any scheduler that aims to provide QoS. In the E-UTRAN, it is the eNB’s responsibility to ensure that the necessary QoS for a bearer over the air interface is met. The QCI label for a bearer determines the way it is handled in the eNB. For example, a packet with a higher priority can be expected to be scheduled before a packet with lower priority [10].

Figure 2.12 illustrates the basic operation of a MAC Scheduler in the downlink direction [5]. Data for multiple services is queued in the Radio Link Control (RLC) sub-layer and the MAC Scheduler receives buffer status updates as new data arrives.
Table 2.1: Standardized QCI Characteristics. Source [7]

<table>
<thead>
<tr>
<th>QCI</th>
<th>Bearer Type</th>
<th>Priority</th>
<th>PDB (ms)</th>
<th>PELR</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td></td>
<td>2</td>
<td>100</td>
<td>10^{-2}</td>
</tr>
<tr>
<td>2</td>
<td></td>
<td>4</td>
<td>150</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>3</td>
<td>GBR</td>
<td>3</td>
<td>50</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>4</td>
<td></td>
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</tr>
<tr>
<td>5</td>
<td></td>
<td>1</td>
<td>100</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>6</td>
<td></td>
<td>6</td>
<td>300</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>7</td>
<td>NGBR</td>
<td>7</td>
<td>100</td>
<td>10^{-3}</td>
</tr>
<tr>
<td>8</td>
<td></td>
<td>8</td>
<td>300</td>
<td>10^{-6}</td>
</tr>
<tr>
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<td></td>
<td>9</td>
<td>300</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>69</td>
<td></td>
<td>0.5</td>
<td>60</td>
<td>10^{-6}</td>
</tr>
<tr>
<td>70</td>
<td></td>
<td>5.5</td>
<td>200</td>
<td>10^{-6}</td>
</tr>
</tbody>
</table>

The MAC Scheduler determines the downlink allocation of the radio resource for each sub-frame. These allocations are signalled to the MAC sub-layer which constructs the UE specific Transport Block (TB). Each TB contains data from one or more service classes.

2.8 Key Scheduler Design Aspects

The OFDMA enables flexible channel-dependent multi-user resource allocation in both the frequency and time domains. The eNB in an LTE system is responsible for managing resource scheduling for both uplink and downlink channels. The scheduler in the eNB distributes the available radio resources in one cell among the radio bearers of each UE. The details of the scheduling algorithm are left to the eNB implementation. The goal of a resource scheduling algorithm is to allocate the RBs for each subframe in order to optimize a set of performance metrics, for example achieving...
spectral efficiency, QoS or fairness among UEs.

Differences among resource allocation schedulers are mainly based on the trade-off between performance metrics. A list of the key design issues that should be considered before defining an allocation policy for LTE presented in [9]

1) **Complexity:** Packet scheduler works with a time granularity of 1 ms: Allocation decisions has to be made every $ms$. Quest for the best allocation through an exhaustive research over all the possible combinations would be computationally too expensive [16]. Therefore low complexity is a key requirement for limiting processing time and memory usage.
2) **System spectral efficiency:** Effective use of radio resources is one of the main goals. One of the efficiency indicators is system throughput that is the actual data transmission in the cell per second. System throughput can be enhanced by by scheduling users experiencing favorable channel conditions.

3) **Fairness among users:** Maximizing the overall cell throughput surely enables effective channel utilization in terms of spectral efficiency, but causes unfair share of radio resource among users. Fairness is therefore another key requirement that should be considered to guarantee certain performance also to the users experiencing unfavorable channel conditions.

4) **QoS Provision:** As previously mentioned, bearers have specific QoS requirements. Applications associated with bearers must be delivered to the end user at specific data rates, packet loss ratio, and delay bounds. Thus, it is important to make sure QoS requirements are satisfied.

In this dissertation, the most commonly used performance metrics are adopted to validate the effectiveness of the proposed scheduling architecture. They include QoS, system throughput and fairness.

### 2.9 Related Works

There are five scheduling strategies: (i) channel-unaware; (ii) channel-aware/QoS-unaware; (iii) channel and QoS-aware; (iv) semi-persistent for VoIP support; and (v) energy-aware [9]. Schedulers that are designed for LTE may focus on one or combine more of these strategies. Round Robin (RR) is the most known channel-unaware scheduler. Resources are allocated to bearers in order. Therefore, it provides
fairness in terms resource distribution, yet it is not an efficient scheduler in terms of throughput since it does not consider channel quality.

Works in [17], [18], [19], [20], [21], [22], [23] and [24] represent channel-aware/QoS-unaware schedulers. Best Channel Quality Indicator (BestCQI) [19] favors UEs with the largest CQI values to maximize system throughput; however, it starves UEs with unfavorable channel conditions [17]. Proportional Fair (PF) Scheduler [18] selects bearers with highest ratio of current throughput to average transmitted throughput. PF delivers reasonable overall cell throughput as well as fairness between bearers. It delivers reasonable overall cell throughput as well as fairness between bearers. PF algorithm was devised for single Channel CDMA/HDR system. Later, authors in [4] have proven that PF can be utilized in multi-carrier systems. When there is a single carrier whose channel state information (CSI) is computed reliably, PF is expected to perform well; however, in typical LTE system where subcarriers’ CQIs are not reported precisely, PF performance degrades [17]. Kushner et al. [11] have shown that UEs’ mean throughput converges to a solution of an ordinary differential equation (ODE) in PF. Many algorithms that consider fairness are either extensions or modifications of PF or in some cases PF is the part of the process. Generalized PF (GPF) method is developed in [20] by introducing two parameters $\xi$ and $\psi$.

$$\arg \max_{i \leq N, j \leq m} \frac{r_{ij}(t+1)^\xi}{\theta_i(t)^\psi}$$

GPF encompasses both Best-CQI and PF simply by tweaking $\xi$ and $\psi$ values in (2.1). The new parameters $\xi$ and $\psi$ must be able to dynamically adjust themselves
depending on current cell load to be useful. Similar adaptive approaches capable of tuning fairness levels dynamically proposed in [21] and [25].

Pokhariyal et al. [24] proposed a two step scheduler. In the first step, Time Domain Scheduler (TDS) selects a subset of active bearers in the current Transmission Time Interval (TTI); in the second step, Frequency Domain Scheduler (FDS) allocates RBs to selected bearers using PF or RR criteria. Channel-aware/QoS-unaware schedulers exploit RRM features such as CQI and link adaption etc, to achieve a certain spectral efficiency; yet, they can not guarantee the QoS. In [22] an UE with maximum CQI values is assigned to RBs and the selected UE is not permitted to be scheduled until the end of that TTI; if all UEs are scheduled and there are still free RBs, the scheduler takes all UEs into consideration.

In [26], [27], [28], [29] and [30] authors proposed schedulers that are both Channel-aware and QoS-aware. QoS is managed by QoS parameters to guarantee data rate, packet delay, or loss. A Guaranteed Data Rate (GDR) approach is proposed in [26] and [27]. In [27], Time Domain Priority Set Scheduler (TD-PSS) divides bearers into two sets. UEs below Target Bit Rate (TBR) comprise Set 1 and are given high priority. Bearers in the set-1 scheduled first, and if there are still RBs, bearers in the set-2 are selected according to PF criteria.

Schedulers that focus on delay are proposed in [29] and [31]. Sandrasegaran et al. [29] proposed Delay Prioritized Scheduler (DPS) that selects UEs based on packets’ head-of-line (HOL) proximity to delay threshold. Bearers whose packets are about to drop, are scheduled first. DPS achieves low packet loss rate. Bojovic et al. in [31] proposed an algorithm called Channel and QoS Aware (CQA) scheduler. The
CQA scheduler is also based on decoupled time and frequency schedulers. In the TD, at each TTI, the scheduler groups bearers that have not met their target data rate based on HOLs. In FD, starting from most urgent flows, it allocates RBs to bearers while favoring GBR bearers over NGBR within each group. Fan et al. [32] proposed a semi-persistent scheduler to support maximum number of VoIP. The idea behind semi-persistent schedulers is that, radio resources are divided into several groups and each block is associated to a set of bearers. This approach minimizes signaling overhead by pre-configuring the bearers.
Chapter 3 - Utilizing Geometric Mean in Proportional Fair Scheduling: Enhanced Throughput and Fairness in LTE DL

In this chapter, a channel-aware QoS-unaware scheduler is proposed to address the challenge of multiuser scheduling in the downlink of commercial LTE networks by bringing innovation in the concept of proportional fairness. Geometric average is plugged into the selection criterion of User Equipments (UEs) as opposed to widely used arithmetic average. It is proved that the geometric average throughput converges to the solution of an ordinary differential equation, a similar result shown in the convergence of arithmetic average based Proportional Fair Scheduling (PFS). Extensive simulation results show that geometric average of UEs throughputs converge faster than arithmetic mean. This feature enables throughput increase in the cell while guaranteeing better fairness and Quality of Service (QoS) and imposing low Block Error Ratio (BLER). The superiority of the proposed algorithm is demonstrated by comparing the performance of the proposed scheduler with well-known standard schedulers under different simulation environments.

3.1 Introduction

Orthogonal Frequency-Division Multiple Access (OFDMA) technology has been widely adopted as downlink radio access technology mainly due to its robustness to interference and multi-path fading and flexibility in resource allocation [19]. OFDMA-based networks such as LTE exploit frequency, temporal and multiuser diversity that this flexibility enables to achieve high system capacity. Resource grid (or time-frequency

\[\text{A version of this chapter has been published in [17] and [33]}\]
grid) of OFDM is divided into several Resource Blocks (RBs), which consists of 12 subcarriers for a time duration of 0.5 ms. The allocation of RBs is governed by a centralized entity called eNB. The User Equipments (UEs) feed back on the Channel Quality Indicator (CQI), that corresponds to a specific code rate and modulation order, to base station (eNB) to maximize system throughput. The eNB can leverage this information to assign resources to the UEs. The objective of the scheduling entity embedded in the eNB is to schedule UEs in a way that the system will maximize the system throughput, while acting fair towards UEs and not penalizing UEs with low data demands.

In this work, two versions of a novel algorithm for scheduling of downlink resources are proposed with the objective of overcoming the performance limits of the well-known existing solutions. Performance of Proportional Fair Scheduler (PFS) [18] (throughout the dissertation PFS and PF will be used interchangeably) and Best Channel Quality Indicator (BestCQI) [19] are severely impaired when UEs experience low Signal-To-Noise-Ratio (SNR) values, and this leads to increased Block Error Ratio (BLER) and therefore lower system throughput. Our objectives are therefore to enhance overall system capacity, Block Error Rate (BLER), fairness, and Quality of Service (QoS) of OFDMA-based wireless systems such as LTE. The proposed algorithm re-designs the concept of proportional fairness, by using the geometric mean of transmitted data, instead of using the arithmetic mean, exploiting the fact that the former converges much faster than the latter. In this way, the proposed solution initially behaves similarly to the BestCQI, and than later incorporates fairness into its decisions.
The contributions of this work can be summarized as follows:

- The performance limits of PFS for OFDMA-based downlink systems characterized by high frequency selective fading, in which channel conditions may not be evaluated properly by UEs, are identified.

- An algorithm for scheduling of downlink resources applicable to centralized OFDMA-based networks, which overcomes the performance of well known PFS and BestCQI existing solutions in terms of system throughput, BLER, QoS, and fairness is proposed.

- It is proven that the geometric averages of UEs’ throughput converge to the solution of an ordinary differential equation (ODE). ODE has a unique equilibrium. The existence of a unique equilibrium of ODE determines the throughput of each user and hence delay [34].

- The performance of the proposed algorithms are evaluated and their general validity is demonstrated by being tested under multiple network conditions.

### 3.2 System Model and Problem Formulation

The system comprises a cellular network with $N$ UEs associated to a single eNB operating on a single channel whose bandwidth is divided into $m$ orthogonal narrow-band subcarriers. Each UE provides feedback on the averaged CQI of all subcarriers to the eNB [35]. At Transmission Time Interval (TTI) $t$, the eNB knows the CQIs for subsequent TTI for each UE. If UE $i$ is selected in TTI $t$ on RB $j$ then it transmits
$r^j_{i,t}$ unit of data where \( \{r^j_{i,t}, t \leq \infty \} \) is bounded. Let $I^j_{i,t}$ be the characteristic function. $I^j_{i,t} = 1$ if RB $j$ is assigned to UE $i$ at time slot $t$ and is equal to 0 otherwise. $\tilde{Q}_{i,t}$, which is defined as follows, represents total data unit that UE $i$ transmitted over all RBs at TTI $t$:

\[
\tilde{Q}_{i,t} = \begin{cases} 
Q_{i,t}, & \text{if } Q_{i,t} > 0 \\
1, & \text{otherwise}
\end{cases}
\]  

(3.2)

and

\[
Q_{i,t} = \sum_{j=1}^{m} r^j_{i,t} I^j_{i,t}.
\]  

(3.3)

One definition of the throughput for the UE $i$ up to time $t$ is the geometric mean:

\[
\beta_{i,t} = \sqrt[t]{\prod_{l=1}^{t} \tilde{Q}_{i,l}}
\]  

(3.4)

At each TTI, each RBs is assigned to only one UE according to the following formula:

\[
\arg\max_{i \leq N, j \leq m} \left\{ \frac{r^j_{i,t+1}}{d_i + \beta_{i,t}} \right\}
\]  

(3.5)

d$_i$ is a negligible positive constant to prevent division by zero when the current throughput is zero. Transmitted data rates can be different than $r_i$ or data may not be successfully transmitted due to poor channel condition. Data unit conveyed with success is denoted with $r^*_i$ from now on. For a given window size $\alpha$ and discount factor $(1 - \frac{1}{\alpha})$, the discounted throughput is defined recursively as:
\[
\beta_{i,t+1} = \beta_{i,t}^{\frac{1}{\alpha}} r_{i,t}^{\gamma_j(\frac{1}{\alpha})}
\] (3.6)

In the case of ties a random UE is selected among UEs with the highest ratio. The PFS aims to maximize the following logarithmic utility function, maintaining fairness:

\[
\sum_i \log \gamma_i
\] (3.7)

where \(\gamma_i\) is the total transmitted data unit of UE \(i\). This objective is known as Kelly’s [36] proportional fair criterion and proposed algorithm is related to fairness criterion. Utility function in (3.7) is adopted as the objective. In order to maximize the utility function, one must maximize in (3.5) for every single RB \(j\) at each TTI [34].

### 3.3 Weak convergence of the geometric average

The geometric average \(\beta_{i,t}\) weakly converges to the limit points of the mean ODE and in this section, proof is provided. For simplicity, the case where there is only one RB, \(m\) is considered as 1, and the superscript \(j\) is dropped off in \(r_{i,t}^j\) and \(I_{i,t}^j\) for notational abbreviation in this section. The weak convergence for general \(m\) RBs is similar. Taking the logarithm of (3.4),

\[
\log \beta_{i,t} = \sum_{t=1}^{t} \frac{\log \tilde{Q}_{i,t}}{t} = \sum_{t=1}^{t} \frac{\log(r_{i,t})I_{i,t}}{t}
\] (3.8)
is obtained. Then the two-term recursive relation is obtained similar with equation (1.2) in [34],

\[
\log \beta_{i,t+1} = \log \beta_{i,t} + \epsilon_t \left[ \log (r_{i,t+1}) I_{i,t+1} - \log \beta_{i,t} \right]
\]  

(3.9)

where \( \epsilon_t = 1/(t + 1) \).

Similarly as in [34], \( \hat{\beta}_t \) is defined (prime stands for matrix transpose)

\[
\hat{\beta}_t = \left[ \log \beta_{1,t}, \ldots, \log \beta_{N,t} \right]'
\]

(3.10)

and

\[
R_t = \left[ \log r_{1,t}, \ldots, \log r_{N,t} \right]'
\]

(3.11)

Since the usual stochastic approximation asymptotic analysis of (3.9) employs continuous time interpolations, for each \( t \), let us define shifted process \( \hat{\beta}^t(\cdot) = \left[ \hat{\beta}^t_1(\cdot), \ldots, \hat{\beta}^t_N(\cdot) \right]' \) such that \( \hat{\beta}^t(0) = \hat{\beta}_t \) and for \( l > 0 \)

\[
\hat{\beta}^t(s) = \hat{\beta}_{t+l}, \text{ for } s \in \left[ \sum_{k=t}^{t+l-1} \epsilon_k, \sum_{l=t}^{t+l} \epsilon_l \right)
\]

(3.12)

where the empty sum is zero. Since \( \hat{\beta}^t(\cdot) \) begins at \( t \), the behavior of \( \hat{\beta}^t(\cdot) \) as \( t \to \infty \) is that of \( \hat{\beta}_t \) as \( t \to \infty \).

To prove the weak convergence, some assumptions similar as in [34] are needed.
A1: Let the $\xi_t$ denote the past $\{R_l : l \leq t\}$. For each $i, t, \xi_t$,

$$h_{i,t}(\beta, \xi_t) = E_t \log(r_{i,t+1}) I_{\left\{ \frac{r_{i,t+1}}{\beta_i} \geq \frac{r_{j,t+1}}{\beta_j} \right\} j \neq i}$$

(3.13)

is continuous in $\beta \in \mathbb{R}^N_+$ where $\beta = [\beta_1, \cdots, \beta_N]'$ is used as the canonical value of $[\beta_{1,t}, \cdots, \beta_{N,t}]$ and $I$ represents the characteristic function. Let $\delta > 0$ be arbitrary, then in the set $\{\beta : \beta_i > \delta, i \leq N\}$, the continuity is uniform in $t$ and $\xi_t$. Assume $R_t$ is bounded.

A2: $\{R_t, t < \infty\}$ is stationary. Define $\tilde{h}_i(\cdot)$ by the stationary expectation

$$\tilde{h}_i(\beta) = E \log(r_i) I_{\left\{ \frac{r_i}{\beta_i} \geq \frac{r_j}{\beta_j} \right\} j \neq i}$$

(3.14)

where $r_i$ is used as the canonical value of $r_{i,n}$. Then by following the similar proof in [34] below theorem hold:

**Theorem 1:** Given the two-term recursive relation (3.9), conditions (A1) and (A2), for any initial condition, $\hat{\beta}^t(\cdot)$ converges weakly to the set of limit points of the solution of the ODE:

$$\dot{\hat{\beta}}_i = \tilde{h}_i(\hat{\beta}) - \hat{\beta}_i, \quad i = 1, 2, \cdots, N.$$  

(3.15)

And the limit point $(\bar{\beta})$ is unique, irrespective of the initial condition. So the process $\hat{\beta}^t(\cdot)$ converge to $\bar{\beta}$ as $t \to \infty$.

**proof of the Theorem 1:** Since the same idea of [34] is followed, the main proof is omitted. Yet, $f(x) = \tilde{h}(x) - x$ must satisfy the $K$-condition [37]. If $x \leq y$, $x_i = y_i$, 

27
then

\[ f_i(x) - f_i(y) = \tilde{h}_i(x) - \tilde{h}_i(y) \]

\[ = E \log(r_i)I\left\{ \frac{r_i}{d_i+y_i} \geq \frac{r_j}{d_j+y_j} \right\} \quad (3.16) \]

\[ - E \log(r_i)I\left\{ \frac{r_i}{d_i+y_i} \geq \frac{r_j}{d_j+y_j} \right\} \]

notice that \( \frac{r_i}{d_i+y_i} = \frac{r_i}{d_i+y_i} \) but \( \frac{r_j}{d_j+y_j} \geq \frac{r_i}{d_i+y_i} \), then

\[ I\left\{ \frac{r_i}{d_i+y_i} \geq \frac{r_j}{d_j+y_j} \right\} \leq I\left\{ \frac{r_i}{d_i+y_i} \geq \frac{r_j}{d_j+y_j} \right\} \quad (3.17) \]

which leads to \( f_i(x) \leq f_i(y) \), the K-condition.

### 3.4 Proposed Algorithm

Two different version of the Fair Allocation High Throughput (FAHT) Algorithm- 

FAHT\(_{60}\) and FAHT\(_{100}\) - are illustrated here.

**Algorithm 1** FAHT Algorithm

1: Get CQI values from each UE
2: Compute the ratio of instantaneous data rate to average transmitted data rate for each RB for each UE
3: while Number of RBs has not been assigned \( > 0 \) do
4: Allocate RBs to the UE with maximum ratio
5: Delete the RB that has been allocated
6: end while
7: Update average throughput values \( \beta \) for each UE

The steps for FAHT\(_{60}\) and FAHT\(_{100}\) are same. The only difference is in calculating geometric mean. For FAHT\(_{60}\) true transmitted data rate is used to calculate \( \beta \); however, to compute \( \beta \) in FAHT\(_{100}\) true transmitted data is divided by 100 and add
1 to speed up the convergence.

### 3.4.1 Intuition behind FAHT

In the following, the intuition behind *FAHT* and the reasons for its performance is discussed. Proof of the convergence rate is currently an ongoing work. Fig. 3.1 represents the average throughput of each users in scenario 2 discussed in simulation result throughout the simulation. As seen, $\beta_i$ values, for *FAHT*$_{60}$ and *FAHT*$_{100}$ (second and third images from the top), converge fast and are very close to each other’s. The ranges of Y-axis for both algorithms are much smaller then of PFS. That said, any small changes in the numerator (instantaneous data rate) of the selection criterion (3.5) results in selection of a different UE. However, for PFS, it takes 300 subframes for some UEs’ mean throughputs to congregate around a value. Yet, those values are not that close till the end of the simulation. Therefore, even when big changes happen in numerator of equation (1.6) in [34], it does not affect what will be selected next.

**Table 3.1: Simulation Parameters**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of User Equipments (UEs)</td>
<td>25</td>
</tr>
<tr>
<td>Channel Bandwidth</td>
<td>1.4 MHZ</td>
</tr>
<tr>
<td>Simulation Length</td>
<td>300 subframes</td>
</tr>
<tr>
<td>Transmit Mode</td>
<td>MU-SISO</td>
</tr>
<tr>
<td>Scheduling Algorithms</td>
<td>BestCQI, PFS, FAHT$<em>{60}$, FAHT$</em>{100}$</td>
</tr>
</tbody>
</table>
3.5 Simulation Parameters, Results and Discussion

3.5.1 Simulation Parameters

The Vienna University’s MATLAB based LTE link-level simulator [38] has been used to evaluate the performance of the proposed algorithm in comparison with PFS and BestCQI solutions. The simulations are performed for frequency-selective channels modeled by ITU, for Pedestrian-B (PedB) channels. Table 3.1 summarizes the main simulation parameters adopted.
Figure 3.2: Cell throughput

Figure 3.3: BLER of 25 UEs for 3 scenarios
3.5.2 Simulation Results

The scheduling algorithms are evaluated with regards to overall cell throughput, BLER, QoS and fairness. In fact, beside system throughput, BLER is also very important metric. Then, individual UEs’ throughput, and allocated RBs quantify the fairness of each of the scheduling algorithms. Three different network environments are considered to demonstrate the superiority of the proposed algorithm over PFS’ and BestCQI’s performances. The first simulation scenario considers 25 UEs having SNRs ranging from 2 to 50 dB in 2dB steps. In the second scenario, UEs’ SNRs are normally distributed with parameter $\mu=25\,\text{dB}/\sigma=10$. UEs undergo similar SNR value of 18 dB in the third scenario.

Figure 3.2 and 3.3 displays the system throughput and BLER for the three scenarios respectively. The proposed algorithm performs better than PFS in three scenarios in terms of system throughput. In the low SNR region, which is the third scenario, our algorithm outperforms BestCQI as well. Although BestCQI excels when the network is characterized by large variation of SNR experienced by UEs -first and second scenarios- this comes at the cost of compromising fairness. BLER performances of the schedulers are in accordance with their throughput performances. Fig 3.4 shows the throughput achieved by different UEs with each scheduler in second scenario. UEs’ SNR values are sorted during the simulation. BestCQI achieves high throughput for UEs with favorable SNR but UEs with low SNR starve. Proposed algorithms favor UEs with high SNR but do not let starvation. Under PFS, differences between UEs throughput values do not change drastically. Considering the nature of wireless
network applications, differences between UEs’ throughputs are necessary to increase system throughput. For example an UE streaming high definition video should have higher throughputs than UEs receiving a voice over IP stream in order to be “proportionally” fair.

Fig. 3.5 shows the number of RBs allocated to different UEs with different schedulers in the second scenario. Again, UEs with favorable SNR receive most of RBs in BestCQI. PFS assigns most of RBs to UEs with low SNR. Although proposed algorithm has a tendency to favor underdog, it is not as radical as PFS. There are two weaknesses of PFS observed here: First, PFS sacrifices radio resources in spite of fairness provided to the single UE throughput. For example, $UE_1$, who has the lowest SNR, receives almost 500 RBs to achieve what he achieves in Fig 3.4. Second,
Figure 3.5: Number of assigned RBs to each UE in second scenario $\mu = 25\text{dB}$ $\sigma = 10$.

$UE_4$ at both Fig.3.5 and Fig.3.4 has the lowest statistics. This is because $UE_4$ is the UE whose average throughput converges in 300 subframes in Fig.3.1 at the top figure (UEs with blue legend). Therefore, it is never assigned any RBs except the first time it was scheduled.

Fairness is quantified by using Jain’s fairness index [39]. BestCQI is not compatible with fairness neither in terms of throughput nor in RB distribution when UEs experience different SNR, respectively first and second scenarios. Proposed algorithms achieve highest fairness in all cases except in terms throughput in the first scenario yet as good as PFS. Figure 3.6 and 3.7 illustrates fairness index under each algorithm in different scenarios with respect to throughput and RB distribution respectively. PFS is not compatible with fairness at all in terms of RB distribution. The only time
PFS achieves highest fairness is the first scenario in terms of throughput where UEs having SNRs ranging from 2 to 50 dB in 2dB steps.

Another important limitations of both PFS and BestCQI that has been discovered from the results of extensive experiments is this: The proposed algorithm tends to assign at most one RB to a single UE in low SNR conditions, whereas BestCQI and PFS tend to assign chunk of subcarriers to a single UE at each TTI. Since all RBs allocated to a given UE in any scheduling period will use the same modulation and coding scheme (MCS), frequency selective fading may cause high BLER and consequent performance loss in BestCQI and PFS for low SNR due to low or erroneous CQI (and consequently MCS) selection. It is obvious from the Fig 3.6 that PFS is as fair as proposed algorithm in the third scenario where UEs experience same SNR of 18dB; however, proposed algorithm outperforms BestCQI with regarding to cell throughput.
Finally, Fig. 3.8 illustrates average delay in packet delivering. Whole simulation, which is 300 subframes, is divided into small intervals. The length of each interval is different than each other for each UE and within each UE; for example, for each UE, first interval starts from the first TTI and ends at the very first TTI that follows one or series of TTIs which that particular UE is not scheduled at; second interval starts from where first interval ends and so on. Average waiting time, for each interval, is determined by dividing number of TTIs the UE is not scheduled at to the length of that interval. Lastly, the mean of average waiting times is calculated by dividing the sum of these values by total number of intervals for each UE. Under proposed algorithm and PFS most UEs wait, on average, 4-6 ms in every 10 ms to be scheduled. This is way lower than threshold for HOL packet delay set in [29] which is 20 ms. As for BestCQI some users are never scheduled in first and second scenarios.
3.6 Conclusion

In this chapter, two versions of a novel scheduling algorithm are, $FAHT_{60}$, and $FAHT_{100}$ proposed for OFDMA downlink transmission and their performances are compared with two well-known algorithms, BestCQI and PFS. The performances of new schedulers are investigated with regards to system throughput, BLER, fairness. It is proved that the geometric average of UEs’ throughputs also converge to the solution of an ODE and experimental results show that proposed algorithms improve
system throughput, BLER, and balances the use of shared radio resources among
UEs. Extensive evaluations illustrated that the geometric mean throughput converge
much faster than arithmetic mean.
Chapter 4 - A Priority and QoS-Aware Scheduler for LTE based Public Safety Networks

LTE has also been selected by the U.S. federal and UE authorities to be the access technology for PSBNs that would allow first responders to seamlessly communicate between agencies nationwide. From Release 11 on, 3rd 3GPP has been outlining the standards for the features that will enable LTE to be used as part of a PSBN. The requirements for scheduling UEs with appropriate QoS and priority has not been addressed yet. In this chapter, we highlight the scheduling challenges in LTE based PSBN and propose a solution that considers all the parameters described in the QCI table. Simulations results show that proposed solution produces better outcomes in terms QoS requirements and increases cell throughput while differentiating bearers based on priorities in comparison with algorithms that exist in the literature when considering public safety scenarios.

This work was in part supported by the National Institute of Standards and Technology (NIST) through Professional Research Experience Program - Communications Technology Laboratory (PREP-CTL) with award number 70NANB16H021.

4.1 Introduction

On Sept. 11, 2001, firefighters and police officers could not communicate to each other on their radios at the World Trade Center. Same problem was seen in 2005 Hurricanes Katrina and Rita. Public safety (PS) officers from different jurisdictions arrived at the scene only to find that they were unable to communicate with each other by radio [40]. Traditional Land Mobile Radio (LMR) communication networks (e.g. P25, and
TETRA) no longer meet the needs of public safety agencies be it police, fire or EMS. Public safety agencies need wireless networks that provide more than push-to-talk. Some public safety wireless networks today are limited to voice communications only and are not capable of transmitting multimedia data. Besides being reliable, scalable, and secure, public safety networks have to provide high quality of service (QoS), so that it can meet first responders’ (FRs) needs at all times. LTE satisfies the growing need for broadband in public safety [41].

LTE will also provide an unprecedented opportunity for interoperability — even on a nationwide scale — which has always been an issue since most agencies use their own private radio systems, therefore they typically do not connect to other networks. To overcome the problems LMR is facing and to benefit from the advantages of the LTE, the Federal Communications Commission (FCC) has announced LTE to be the access network technology for the NPSBN [6]. This comes with a number of unprecedented challenges for the NPSBN. When disasters strike whether they are man-made such as terrorist attacks or natural disasters such as hurricanes, communication networks get congested. This saturation may result in a heavy load at a given cell, and it may be so severe that a responder is prevented from accessing the cell or receiving the QoS his/her applications require [6]. In order to prevent such situations, prioritization and QoS, both in access and core network, must be taken care of. In this work, a solution for prioritization and QoS provisioning in the access network is presented.

Public Safety Broadband Networks (PSBN) are private networks with very strict performance constraints. Scheduling algorithms developed for commercial LTE networks mainly focus on increasing throughput, enhancing QoS, and providing fairness.
Besides these requirements, PSBN needs to differentiate the bearers based on their priorities. To our knowledge, no scheduler has addressed priority along with other requirements yet. The contributions of this chapter can be summarized as follows:

- The potential problems associated with scheduling packets in the PSBN are identified.
- A scheduling algorithm that meets the priority and QoS requirements of PSBN is proposed.
- The performance of the proposed algorithm is compared against performances of algorithms in the literature — RR \[42\] and Channel and QoS Aware (CQA) \[31\] — and its general validity is demonstrated by testing it under various network conditions.

4.2 Scheduling Priority

LTE transports data between the UE and the P-GW, which can be considered as bidirectional data pipe with a specific requirements \[10\]. Bearers have a corresponding QoS description which should influence the behavior of the eNB resource scheduling algorithm.

The 3GPP has studied the needs of applications on LTE and identified their attributes in \[7\]. Standardized combinations of these characteristics are called QCI\s. It is a scalar that acts as a pointer into a look-up table (see table-4.2) which describes four other quantities — bearer type, priority, PDB and PELR. There are two types of bearers; dedicated and default. Dedicated bearers can be GBR or NGBR, yet
default bearers can only be NGBR type. The PELR is an upper bound for a rate of non-congestion related packets losses. The PDB defines an upper bound, with 98% confidence, for the time that a packet may be delayed between the UE and the P-GW. Priority determines when packets should be sent to or received from the UEs and is handled in the access network by eNB. High priorities are associated with low numbers. A QCI assigned to a bearer may or may not be changed afterward.

Currently, PS agencies use different technologies for over-the-air Mission Critical Push-to-Talk (MCPTT) and data services to maintain a distinction between applications. MCPTT is provided with a pool of guaranteed resources by reserving certain bandwidth. With LTE, MCPTT, data, voice, bandwidth-intensive video and multi-
media services and all other applications will share same resources, so this distinction will be removed. From the PS perspective, it is important to discern the most important applications [6].

According to the UE Priority Model which has been developed by National Public Safety Telecommunications Council’s (NPSTC) Priority and QoS Working Group, one of the attributes that is closely related to the scheduling is Type of Application (see fig. 4.1) [6]. The Type of Application feature is intended to demonstrate the relative default significance of all applications on the PSBN. The purpose is that mission critical applications receive elevated priority on the system. As congestion rises at a given cell, higher priority applications will receive more resources by default. Even in the case of saturated network, every effort must be made to maintain mission critical voice.

Higher priority applications should be linked to GBR bearers by core network
so that when congestion arises in the cell, these applications can be guaranteed with proper QoS. Assigning such applications to GBR bearers may still not guarantee good service or continuity if priority is not considered. MCPTT is selected as the most important applications [6]. Thus, this application should always have the highest priority. In addition, in case of Responder Emergency situation (Fig. 4.1), where responder him/herself is in a life threatening situation, regardless of application type, any applications used by FR must be assigned to highest priority bearer for the maintenance of uninterrupted communication. The process of assigning application to bearers is beyond the scope of this work. Yet, scheduler in the air interface should consider the priorities of bearers when allocating RBs in order to assure proper QoS for most important applications.

4.3 Problem Formulation

Table 4.3 shows the important notations used throughout the paper:

Supposed followings are given:

- There is a single cell and the total number of RBs available at each 1 second window is $n$

- $m$ is the number of bearers in the system

- Each bearer $i$ ($1 \leq i \leq m$) has different QoS requirements

The constraints are given as:

i) The number of RBs needed to satisfy GBR bearers’ bit rate requirements and
Table 4.2: Notations

<table>
<thead>
<tr>
<th>Notation</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bearer $i$</td>
<td>Bearer with QoS Class index of $i$</td>
</tr>
<tr>
<td>$BII(i)$</td>
<td>Importance index of bearer $i$</td>
</tr>
<tr>
<td>$PELR(i)$</td>
<td>PELR of bearer $i$</td>
</tr>
<tr>
<td>$PDB(i)$</td>
<td>PDB of bearer $i$</td>
</tr>
<tr>
<td>$GBR(i)$</td>
<td>GBR of bearer $i$</td>
</tr>
<tr>
<td>$HOL(i)$</td>
<td>Head of Line of bearer $i$</td>
</tr>
<tr>
<td>$RT(i)$</td>
<td>Remaining Time of bearer $i$</td>
</tr>
<tr>
<td>$\alpha(i)$</td>
<td>Number of RBs needed to satisfy bearer $i$’s GBR (demand in case of NGBR) within 1 sec window</td>
</tr>
<tr>
<td>$\theta(i, t)$</td>
<td>Throughput of bearer $i$ at Transmission Time Interval (TTI) $t$</td>
</tr>
<tr>
<td>$\beta(i, t)$</td>
<td>Loss rate bearer $i$ at TTI $t$</td>
</tr>
<tr>
<td>$UE_i^j$</td>
<td>UE $j$ who employs bearer $i$</td>
</tr>
<tr>
<td>IAT</td>
<td>Inter-arrival time</td>
</tr>
<tr>
<td>MCS</td>
<td>Modulation and Coding Scheme</td>
</tr>
</tbody>
</table>

NGBR bearers’ demands which are calculated based UEs’ Modulation and Coding Schemes (MCSs), sizes and Inter-arrival times (IATs) of packets at any moment

$$\sum \alpha(i) \leq n$$

$ii)$ For each GBR bearer $i$ at any TTI $t$, if throughput of the bearer is less than promised GBR, $\theta(i, t) \leq GBR(i)$, than packet loss rate of the bearer must be less than or equal to threshold

$$\beta(i, t) \leq PELR(i), \text{if } \theta(i, t) \leq GBR(i)$$

$iii)$ The bit rate requirements for GBR bearers with different BII must be satisfied
based on relative importance of bearers. Let’s say there are two GBR bearers $i$ and $j$. At any TT $t$:

$$\frac{\theta(i, t)}{GBR(i)} > \frac{\theta(j, t)}{GBR(j)} \text{ if } BII(i) > BII(j)$$

The objective is to minimize $(iv)$ while satisfying constraints $(i)$, $(ii)$, and $(iii)$.

$(iv)$ $\Sigma\{\beta(i, t) \mid (1 \leq i \leq m) \text{ and } 1 < t < \infty\}$

Simply put, the objective is to minimize the packet losses in the system while satisfying GBR and PELR requirements of the bearers in relative importance order. It is assumed that once throughput requirement for GBR bearers is met, packet losses are allowed.

4.4 The design of Proposed Algorithm

The access network may use the QCI parameters to manage packet forwarding treatment because the goal of standardizing a QCI with corresponding parameters is to ensure that bearers mapped to that QCI receive the same minimum level of QoS in multi-vendor network deployments and in case of roaming [7]. Every QCI is mapped to an appropriate Bearer Importance Index (BII) as shown in Table 4.4. The intention is to make sure that GBR bearers have higher importance than NGBR while the relative priority among GBR and NGBR bearers are preserved. These values will suffice that. High numbers are associated with high importance. Priority and QoS Aware (PQA) scheduler (Algorithm 2) is proposed, which takes all the QCI pa-
Table 4.3: QCI-BII Mapping Table

<table>
<thead>
<tr>
<th>QCI</th>
<th>Bearer Type</th>
<th>Priority</th>
<th>BII</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>GBR</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>2</td>
<td>GBR</td>
<td>4</td>
<td>7</td>
</tr>
<tr>
<td>3</td>
<td>GBR</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>4</td>
<td>GBR</td>
<td>5</td>
<td>6</td>
</tr>
<tr>
<td>65</td>
<td>GBR</td>
<td>0.7</td>
<td>10.3</td>
</tr>
<tr>
<td>66</td>
<td>GBR</td>
<td>2</td>
<td>9</td>
</tr>
<tr>
<td>5</td>
<td>NGBR</td>
<td>1</td>
<td>5</td>
</tr>
<tr>
<td>6</td>
<td>NGBR</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>7</td>
<td>NGBR</td>
<td>7</td>
<td>3</td>
</tr>
<tr>
<td>8</td>
<td>NGBR</td>
<td>8</td>
<td>2</td>
</tr>
<tr>
<td>9</td>
<td>NGBR</td>
<td>9</td>
<td>1</td>
</tr>
<tr>
<td>69</td>
<td>NGBR</td>
<td>.5</td>
<td>5.5</td>
</tr>
<tr>
<td>70</td>
<td>NGBR</td>
<td>5.5</td>
<td>4.5</td>
</tr>
</tbody>
</table>

rameters into account. Utility function $\psi$ is used to help determining the scheduling priority of bearers.

$$
\psi(i) = \begin{cases} 
\min\left\{ \frac{BII(i)}{1 - \frac{HOL(i)}{PDB(i)}}, 500 \right\} & \text{if } PDB(i) - HOL(i) > 15 \\
500 & \text{if } PDB(i) - HOL(i) \leq 15
\end{cases}
$$

(4.18)

$HOL(i)$ refers to the time difference between the current time and the arrival time of the packet in the head of line of the bearer $i$. The rationale behind $\psi$ is this: When the ratios of HOL to PDB for two or more different bearers with different QCIs are same the one with higher importance index must have higher utility except for the last 15 ms. Bearers share same utility value when they are closed to be dropped — last 15 ms. Based on our studies on this parameters, let’s call it $l$, 15 ms is an optimal value as opposed to the optimal value since there are several values that achieve same results. It is observed that when there are only GBR bearers in the cell, lower value
for $l$ produces better results. Yet, if there are both GBR and NGBR bearers in the system, higher $l$ values result in better performances in terms of packet losses. The delay between P-GW and radio base station —20 $ms$ — should be subtracted from a given PDB to derive the packet delay budget that applies to the radio interface. 20 $ms$ is added to the HOL as soon as packets arrive to the queue. Figure 4.2 shows the outcome of $\psi$ when all the parameters for each bearer with different requirement plugged into the equation (4.18). 500 is selected as the highest achievable utility value because it is one of high $\psi$ values within the range of every bearers’ utility values. This is an arbitrary value. Yet, higher value helps the algorithm to differentiate between the state of each packets better. So, a value where most bearers’ $\psi$ values reach or exceed in last 1 to 10 $ms$ is picked.

Figure 4.2: Utility Function $\psi$. Utility values of each QCI bearer when values plugged into the Equation (4.18)
Algorithm 2 PQA Scheduler

1: Get the list of bearers that have data to transmit
2: Obtain throughput, HOL and $\beta(i,t)$ values for each bearer
3: Discard packets whose HOLs exceed their PDBs
4: Compute $\psi$ based on HOL
5: while there are available RBs do
6: Select the bearer with the highest metric
7: if there is a tie (assume bearer $k$ and $l$) then
8: if $BII(k) = BII(l)$ then
9: Pick the one with lower RT
10: else if $BII(k) > BII(l)$ and Both are GBR then
11: if $\theta(k,t) \geq GBR(k)$ and $RT(l) \leq RT(k)$ then
12: Pick $l$
13: else if $\theta(k,t) \geq GBR(k)$ and $\theta(l,t) < GBR(l)$ then
14: Pick $l$
15: else if
16: $\frac{\theta(l,t)}{GBR(l)} \leq \frac{\theta(k,t)}{GBR(k)}$
17: then
18: Pick $l$
19: else
20: Pick $k$
21: end if
22: else if $BII(k) > BII(l)$ and Both are NGBR then
23: if $\beta(k,t) \leq PELR(k)$ and $RT(l) < RT(k)$ then
24: Pick $l$
25: else
26: Pick $k$
27: end if
28: else if $BII(k) > BII(l)$ and $k$ is a GBR bearer then
29: if $\theta(k,t) < GBR(k)$ then
30: Pick $k$
31: else
32: Pick the one with lower RT
33: end if
34: Assign enough RBs to transmit all the packets in the selected bearer’s queue
35: Discard it from list of bearers
36: end while

In every TTI, PQA (Algorithm 2) checks QoS parameters and computes $\psi$ values
for each bearer that has data to transmit and discard those whose HOLs exceed their PDBs. While there are RBs to allocate, it selects bearer with the highest value. If there is tie, it checks bearer types first. For the sake of simplicity, let’s assume there are two bearers with highest $\psi$ values. If bearers have same BIIs, it picks the one with lower RT. Else, if BIIs are different and both are GBR bearers; it picks the one with higher importance index, if it has not reached its required GBR. If it has, then it checks (1) if the one with lower importance has lower RT, (2) it has not achieved its GBR, (3) it has lower ratio of throughput to minimum bit rate in order, if any of these hold true in the order they are laid out, it picks the one with lower BII.

Else, if BIIs are different and both are NGBR bearers; if the one with higher importance index has a $\beta$ value that is less than what it can tolerate and its RT is higher, then it picks the one with lower BII. Otherwise, it picks the one with higher BII.

Else, if BIIs are different and one is GBR and the other is NGBR bearer; it picks the one with higher importance index, if it has not reached its promised GBR, else it picks the one with lower RT. It assigns enough RBs to the selected bearer to transmit all of its packets stacked in the queue. If there is less than required assign all the remaining bearers and realize transmission. Finally, it discards the bearer from the list.
4.5 RESULTS

4.5.1 Simulation Setup Parameters

After an initial study on different schedulers tested in the ns-3 LTE module [43] conducted by National Institute of Standards (NIST) Communications Technology Laboratory (CTL) group, RR and CQA schedulers are selected as baselines of comparison, since they provide the better performance in the studied public safety scenario. CQA implements two channel awareness metrics, PF metric is implemented for this project and will be referred as $CqaPf$ from now on. A simulator, which contains bearer features described in QCI table (table 4.2), is developed in order to examine the schedulers. Two different deployment scenarios are considered to test performances of the schedulers with respect to GBR, PELR, PDB, priority and system throughput. Simulation runtime is 65 seconds and the bearers are active until the end of the 59th second. Table 4.5 summarizes the simulation’s parameters that are common for three scenarios presented. There are 50 RBs in every ms; thus, 50000 RBs are available in every second. Pre-emption and Admission and Retention Priority (ARP) are not implemented. Every transmission is successful meaning there is no failure due to channel impairment. Radio link control (RLC) queue size is set high, 1MB, to observe losses only due to PDB.
Table 4.4: Common Simulation Parameters for All Scenarios

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of RB available at each TTI</td>
<td>50 RB</td>
</tr>
<tr>
<td>RLC Queue Size</td>
<td>1 MB</td>
</tr>
<tr>
<td>Schedulers</td>
<td>CqaPf, RR and PQA</td>
</tr>
<tr>
<td>Simulation Runtime</td>
<td>65 sec</td>
</tr>
<tr>
<td>Pre-emption</td>
<td>Not Implemented</td>
</tr>
<tr>
<td>ARP</td>
<td>Not Implemented</td>
</tr>
</tbody>
</table>

4.5.2 First Scenario - All QCI Bearers

Table-4.6 presents application configurations for the first scenario, all QCI bearers, where every types of bearers running in the cell. First column represents the instance names. The number at the end of instance names also represent the QCI bearer the is linked to. For example, App-1 is assigned to QCI-1 bearer, App-2 is linked to QCI-2 and so on. Second and third columns indicate the sizes and IATs of the packets respectively. Session intervals are set to 0 for all the applications. Each application is associated with one QCI bearer and each is employed by 3 UEs who experience different channel conditions: bad, good and better. Column 4, 5 and 6 show the MCS values of UEs utilize the applications. The number of RBs needed to provide QoS to the bearers is 49876 in 1 second for this scenario. This is calculated based on MCS values of the UEs and IAT and sizes of packets. Applications are initiated at different times within the first 350 ms. In every figure, except fig 4.9 and 4.10, the x-axis represents QCI of the bearers and they are ordered with respect to MCS values from low MCS to higher MCS. For example, consecutive 1-1-1 in the x-axis in figure 4.3 represents $UE_1^1$ with MCS of 5, $UE_2^1$ with MCS of 18, and $UE_3^1$ with MCS of 28 in table-4.6 employing QCI-1 bearers respectively.
Figure 4.3: GBR requirements — First Scenario

Figure 4.3 illustrates ratio of average throughput of the bearers to set minimum bit rate per GBR bearer — QCI-1, QCI-2, QCI-3, QCI-4. PQA and CqaPf provide all GBR bearers with required minimum bit rate, whereas RR fails to provide GBR for \( \text{UE}_1 \) — first UE with MCS of 5 that utilizes App-1 that is linked to QCI-1 bearer. That is the bearer with highest BII, in another word, it is the one of the bearers with the highest priority among GBR bearers.

Figure 4.4 shows ratio of packet loss to total number of packet generated per bearer. NGBR bearers — QCI-5, QCI-6, QCI-7, QCI-8, QCI-9 — do not demand certain data rate but do have strict PELR requirements. CqaPf fails to meet this requirement for \( \text{UE}_5 \) — QCI-5 bearer that is used by UE with bad channel condition.

Figure 4.5 illustrates average waiting time for packets to be transmitted in \( ms \). Waiting time for packet for CQA and RR except \( \text{UE}_1 \) and \( \text{UE}_5 \), are almost uniform.
As for PQA, it is proportional to PDBs of bearers.

Table 4.5: Application Configuration Settings - First Scenario

<table>
<thead>
<tr>
<th>Instance</th>
<th>Size (B)</th>
<th>IAT (ms)</th>
<th>$UE_1^1$</th>
<th>$UE_2^2$</th>
<th>$UE_3^3$</th>
<th>GBR (Bps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>App-1</td>
<td>338</td>
<td>2.47</td>
<td>5</td>
<td>18</td>
<td>28</td>
<td>136375</td>
</tr>
<tr>
<td>App-2</td>
<td>320</td>
<td>85.3</td>
<td>2</td>
<td>9</td>
<td>17</td>
<td>3750</td>
</tr>
<tr>
<td>App-3</td>
<td>256</td>
<td>148</td>
<td>6</td>
<td>11</td>
<td>22</td>
<td>17250</td>
</tr>
<tr>
<td>App-4</td>
<td>6</td>
<td>2.66</td>
<td>2</td>
<td>11</td>
<td>18</td>
<td>2255</td>
</tr>
<tr>
<td>App-5</td>
<td>254</td>
<td>1.86</td>
<td>3</td>
<td>16</td>
<td>19</td>
<td>NA</td>
</tr>
<tr>
<td>App-6</td>
<td>384</td>
<td>236.3</td>
<td>6</td>
<td>13</td>
<td>23</td>
<td>NA</td>
</tr>
<tr>
<td>App-7</td>
<td>253</td>
<td>7.41</td>
<td>7</td>
<td>14</td>
<td>24</td>
<td>NA</td>
</tr>
<tr>
<td>App-8</td>
<td>256</td>
<td>14.7</td>
<td>8</td>
<td>16</td>
<td>20</td>
<td>NA</td>
</tr>
<tr>
<td>App-9</td>
<td>483</td>
<td>28</td>
<td>8</td>
<td>15</td>
<td>25</td>
<td>NA</td>
</tr>
</tbody>
</table>

**Discussion over the results of the first scenario:** The results are in accordance with the working mechanisms of CqaPf, RR and PQA. RR schedules bearers in order that is why all packets wait more or less same with very small standard deviation. The applications associated with $UE_1^1$ and $UE_3^3$ require high throughput...
with relative to MCS of the UEs and since it takes RR multiple consecutive TTIs to transmit a single packet for these UEs—again, because of low MCS—packets are dropped once they reach to delay threshold, thus it fails to provide $UE_1$ with appropriate data rate and PELR and $UE_5$ with appropriate PELR (fig. 4.3 and 4.4). For the same reason, average waiting time is longer for these bearers.

CqaPf divides bearers into different groups in the TD. Since grouping parameter implemented in [31] is too high—300 ms—all the bearers fall into the same group. However, in the FD, bearers with GBR requirements are favored. That is why, $UE_1^5$ suffer losses but not $UE_1^1$, although they both have short packet IATs, larger packet sizes and experience bad channel conditions. CqaPf is also a channel-aware scheduler; thus, it favors bearers associated with better channel conditions. That is why, $UE_1^5$ suffer packet losses but not $UE_2^5$ and $UE_2^5$ (fig 4.4). For same reason, packet of UEs with better channel conditions wait shorter (fig 4.5). That is obvious for QCI-5 bearers used by different UEs but if looked closely, it is seen that it holds true for others as well.

PQA differentiate bearers based on their importance index, in another word, based on bearer types and priorities of bearers. Average waiting time for packets are proportional to PDB of bearers (fig 4.5), that is because PQA selects bearers based on the ratio of PDB to HOL. Once a packet gets closer to its PDB the utility value for the packet grows asymptotically (fig. 4.2) and thus, it increases its chances to be transmitted. Because QCI-3 has shorter PDB than QCI-1, QCI-3 bearers’ packets wait shorter than QCI-1 ones (fig. 4.5), although QCI-1 has higher priority. Same explanation is valid between for QCI-7 and QCI-6 as well. PQA exploits the differences
between delay requirements. It knows how far a packet is away from being dropped. It keeps packet with low importance index waiting while satisfying QoS requirements of bearers with relatively higher importance until it has the highest utility value. By doing so, PQA achieves zero packet loses (fig. 4.4) and meets GBR requirements (fig. 4.3). Also, that is why, QCI-4 has shorter waiting time than QCI-6, QCI-6 than QCI-8 and QCI-8 than QCI-9 although they all share same PDB. One more observation is that the standard deviations for bearers with higher PDB is higher that is because reaching high utility value takes these bearers longer. Therefore, they accumulate plenty of packets with different arrival time in the queue until they are selected to transmit, once they are selected by the schedulers all the packets in the RLC queue are transmitted if there are enough RBs.

For this scenario, PQA satisfies all the bearers and performs zero packet losses, while CQA losses over 10,000 packets from a single bearer and RR performs over 24,000 packet loss from two different bearers.

### 4.5.3 Scenario - GBR Bearers Only

In the second scenario there are only GBR bearers in the system, which is a likely situation in PS environment because in case of emergency when congestion arises in the cell, just mission critical applications will be admitted to the system. Each application is used by 6 different UEs with various channel conditions. Table 4.7 summarizes the applications’ configuration settings the second scenario. Packet sizes, IATs and GBRs of are same as table 4.5 for the applications used in this scenario.
Applications are initiated at different time within the first 350 ms and the number of RBs needed to provide QoS to the bearers is 49881 in 1 second. Figure 4.6 depicts ratio of average throughput of the bearers to set GBR per each bearer. Both CqaPf and RR fail to provide required minimum bit rate for $UE_1$ — the bearer with the highest priority among GBR bearers used by UE with MCS of 5 — therefore, $UE_1$ suffers packet losses (fig. 4.7).

**Discussion over the outcomes of the second scenario:** Since CqaPf does not differentiate between GBR bearers and because it takes channel quality into account, one of the most important bearers used by UE with bad channel condition performs poorly — $UE_1$. Although all the UEs with worst channel conditions — $UE_1$, $UE_2$, $UE_3$ and $UE_4$ — share similar MCS — MCS of 3 —, since the App-1 has the highest packet size with respect to MCS value and smallest packet IAT, it losses packets but
not others (fig. 4.7). From a public safety perspective this is unacceptable. As said in section-3, all the effort must be made to maintain the most important application. Yet, CQA fails to comply with this principal. For the same reason, a peak is seen in the average waiting time of $UE_1^1$ (see fig. 4.8).

RR can’t provide GBR for same reasons explained in the first scenario. It allocates RBs to bearers in order, for that reason all packets wait same amount of time to be transmitted. The applications associated with $UE_1^1$ require high throughput with relative to MCS of the UEs and since it takes RR multiple consecutive TTIs to transmit a single packet for this UEs— again, because of low MCS — packets are dropped once they reach to delay threshold (fig. 4.7), thus it fails to provide $UE_1^1$ with appropriate data rate. Also, for the same reason average waiting time is longer for this bearer (fig. 4.8).

PQA differentiate between GBR bearers. In this scenario, as well, average waiting time for packets are proportional to PDBs of bearers (fig 4.8) for the same reason explained in the discussion of the first scenario. Because QCI-3 has shorter PDB than QCI-1 has, QCI-3 bearers’ packets wait shorter than QCI-1 ones, although QCI-1 has higher priority. PQA again achieves zero packet loses (fig. 4.7) and provides minimum data rates to all the GBR bearers (fig. 4.6).

In a scenario where PQA satisfies all the bearers and performs zero packet losses, CQA losses over 10,000 packets from two bearers and similarly RR performs over 13,000 packet losses from two bearers.
Table 4.6: Application Configuration Settings - Second Scenario

<table>
<thead>
<tr>
<th>Instance</th>
<th>$UE_1^j$</th>
<th>$UE_2^j$</th>
<th>$UE_3^j$</th>
<th>$UE_4^j$</th>
<th>$UE_5^j$</th>
<th>$UE_6^j$</th>
<th>GBR (Bps)</th>
</tr>
</thead>
<tbody>
<tr>
<td>App-1</td>
<td>3</td>
<td>8</td>
<td>10</td>
<td>16</td>
<td>17</td>
<td>27</td>
<td>136375</td>
</tr>
<tr>
<td>App-2</td>
<td>3</td>
<td>8</td>
<td>10</td>
<td>16</td>
<td>17</td>
<td>28</td>
<td>3750</td>
</tr>
<tr>
<td>App-3</td>
<td>3</td>
<td>8</td>
<td>10</td>
<td>16</td>
<td>17</td>
<td>28</td>
<td>17250</td>
</tr>
<tr>
<td>App-4</td>
<td>3</td>
<td>8</td>
<td>10</td>
<td>16</td>
<td>17</td>
<td>28</td>
<td>2255</td>
</tr>
</tbody>
</table>

Figure 4.6: GBR requirements — Second Scenario

4.5.4 Third Scenario- All QCI Bearers with Higher Demand

With this scenario, priority performances are intended to be gauged. This scenario is same as first scenario — All QCI bearers— except the number RBs needed to satisfy GBR requirements - 50000 RBs. The MCS value of UE2 who utilizes App-8 reduced from 8 to 7 in order to increase resource demand. RB demand is increased in order to have the PQA perform packet losses for the first scenario where it did not before. Priority performances are measured by observing in what bearers losses occur the
most. Figure 4.9 shows aggregated packet losses for bearers with same QCI in every second.

**Discussion over the results of Third scenario:** The PQA achieves lowest number of losses and starts losing packet at 37th second. Losses, mostly, occur in the three bearers with lowest priorities — QCI-7, QCI-8 and QCI-9. That is because PQA considers priorities while satisfying minimum bit rates for GBR bearers and PELR for NGBR bearers. If, at any TTIs, a packets has to be dropped PQA selects bearers with lowest BII unless there is a bearer with relatively higher BII that has met its QoS requirements in the system at that moment. The reason that losses in QCI-5 is higher than QCI-6 is because application that is associated with QCI-5 has much shorter IAT — 1.86 ms vs 236.6 ms — (Table 4.6). That means, at any time, the chances that a packet belong to QCI-5 being the packet with lowest BII is higher
Figure 4.8: Average time packets wait to be transmitted — Second Scenario

than for QCI-6 bearer’s ones in the system. Second reason is that QCI-5 has much shorter PDB than QCI-6 although they share similar PELR (Table 4.2). Longer delay budget decreases the chances of a packet being dropped.

As for CqaPf, losses happen immediately after simulations starts and occur only in CQI-5 bearers. It is observed that this is the UE with the lowest MCS — $UE_1^5$. This happens for two reasons; first, application associated with QCI-5 has relatively bigger packet size and the shortest packet IAT. This is why it happens only in QCI-5 but not in other NGBR bearers. Second, CqaPf considers channel quality in its decision making which is why losses occur only in the $UE_1^5$ but not in other UEs with better channel conditions — $UE_2^5$ and $UE_3^5$.

Similarly, in RR, losses only occur to QCI-1 and QCI-5 bearers that are used by UEs with unfavorable channel conditions.
In a scenario where PQA satisfies all the bearers and performs 67 packet losses only, CQA losses over 10,000 packets from two bearers and similarly RR performs over 25,000 packet losses from two bearers.

Finally, figure 4.10 illustrates the system throughput achieve by each scheduler in two scenarios discussed. Since PQA performs least packet losses in all the scenarios, it accomplishes the highest cell throughput. CqaPf perform less packet losses than RR, that is why it has better system throughput than RR.

Figure 4.9: Packet Losses — Scenario-3
4.6 Conclusion

In this chapter, a novel scheduling solution in the context of public safety networks to provide QoS requirements for the UE is discussed. Existing solutions are analyzed, scheduling priority is described, and why it needs to be addressed is explained. PSBN is a private network with very strict requirements. Scheduling algorithms developed for commercial LTE networks are unable to deliver proper QoS, thus depriving first responders of critical communications. Channel and/or QoS schedulers can not guarantee that the most important application will be served at all time. Therefore, priorities of bearers must also involve in the scheduling process. Proposed solution is the only algorithm, so far, that considers all the scheduling attributes — bearer type, priority, PDB and PELR — when scheduling packets. It decreases packet losses due
PDB; thus, increases cell throughput while handling QoS parameters of bearers in a priority-aware manner.
Chapter 5 - A Channel and QoS-Aware Scheduler for LTE Networks

In the third chapter, we propose a channel-aware and QoS-unaware scheduler, FAHT, to address the challenge of multiuser scheduling in the downlink of LTE networks. For this chapter, we incorporate QoS provisioning into decision making process of FAHT and implement it in the scenarios we developed in the Chapter 4. We call this new algorithm as QoS-Aware FAHT (QFAHT). We compare its performances with PQA’s and other existing solutions’ in terms of GBR provisioning, packet loss ratio, delay and spectral efficiency.

In order to support QoS requirements for different type applications the 3GPP studied the needs of applications on LTE and identified their attributes in [7]. Each EPS bearer is associated with different QoS requirements. Applications in LTE are mapped to different QCI bearers depending on their characteristics. The proposed scheduler aims at maximizing spectral efficiency while providing QoS requirements in terms of delay, in which PLER and GBR requirements are met indirectly.

5.1 The Proposed Scheduling Algorithm

The QFAHT is based on joint time domain (TD) and frequency domain (FD) scheduling. In the TD, at each ms, the QFAHT selects from bearers that have data to transmit and groups them by RT calculating the metric $m_{td}^i(t)$ in the following way:

$$m_{td}^i(t) = \left\lfloor \frac{d_{RT}^i(t)}{g} \right\rfloor$$  \hspace{1cm} (5.19)
where $d_{RT}^j$ is the current value of RT delay for bearer $i$ and $g$ is the grouping parameter that determines granularity of the groups, i.e. the number of flows that will be considered in the FD scheduling, which is set to 15 ms. For example, a bearer with RT less than or equal to 15 ms will go into group id 0, and bearer with remaining time larger than 15 ms and less than or equal to 30 ms will go into group id 1, and so on. GBR and NGBR bearers are grouped differently. After all grouping is done. GBR bearers group ids are mapped to $2 \times \text{group.id}$ and NGBR bearers’ groups are mapped to $2 \times \text{group.id} + 1$

The grouping is used to select the most urgent bearers, i.e., with the lowest value of RT delay, and to enforce the scheduling mechanism to consider those bearers in the following FD scheduling iteration. A low value for $g$ gives more importance to the $d_{RT}$ metric in the scheduling; on the other hand, it reduces the users diversity, thus decreases scheduler’s gains in the FD. On the contrary, a high value for $g$ increases the users diversity, thus increases FD gains, but $d_{RT}$ has less impact in scheduling decisions [31]. The proposed algorithm aims to meet the requirements of both commercial LTE and PSBN. We set grouping parameter to 15 ms for all the scenarios tested. A low grouping parameter value is a better fit for PSBN in order to give more importance to the $d_{RT}$ metric and achieve low packet loss ratio; yet, as for commercial LTE networks, a higher grouping parameter will serve better to increases FD gains.

In the FD, starting from group with lowest group id, the QFAHT assigns the each RB $j$ to the bearer $i$ that maximizes FD metric, which we define as in the equation (3.5) in Chapter 3:
\[
\arg \max_{i \leq N, j \leq m} \left\{ \frac{r_{i,t+1}^j}{d_i + \beta_{i,t}} \right\}
\]

where \( m \) is the number RBs and \( N \) is the number of bearer. \( d_i \) is a negligible positive constant to prevent division by zero when the current throughput is zero and \( \beta_{i,t} \) is geometric mean of the throughput for the bearer \( i \) up to time \( t \) and calculated as in the equation \((3.4)\) in Chapter 3. Once all the bearers in the current group are allocated enough RBs to transmit all the packet they have in the queue and there are still RBs available, the scheduler moves to next group with lowest group id that is larger than the id of the current group.

5.2 Performance Evaluation

5.2.1 Description of Scenarios and Simulation Setup

We use the three scenarios we define in Chapter 4 for evaluation because our purpose is to compare the performance of QFAHT with other QoS-aware schedulers. All the simulation parameters defined in Chapter 4 are valid here. We compare the performance of proposed algorithm with CQA, PQA and QoS-Aware PF (QPF). The steps of QPF are same as QFAHT. The only difference is we employ PF metric, e.g. the ratio of instantaneous achievable data rate rate to arithmetic average of bearer’s throughput, in the FD for QPF . With that, we would like to compare different metrics.
5.2.2 Results

First Scenario - All QCI Bearers

Figure 5.1 illustrates ratio of average throughput of the bearers to set minimum bit rate per GBR bearer — QCI-1, QCI-2, QCI-3, QCI-4. All the algorithms provide all GBR bearers with required minimum data rate.

Figure 5.2 shows ratio of packet loss to total number of packets generated per bearer. CqaPf fails to meet this requirement for $UE_1^5$ — QCI-5 bearer that is used by UE experiencing bad channel condition. Figure 5.3 illustrates average waiting time for packets to be transmitted in $ms$.

Discussion over the results of the first scenario: The applications associated with $UE_1^1$ and $UE_1^5$ require high throughput with relative to MCS of the UEs. CqaPf
Figure 5.2: Ratio of Packet Losses to PELR — First Scenario

Figure 5.3: Average time packets wait to be transmitted — First Scenario
divides bearers into different groups in the TD and, in the FD, bearers with GBR requirements are scheduled first and it schedules GBR bears first. That is why, $UE_1^5$ suffer losses but not $UE_1^1$, although they both have short packet IATs, larger packet sizes and experience bad channel conditions. CqaPf is also a channel-aware scheduler; thus, it favors bearers associated with better channel conditions. That is why $UE_1^5$ suffer packet losses but not $UE_2^5$ and $UE_3^5$ (fig 5.2). For same reason, packet of UEs with better channel conditions wait shorter (fig 5.3).

Waiting times for packets in CqaPf, except $UE_1^5$, are almost uniform. As for PQA, QFAHT and QPF, they are proportional to PDBs of bearers with one subtle nuance. Let’s call the multiplication of packet size and $1/IAT$ as demand. That is basically how much data an application produces in 1 second. For bearers that are associated with low demand — relatively lower packet size and/or longer IATs, e.g. QCI-2, QCI-4, and QCI-6 bearers in this scenario — the average waiting time for QFAHT and QPF are longer than PQA (Figure 5.3). In case of relatively higher demand, — relatively higher packet size and/or shorter IATs— it is other way around, except QCI-1 bearers. Remember from chapter 3 that average throughputs of bearers converge around a value. In order to preserve the equilibrium, QFAHT and QPF favors bearers that is hard to satisfy due channel conditions and/or high demand. That is why bearers QCI-2, QCI-4, and QCI-6 has longer waiting time in QFAHT and QPF than in PQA. Yet, since PQA favors QCI-1 the most, QCI-1 bearers have shorter waiting times in PQA, although applications associated with it have relatively higher demand.
Second Scenario - GBR Bearers Only

Figure 5.4 illustrates ratio of average throughput of the bearers to set minimum bit rate per GBR bearers. CqaPf fails to provide required minimum bit rate for $UE_1$. Thus, $UE_1$ suffers packet losses (fig. 5.5). Lastly, figure 5.6 illustrates average waiting time for packets to be transmitted in $ms$.

![Ratio of Average Throughput to GBR per Bearer](image)

Figure 5.4: GBR requirements — Second Scenario

**Discussion over the outcomes of the second scenario:** In chapter 4, in "Discussion over the outcomes of the second scenario", we explain why CqaPf fails and PQA manages to provide all the GBR bearers with required bit rate. Same explanation is valid here. In addition, CqaPf does not consider bearers priorities while scheduling packets. For this reason, bearer with highest priority among GBR bearers, $UE_1$, losses packets because of high demand and bad channel condition. Although QFAHT and QPF do not consider priorities either, they perform no losses
for the same user. That is where grouping parameter \( g \) comes into play. CqaPF uses 300\( ms \) as grouping parameter, thus, all the bearer goes into the same group as opposed to QFAHT and QPF where \( g \) is set to 15\( ms \). Therefore, TD has no impact in scheduling decisions at all in CqaPf.

**Third Scenario - All QCI Bearers with Higher Demand**

With this scenario we would like to illustrate priority performances. Figure 5.7 shows aggregated packet losses for bearers with same QCI in every second.

**Discussion over the results of Third scenario:** In addition to what we write in the discussion of this scenario in Chapter 4 for PQA and CqaPf, both QFAHT and QPF favor bearers with lower RT. Yet, grouping parameter is much shorter the one used in CqaPf. That is why, they both perform as good as PQA, if not better, in
Figure 5.6: Average time packets wait to be transmitted — Second Scenario

In terms of packet losses; however, since they do not consider priority, losses occur in QCI-5 bearers.

As a final observation, when grouping parameter is set to 15ms, there is negligible differences between the performances of QFAHT and QPF in the three scenarios studied.
Figure 5.7: Packet Losses — Scenario-3
Chapter 6 - Conclusion

This dissertation addresses the key challenges such as QoS, fairness, spectral efficiency, all of which are associated with resource managements in LTE networks.

In the first part, a channel-aware scheduler is designed in which fairness and system throughput challenges were addressed. Afterwards, a priority and QoS aware scheduler is proposed to handle the challenging case of scheduling packets in PSBNs. Finally, QoS awareness incorporated in the decision making process of the algorithm introduced in the first part to accomplish lower packet loss ratio; thus, better QoS provisioning and spectral efficiency.

6.1 Contributions

The contributions of this dissertation research for LTE and LTE based PSBN can be summarized as follows:

6.1.1 LTE

- The concept of proportional fairness is re-designed by using geometric average.
- The proof of weak convergence of geometric average of bearers’ throughputs is provided.
- The proof of weak converges of geometric average of throughputs to the limit points of the mean ODE is provided. The existence of a unique equilibrium of ODE determines the throughput of each user and hence delay [34].
• Performance limits of PFS for OFDMA-based downlink systems characterized by high frequency selective fading are identified.

• The improvement in system throughput, QoS, and fairness are quantified in comparison with well-known channel and QoS unaware, channel-aware QoS-unaware, and both channel and QoS aware schedulers.

6.1.2 LTE based PSBN

• Potential problems associated with scheduling packets in the PSBN are presented.

• A novel and the first scheduling algorithm, which considers all the QoS parameters, when scheduling packets, specifically designed for PSBN is devised to meet the stringent performance requirements of PSBN.

• The enhancement in fairness and spectral efficiency, and QoS provisioning are demonstrated with simulation results in comparison with algorithms in the literature.

6.2 Future Directions

This research can be extended in the following directions:

1. **FAHT.** The algorithm performs better because of fast convergence. The proof of convergence rate constitutes an important and complementary research topic. Furthermore, research can be extended to include advanced LTE features such as
MU-MIMO, carrier aggregation (CA) as well as new application paradigms with different UE traffic characteristics such as Internet of Things (IoT) applications.

2. **PQA.** The research work assumes that a successful ARP and Preemption mechanisms is already implemented in the core network, meaning in the case of congestion, FRs, who need to access to the network the most, are admitted to the system somehow. A new and novel way admitting and preempting bearers in PSBN will be a complementary research topic. Also, the priority issue in the EPC — assigning applications to proper bearer type by considering user type, incident type and application type — is crucial for a successful PSBN. Proof of optimality of proposed solution is not provided. This is a challenging research aspect.
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