Performance Evaluation of Packet Scheduling Algorithms for LTE Downlink

Ömer ARSLAN
Olufemi Emmanuel ANJORIN

School of Engineering
Blekinge Institute of Technology
371 79 Karlskrona
Sweden
This thesis is submitted to the School of Engineering at Blekinge Institute of Technology in partial fulfillment of the requirements for the degree of Master of Science in Electrical Engineering. The thesis is equivalent to 24 weeks of full time studies.
Contact Information:
Authors:
Ömer ARSLAN
E-mail: omeraslan3@gmail.com

Olufemi Emmanuel ANJORIN
E-mail: anjorinoluwafemi@yahoo.com

University advisor:
Prof. Abbas Mohammed
Department of Electrical Engineering

School of Engineering
Blekinge Institute of Technology
371 79 Karlskrona
Sweden

Internet : www.bth.se/com
Phone  : +46 455 38 50 00
Fax    : +46 455 38 50 57
Abstract

Long Term Evolution (LTE) of the Universal Mobile Telecommunications System (UMTS) is designed to revolutionize mobile broadband technology with key considerations of higher data rate, improved power efficiency, low latency and better quality of service. It promises high peak data rates of 100 Mbps downlink and 50 Mbps uplink transmissions and can operate in different bandwidths ranging from 1.4 MHz up to 20 MHz.

Scheduler makes a decision on allocation of Resource Blocks (RB) to User Equipments (UE) through the frequency and time domains. Channel Quality Indicator (CQI) is used as a main parameter during the decision process. This master thesis focuses on performance of LTE downlink scheduling. Round Robin (RR), Best CQI and a proposed Empirical scheduling solution are investigated under different bandwidth and antenna configurations.

Keywords: LTE, 3GPP, OFDMA, Downlink Scheduling, CQI.
ACKNOWLEDGEMENT

We like to express our sincere gratitude to God and to all who have contributed in various ways to the success of this work. Our deep and profound appreciate goes to our supervisor and examiner, Prof. Abbas Mohammed for his time, guidance, support and invaluable contributions given to us right from the start of the thesis work to the completion. Special thanks to all our friends, colleagues and BTH staffs/teachers whose support also helped us greatly.

Olufemi and Ömer
DEDICATION

I would like to dedicate my thesis to my parents Fatma and Bekir, my sisters Ilknur and Elif, and lastly to my nephew and niece Alper Talha and Meryem Yaren.
I would like to dedicate to Professor Abbas Mohammed for his guidance and instruction.
Lastly, thank you to my friends Farid, Yinka, Özge and everyone who has ever been in my life.

Ömer Arslan

To the Almighty God for his numerous blessings I have enjoyed.
To my great family: My Dad & Mum, Tosin & Leye, Adeleke, Adetunji and Ayo.
To my lovely friends: Elder & Mrs Olowo, Mr & Mrs Layi Oresanya, Sunday Adebanjo, Wale Opekete, Vivien, Yinka, Sesan, Emmanuel, Bro. Emma and to all well wishers.
Tack så mycket.

Olufemi Emmanuel ANJORIN
# CONTENTS

PERFORMANCE EVALUATION OF PACKET SCHEDULING ALGORITHMS FOR LTE

DOWNLINK .......................................................................................................................... I

ABSTRACT ............................................................................................................................ IV

ACKNOWLEDGEMENT ......................................................................................................... V

DEDICATION ........................................................................................................................ VI

CONTENTS ........................................................................................................................... VII

LIST OF FIGURES ................................................................................................................ IX
LIST OF TABLES ................................................................................................................... X
ACRONYMS AND NOTATION DESCRIPTION ...................................................................... XI

CHAPTER 1 - INTRODUCTION ......................................................................................... 1

1.1. BACKGROUND AND GENERAL OVERVIEW ................................................................. 1
1.2. EVOLUTION OF LTE AND RELATED CONCEPTS ...................................................... 3
1.3. DESIGN GOALS AND TARGETS ................................................................................... 4
1.4. KEY CHARACTERISTICS AND TECHNOLOGIES ........................................................... 6
1.4.1 Orthogonal Frequency division Multiplexing (OFDM) ................................................. 6
1.4.2 Single Carrier Frequency Division Multiple Access (SC-FDMA) ............................... 7
1.4.3 Multiple Input Multiple Output (MIMO) Antenna ...................................................... 7
1.5. MOTIVATION AND OBJECTIVES OF THE THESIS ................................................... 7
1.6. THESIS SCOPE AND OUTLINE ................................................................................... 8

CHAPTER 2 - SYSTEM DESCRIPTION ........................................................................... 9

2.1. LTE ARCHITECTURE .................................................................................................... 9
2.2. PHYSICAL LAYER INTERFACE .................................................................................. 11
2.2.1. BASIC TRANSMISSION SCHEME ...................................................................... 12
2.2.2. TRANSMITTER STRUCTURE ............................................................................. 13
2.2.3. LTE DOWNLINK CHANNELS ........................................................................... 14
2.2.4. LTE UPLINK MODULATION SCHEME AND CHANNELS ................................ 14
2.2.5. MULTIPLE INPUT MULTIPLE OUTPUT (MIMO) ANTENNAS ............................. 15

Single Input Multiple Output (SIMO) .............................................................................. 15
Multiple Input Single Output (MISO) .............................................................................. 15
Single User MIMO (SU-MIMO) ...................................................................................... 15
Multi User MIMO (MU-MIMO) ...................................................................................... 15

2.3. FDD AND TDD FREQUENCY BANDS ....................................................................... 16
2.4. CHANNEL BANDWIDTH AND RESOURCE ALLOCATION .................................... 17
2.5. RADIO RESOURCE MANAGEMENT (RRM) .............................................................. 19
2.6. PROTOCOL ARCHITECTURE ..................................................................................... 19
2.7. CHANNEL CAPACITY ............................................................................................... 22
2.8. RRM ALGORITHMS ON PROTOCOL STACK .......................................................... 23
2.9. CHANNEL QUALITY INDICATOR – CQI ................................................................. 25

CHAPTER 3 ...................................................................................................................... 27

3.1. DYNAMIC SCHEDULING .......................................................................................... 28
3.2. GENERALIZED SCHEDULING MODEL ................................................................. 29
3.3. ROUND ROBIN ........................................................................................................ 29
3.4. BEST CQI ............................................................................................................... 31
3.5. EMPIRICAL SCHEDULING ALGORITHM ................................................................. 33

CHAPTER 4 ...................................................................................................................... 36

4.1. RADIO PROPAGATION ENVIRONMENT AND CHANNEL CONDITIONS .......... 36
4.2. ITU CHANNEL MODEL ............................................................................................. 37
4.3. SIMULATION ASSUMPTIONS ................................................................................... 38
4.4. SCENARIO 1 – MULTI-USER SISO ......................................................................... 38
List of Figures

Figure 1.1 Flat architecture of LTE .......................................................... 2
Figure 1.2 Evolution of Mobile Networks .................................................. 3
Figure 1.3 Evolution of LTE ................................................................. 4

Figure 2.1 LTE architecture ..................................................................... 9
Figure 2.2 OFDM Spectrums [1] ............................................................... 11
Figure 2.3 LTE downlink physical resource based on OFDM .................... 12
Figure 2.4 LTE eNodeB Transmitter signal chain ..................................... 13
Figure 2.5 LTE UE Receiver signal chain ................................................ 13
Figure 2.6 Frame structure type 1 FDD [1] .............................................. 17
Figure 2.7 Frame structure type 2 TDD [1] .............................................. 17
Figure 2.8 Channel bandwidth definition and transmission bandwidth configuration for one E-UTRA carrier ................................................. 18
Figure 2.9 LTE protocol structures .......................................................... 20
Figure 2.10 Channel capacity for different bandwidths in SISO .................. 23
Figure 2.11 Mapping of the primary RRM functionalities to the different layers [13] ................................................................. 24

Figure 3.1 Generalized scheduling model ................................................. 29
Figure 3.2 Flowchart of RR schedule algorithm ....................................... 30
Figure 3.3 RR scheduler behavior for two users ....................................... 31
Figure 3.4 Basic FDPS concept and terminology ..................................... 31
Figure 3.5 Flowchart of Best CQI scheduler algorithms .......................... 32
Figure 3.6 Channel dependent scheduling .............................................. 32
Figure 3.7 Data Rate Control ................................................................. 33
Figure 3.8 Flowchart of empirical scheduler algorithm ............................ 35

Figure 5.1 Throughput Graphs for (A) 1.4 MHz and (B) 3 MHz ............... 41
Figure 5.2 Throughput Graphs for (A) 5 MHz and (B) 10 MHz ............... 41
Figure 5.3 Throughput Graphs for (A) 15 MHz and (B) 20 MHz ............ 42
Figure 5.4 BLER Graphs for (A) 1.4 MHz and (B) 3 MHz ..................... 43
Figure 5.5 BLER Graphs for (A) 5 MHz and (B) 10 MHz ..................... 44
Figure 5.6 BLER Graphs for (A) 15 MHz and (B) 20 MHz .................... 44
Figure 5.7 Throughput Graphs for (A) 1.4 MHz and (B) 3 MHz ............. 45
Figure 5.8 Throughput Graphs for (A) 15 MHz and (B) 20 MHz ............ 46
Figure 5.9 Throughput Graphs for (A) 15 MHz and (B) 20 MHz ............ 46
Figure 5.10 BLER Graphs for (A) 1.4 MHz and (B) 3 MHz ................... 47
Figure 5.11 BLER Graphs for (A) 5 MHz and (B) 10 MHz ................... 47
Figure 5.12 Throughput Graphs for (A) 15 MHz and (B) 20 MHz .......... 48
List of Tables

Table 1.1 LTE user throughput and spectrum efficiency requirements [1] .......................5
Table 1.2 Interruption time requirement [1] ..................................................................5

Table 2.1 Parameters for downlink transmission scheme [14] ..................................12
Table 2.2 (A) FDD and (B) TDD frequency band ..................................................16
Table 2.3 Transmission bandwidth configuration in EUTRAN ..................................18
Table 2.4 Cyclic Prefix Value ..................................................................................21
Table 2.5 CQI Table (4-bit) [14] ...........................................................................25

Table 4.1 ITU Pedestrian B [25] ...........................................................................38
Table 4.2 Simulation Parameters of Multiple-Users SISO Scenario .....................39
Table 4.3 Simulation Parameters of Multiple-Users MIMO Scenario ..................40
## Acronyms and Notation Description

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>3GPP</td>
<td>3rd Generation Partnership Project</td>
</tr>
<tr>
<td>4G</td>
<td>4th Generations</td>
</tr>
<tr>
<td>BLER</td>
<td>Block Error Rate</td>
</tr>
<tr>
<td>BS</td>
<td>Base Station</td>
</tr>
<tr>
<td>CDMA</td>
<td>Code Division Multiple Access</td>
</tr>
<tr>
<td>CP</td>
<td>Cyclic Prefix</td>
</tr>
<tr>
<td>CQI</td>
<td>channel quality indicator</td>
</tr>
<tr>
<td>DL</td>
<td>Downlink</td>
</tr>
<tr>
<td>eNodeB</td>
<td>E-UTRAN Node B</td>
</tr>
<tr>
<td>E-UTRAN</td>
<td>Evolved Universal Terrestrial Radio Access Network</td>
</tr>
<tr>
<td>EPC</td>
<td>Evolved Packet Core</td>
</tr>
<tr>
<td>FDD</td>
<td>Frequency Division Duplex</td>
</tr>
<tr>
<td>FDMA</td>
<td>Frequency Division Multiple Access</td>
</tr>
<tr>
<td>GSM</td>
<td>Global System for Mobile Communications</td>
</tr>
<tr>
<td>HARQ</td>
<td>Hybrid Automatic Repeat Request</td>
</tr>
<tr>
<td>HSPA</td>
<td>High Speed Packet Access</td>
</tr>
<tr>
<td>LA</td>
<td>Link Adaptation</td>
</tr>
<tr>
<td>LTE</td>
<td>Long Term Evolution</td>
</tr>
<tr>
<td>MAC</td>
<td>Medium Access Control</td>
</tr>
<tr>
<td>MME</td>
<td>Mobility Management Entity</td>
</tr>
<tr>
<td>MIMO</td>
<td>Multi Input Multiple Output</td>
</tr>
<tr>
<td>MUMIMO</td>
<td>Multi User Multiple Input Multiple Output</td>
</tr>
<tr>
<td>MUSISO</td>
<td>Multiple User Single Input Single Output</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency Division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency-Division Multiple Access</td>
</tr>
<tr>
<td>PAPR</td>
<td>Peak-to-Average Power Ratio</td>
</tr>
<tr>
<td>PedB</td>
<td>Pedestrian B</td>
</tr>
<tr>
<td>PBCH</td>
<td>Physical Broadcast Channel</td>
</tr>
<tr>
<td>PCFICH</td>
<td>Physical Control Format Indicator Channel</td>
</tr>
<tr>
<td>PDCCH</td>
<td>Physical Downlink Control Channel</td>
</tr>
<tr>
<td>PDSCH</td>
<td>Physical Downlink Shared Channel</td>
</tr>
<tr>
<td>P-GW</td>
<td>Public Data Network Gateway</td>
</tr>
<tr>
<td>PRACH</td>
<td>Physical Random Access Channel</td>
</tr>
<tr>
<td>PMCH</td>
<td>Physical Multicast Channel</td>
</tr>
<tr>
<td>Abbreviation</td>
<td>Description</td>
</tr>
<tr>
<td>--------------</td>
<td>-------------</td>
</tr>
<tr>
<td>PUCCH</td>
<td>Physical Uplink Control Channel</td>
</tr>
<tr>
<td>PUSCH</td>
<td>Physical Uplink Shared Channel</td>
</tr>
<tr>
<td>QAM</td>
<td>Quadrature Amplitude Modulation</td>
</tr>
<tr>
<td>OFDM</td>
<td>Orthogonal Frequency division Multiplexing</td>
</tr>
<tr>
<td>OFDMA</td>
<td>Orthogonal Frequency Division Multiple Accesses</td>
</tr>
<tr>
<td>QoS</td>
<td>Quality of Service</td>
</tr>
<tr>
<td>QPP</td>
<td>Quadratic Permutation Polynomial</td>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
</tr>
<tr>
<td>RAN</td>
<td>Radio Access Network</td>
</tr>
<tr>
<td>RB</td>
<td>Resource Block</td>
</tr>
<tr>
<td>RLC</td>
<td>Radio Link Control</td>
</tr>
<tr>
<td>RR</td>
<td>Round Robin</td>
</tr>
<tr>
<td>RRM</td>
<td>Radio Resource Management</td>
</tr>
<tr>
<td>S1</td>
<td>The interface between eNodeB and the SAE</td>
</tr>
<tr>
<td>SAE</td>
<td>System Architecture Evolution</td>
</tr>
<tr>
<td>SC-FDMA</td>
<td>Single Carrier Frequency Division Multiple Access</td>
</tr>
<tr>
<td>S-GW</td>
<td>Serving Gateway</td>
</tr>
<tr>
<td>SISO</td>
<td>Single Input Single Output</td>
</tr>
<tr>
<td>SINR</td>
<td>Signal to Interference and Noise Ratio</td>
</tr>
<tr>
<td>SNR</td>
<td>Signal to Noise Ratio</td>
</tr>
<tr>
<td>TDD</td>
<td>Time Division Duplex</td>
</tr>
<tr>
<td>TD-SCDMA</td>
<td>Time Division Synchronous Code Division Multiple Access</td>
</tr>
<tr>
<td>TTI</td>
<td>Transmission Time Interval</td>
</tr>
<tr>
<td>TTL</td>
<td>Time To Live</td>
</tr>
<tr>
<td>UE</td>
<td>User Equipment</td>
</tr>
<tr>
<td>UL</td>
<td>Uplink</td>
</tr>
<tr>
<td>UMTS</td>
<td>Universal Mobile Telecommunications System</td>
</tr>
<tr>
<td>UTRA</td>
<td>Universal Terrestrial Radio Access</td>
</tr>
<tr>
<td>W-CDMA</td>
<td>Wideband Code Division Multiple Access</td>
</tr>
</tbody>
</table>
CHAPTER 1 - INTRODUCTION

1.1. Background and General Overview

Mobile broadband has changed the way we live and work. The way we communicate is becoming enriched with higher speeds and exciting new services both at home and on the road. Long Term Evolution (LTE) plays a key role in making this happen. LTE system is a 3.9\textsuperscript{th} Generation (3.9G) radio access standard, but it is advertised as 4\textsuperscript{th} Generation (4G) by mobile carriers. It is designed to revolutionize mobile broadband technology with key considerations of higher data rates, improved power efficiency, low latency and better quality of service. It is an access technology that allows communication between a User Equipment (UE) and the Base Station (BS). It is a fully switched packet network and hence it supports the transmission of data between compliant UE’s.

Before the advent of LTE, broadband solutions including Global System for Mobile Communications (GSM) and Universal Mobile Telecommunications System (UMTS) delivered functionalities like voice, short message service, video calls and data file transfers with a maximum data rate of 20 Mbps. Although it was a great achievement when compared with older technologies, however the kind of applications and solutions developed today for users especially on mobile devices require more optimized functionalities and faster transmission rate. Any technology proposed must adopt solutions and methods that are mobile tolerant, and can operate properly in a rapidly changing channel conditions. The key performance metrics from user’s point of view for new mobile solutions are high data rates at high mobility with good quality of service and minimal transmission error. Therefore, LTE technology network is designed with radio access technique that is better optimized when compared to older radio access techniques [1].

The new Radio Access Network (RAN) developed for the new generation mobile solution is called Evolved Universal Terrestrial Radio Access Network (E-UTRAN) is composed of one node, the E-UTRAN Node B (eNodeB). This carries all the
functionalities of radio resource management. LTE is a 3rd Generation Partnership Project (3GPP) trademarked with a high performing air interface for mobile technology. The specifications, releases and standard for LTE are documented by 3GPP group. LTE specification provides downlink peak rates of at least 100 Mbps, an uplink of at least 50 Mbps and RAN round-trip times of less than 10 ms. LTE supports scalable carrier bandwidths, from 1.4 MHz to 20 MHz and supports both Frequency Division Duplex (FDD) and Time Division Duplex (TDD).

LTE is a step toward the 4th generation of radio technologies designed to increase the capacity and speed of mobile telephone networks. Operators including Ericsson, TeliaSonera and Nokia have made LTE services available on their network. Much of 3GPP Release 8 focuses on adopting 4G mobile communications technology, including an all-IP flat networking architecture. Figure 1.1[2] is a display of LTE flat architecture. The diagram describes a comprehensive architecture of LTE radio system and its core network elements, the mobility management entity and the system architecture evolution gateway. It incorporates the interconnection of existing technologies like GSM, Wideband Code Division Multiple Access (WCDMA) / High Speed Packet Access (HSPA), Code Division Multiple Access (CDMA) solutions to the LTE system.

![Figure 1.1 Flat architecture of LTE](image-url)
LTE is designed to support seamless passing to cell towers with older network technology such as GSM, CDMA and WCDMA. The main advantages with LTE systems are high throughput, low latency, plug and play features, FDD and TDD on the same platform, an improved end-user experience and a simple architecture resulting in low operating costs. The next step for LTE evolution is LTE Advanced which is currently being standardized in 3GPP Release 10.

### 1.2. Evolution of LTE and Related Concepts

The first work on LTE began with improvement on HSPA specifications in release 7 of the 3GPP UMTS specifications. HSPA is an evolution of WCDMA built with a strong requirement for backward compatibility to existing networks while LTE has fewer restrictions on backward compatibility, and is built to solve more complex spectrum situations. Release 8 is characterized by development of the specification of LTE and System Architecture Evolution (SAE). On the radio access network, LTE was originally referred to as the Evolved UTRAN access network while on the core network, the evolution towards the Evolved Packet Core (EPC) is known as the System Architecture Evolution. Future works are done on the current release 10. A summary of the trend of various 3GPP releases is given in Figure 1.2 [3] and Figure 1.3 [3].

![Figure 1.2 Evolution of Mobile Networks](image)

Figure 1.2 Evolution of Mobile Networks
The goals and targets for LTE are set and documented in 3GPP TR 25.913. These requirements are divided into 7 areas [1]:

- **Capabilities**
  - Increased data rates supported on varying frequency ranges across the spectrum allocation. When the system operates at 20 MHz the target peak data rate should be 100 Mbps and 50 Mbps for downlink and uplink transmissions respectively.
  - The latency requirements are subdivided into control plane and user plane requirements. Control plane manages UE transition states while User plane defines the time it takes to transmit packet from the terminal to RAN and vice-versa and which should not exceed 5 ms. Transition of UE from a camped state or idle mode state, should have a latency of 100 ms and transition time from a dormant state, a latency of 50 ms.

- **System performance:** This covers throughput, spectrum efficiency, mobility and coverage.
  - Users throughput requirement is specified at fifth percentile of user distribution which mean 95 percent of users will have improved performance.

---

**Figure 1.3 Evolution of LTE**

1.3. **Design Goals and Targets**

The goals and targets for LTE are set and documented in 3GPP TR 25.913. These requirements are divided into 7 areas [1]:

- **Capabilities**
  - Increased data rates supported on varying frequency ranges across the spectrum allocation. When the system operates at 20 MHz the target peak data rate should be 100 Mbps and 50 Mbps for downlink and uplink transmissions respectively.
  - The latency requirements are subdivided into control plane and user plane requirements. Control plane manages UE transition states while User plane defines the time it takes to transmit packet from the terminal to RAN and vice-versa and which should not exceed 5 ms. Transition of UE from a camped state or idle mode state, should have a latency of 100 ms and transition time from a dormant state, a latency of 50 ms.

- **System performance:** This covers throughput, spectrum efficiency, mobility and coverage.
  - Users throughput requirement is specified at fifth percentile of user distribution which mean 95 percent of users will have improved performance.
Spectrum efficiency target is defined as system throughput per cell in bit/s/MHz/cell as defined in Table 1.1.

Table 1.1 LTE user throughput and spectrum efficiency requirements [1]

<table>
<thead>
<tr>
<th>Performance Measure</th>
<th>Downlink Target Relative to Baseline</th>
<th>Uplink Target Relative to Baseline</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average user throughput</td>
<td>3x-4x</td>
<td>2x-3x</td>
</tr>
<tr>
<td>(per MHz)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Cell-edge user throughput</td>
<td>2x-3x</td>
<td>2x-3x</td>
</tr>
<tr>
<td>(per MHz, 5th percentile)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Spectrum efficiency</td>
<td>3x-4x</td>
<td>2x-3x</td>
</tr>
<tr>
<td>(bit/s/Hz/cell)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

- Mobility requirements
  - Maximum performance low terminal speeds up to 15 km/h.
  - High performance 120 km/h.
  - Maximum speeds limit 350 km/h.
  - Coverage requirements: This centre of cell range and radius. Slight degradation of throughput is permitted for cells with up to 30 km cell range.

- Deployment requirements
  - Standalone system and coexistence with other 3GPP systems scenarios.
  - Interruption requirements: longest allowable interruption differs for both real-time and non-real time services. Table 1.2 summarizes the requirements.

Table 1.2 Interruption time requirement [1]

<table>
<thead>
<tr>
<th></th>
<th>Non-real Time (ms)</th>
<th>Real-time (ms)</th>
</tr>
</thead>
<tbody>
<tr>
<td>LTE to WCDMA</td>
<td>500</td>
<td>300</td>
</tr>
<tr>
<td>LTE to GSM</td>
<td>500</td>
<td>300</td>
</tr>
</tbody>
</table>

- Architecture and Migration
  - LTE RAN architecture should be packet based, while the system should also support real time traffic.

- Radio Resource Management
- Verifies system support for end-to-end Quality of Service (QoS) requirements. Services, applications and protocol requirements must match RAN characteristics and resources.

- Complexity
  - The requirements ensures no redundant function across the network platform

- General aspects
  - Cost and services requirement. Minimized cost and optimized performance is addressed

Summary of 3GPP original LTE requirements:
- Increased peak data rates: 100 Mbps downlink and 50 Mbps uplink
- Reduction of RAN latency to 10 ms
- Improved spectrum efficiency
- Cost-effective migration from release 6 Universal Terrestrial Radio Access (UTRA) radio interface and architecture
- Improved broadcasting
- IP-optimized switched domain
- Scalable bandwidth of 20 MHz, 15 MHz, 10 MHz, 5 MHz, 3 MHz, and 1.4 MHz
- Support for both paired and unpaired spectrum (FDD and TDD)

1.4. Key Characteristics and Technologies

1.4.1 Orthogonal Frequency division Multiplexing (OFDM)
LTE uses OFDM for downlink data transmission by subdividing available bandwidth into narrowband subcarriers while allowing parallel transmission of data on these subcarriers. OFDM ensures the subcarriers are orthogonal when transmitting several data symbols in parallel which results in better spectral efficiency. It eliminates inter-symbol interference by preceding each OFDM symbol by a cyclic prefix and it is robust to time dispersion [1]. The only drawback of OFDM is related to power amplifier inefficiency [3].
1.4.2 Single Carrier Frequency Division Multiple Access (SC-FDMA)

It is the single carrier access technique used by LTE for uplink of data transmission. It utilizes single carrier modulation and orthogonal frequency multiplexing using DFT-spreading in the transmitter and frequency domain equalization in the receiver. A major advantage is the transmitting signal has a lower peak average power ratio (PAPR) which increases the efficiency of the power amplifier.

1.4.3 Multiple Input Multiple Output (MIMO) Antenna

LTE architecture engages the use of multiple antennas both at the transmitter and receivers. The transmitter can transmit data over more than one antenna at the same time. This allows for a significant increase in data throughput from sender to receiver.

1.5. Motivation and Objectives of the Thesis

The motivation of this study comes from the fact that LTE is expected to serve more than 80% of all mobile broadband users in the near future. Users desire for high data rates have increased exponentially hence it is expected that users will engage the network with more resource demanding applications. Therefore effective scheduling of radio resources on LTE system is a key performance indicator for providers.

The Objective of the thesis is to study and analyze the impact of resource scheduling algorithms on the performance of the downlink LTE system under varying channel conditions. Two scheduling algorithms are considered: Round robin scheduling and the Best Channel Quality Indicator (CQI) scheduling. The evaluation will be based on performance metrics like block error rate (BLER), signal-to-noise ratio (SNR) and Throughput vs. SNR for Multi User Single Input Single Output (MUSISO) and Multi User Multiple Input Multiple Output (MU-MIMO) systems. We propose an alternative scheduling algorithm. The algorithm will include the constraints related to a real system. The expected outcome is an algorithm that is able to manage the scheduling of best effort and real time traffic with a good UE satisfaction. A compromise between fairness and throughput is achieved.
1.6. Thesis Scope and Outline

In this thesis we discuss the core architecture of LTE network, radio resource algorithms fundamentals and dependencies, the effect and importance of resource allocation as a key contribution to maintaining an efficient LTE system. The thesis contribution is in the approach and method of evaluation of the LTE network elements. A thorough evaluation was carried out on each factor that contributes to better resource scheduling using MATLAB simulator. The results of the evaluation of three scheduling algorithm are plotted and interpreted in the Thesis.

Chapter one presents an introduction and overview of the LTE system. Chapter two introduces the LTE architecture and related technologies and algorithms for resources management. Chapter three analyzes the scheduling algorithms. Chapter four focuses on simulation requirements. Chapter five presents the simulation results and evaluates the scheduling algorithms and performance of LTE downlink. Chapter six gives the conclusion of the thesis work.
CHAPTER 2 - SYSTEM DESCRIPTION

2.1. LTE Architecture

The 3GPP LTE architecture includes specifications for a core network, the EPC and for a RAN, the E-UTRAN. Figure 2.1 displays a simplified LTE architecture.

The EPC has the components of the mobility management entity (MME), serving gateway (S-GW) and the packet data network gateway (P-GW). The EPC components can be grouped into two main planes: the user plane and the control plane. While MME forms the core of the control plane, S-GW forms the core of the user plane. MME is an entity that manages signalling and connections with RAN. S-GW is the system that forwards and receives packets from RAN. The P-GW is the termination point of the packet data interface and it interfaces with the packet data network [6][7]. The S1 interface connects the eNodeB to the MME and S-GW. It supports the user and control plane traffic between the E-UTRAN and EPC. The 3GPP specification document for general packet radio service enhancements and architecture enhancements defines the EPC standards [9] [10].

The proposed E-UTRAN LTE system is composed of one component eNodeB. Several eNodeB are connected together using the X2 interface which is designed to minimize
packet loss caused by mobility of UE. The LTE-Uu interface is the standard that connects the UE to eNodeB, and it enables transmission/reception and radio resource management functions. To achieve the LTE target, eNodeB uses OFDM for the downlink (base station also known as eNodeB to handset) and single carrier frequency division multiple access (SC-FDMA) for the uplink and employs MIMO with up to four antennas per station.

In order to achieve high peak rates in LTE downlink transmission, LTE adopts a method of using adaptive modulation schemes. Three modulation schemes are supported in 3GPP specification, QPSK, 16QAM and 64QAM. The channel coding scheme for transport blocks is turbo coding and a contention-free quadratic permutation polynomial (QPP) turbo code internal interleaved [7].

LTE supports both FDD and TDD mode. While FDD makes use of paired spectra for uplink (UL) and downlink (DL) transmission separated by a duplex frequency gap, TDD alternates using the same spectral resources used for UL and DL, separated by guard time. Each mode has its own frame structure within LTE and these are aligned with each other meaning that similar hardware can be used in the base stations and terminals to allow for economy of scale. The TDD mode in LTE is aligned with time division synchronous code division multiple access (TD-SCDMA) as well allowing for coexistence [4][9].

The latency requirements are divided into control plane requirements and user plane requirements. The delay experienced by the UE in transiting into an active state from a previous non-active state is addressed by the control plane latency requirements. Two measures are expressed in this requirement: one measure determines the transition time from a camped state or idle mode state, this has a latency of 100 ms and the other measure is transition time from a dormant state with latency of 50 ms.

The user plane latency requirement is stated at the time taken to transmit an IP packet from the UE to the RAN edge node or vice versa. 3GPP recommendation on one-way transmission should not exceed 5 ms in an unloaded network.
2.2. Physical Layer Interface

A key aspect of the LTE systems is the radio physical layer (uplink and downlink) interface. It is the interface that connects the base station to the UE. LTE uses OFDM technology on the interface for the downlink network. The downlink represents the transmission from the base station to the user equipment.

OFDM meets the LTE requirement for spectrum flexibility and enables cost-efficient solutions for very wide carriers with high peak rates. OFDM divides the available bandwidth into a large number of narrowband signals (subcarriers) and each of the signals is 15 kHz apart the sampling point where all other signals are zero. The subcarriers efficiently utilize available bandwidth because they are tightly spaced. Each of the OFDM symbol is preceded by a cyclic prefix (CP). The CP is used to maintain orthogonally between the subcarriers and to eliminate intersymbol interference (ISI). The OFDM spectrum is depicted in Figure 2.2.

![OFDM Spectrum](image)

**Figure 2.2 OFDM Spectrums [1]**

OFDM gives LTE downlink some flexibility in assigning resources to UE. Resources can be assigned both in time and frequency domain. The basic LTE downlink physical resource can be explained as a time-frequency grid, as illustrated in Figure 2.3 [2]. The smallest element or basic unit in LTE is an OFDM symbol also called a resource element (RE). In the time domain the radio frame is 10 ms long and consists of 10 sub-frames of 1 ms each. Every sub-frame has 2 slots and each slot is 0.5 ms. The subcarrier spacing in the frequency domain is 15 kHz and 12 sub-carrier grouped together per slot is called a resource block (RB). Therefore one RB is 180 kHz. 6 RBs fit in a carrier of 1.4 MHz and 100 RBs fit in a carrier of 20 MHz [11][14].
2.2.1. Basic Transmission Scheme

LTE physical layer translates data into a reliable signal for transmission across a radio interface between eNodeB and UE. This involves modulation, multiplexing schemes and antenna technology. The basic transmission parameters are specified more detail in Table 2.1. The sub-frame duration corresponds to the minimum downlink transmission time interval (TTI). It is assumed that eNodeB would signal the TTI either explicitly which is set by higher layer signally or dynamically. In the case of dynamic TTI, the number of sub-frames concatenated can be dynamically varied for initial transmission and re-transmissions.

Table 2.1 Parameters for downlink transmission scheme [14]

<table>
<thead>
<tr>
<th>Transmission BW</th>
<th>1.25 MHz</th>
<th>2.5 MHz</th>
<th>5 MHz</th>
<th>10 MHz</th>
<th>15 MHz</th>
<th>20 MHz</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sub-frame duration</td>
<td>0.5 ms</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sub-carrier spacing</td>
<td>15 kHz</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>1.92 MHz (1/2 × 3.84 MHz)</td>
<td>3.84 MHz (2 × 3.84 MHz)</td>
<td>7.68 MHz (4 × 3.84 MHz)</td>
<td>15.36 MHz (6 × 3.84 MHz)</td>
<td>23.04 MHz (8 × 3.84 MHz)</td>
<td>30.72 MHz (16 × 3.84 MHz)</td>
</tr>
<tr>
<td>FFT size</td>
<td>128</td>
<td>256</td>
<td>512</td>
<td>1024</td>
<td>1536</td>
<td>2048</td>
</tr>
<tr>
<td>Number of occupied sub-carriers</td>
<td>76</td>
<td>151</td>
<td>301</td>
<td>601</td>
<td>901</td>
<td>1201</td>
</tr>
<tr>
<td>Number of OFDM symbols per sub frame (Short/Long CP)</td>
<td>7/6</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP length (μs/samples)</td>
<td>Short: (4.69/9) × 6, (5.21/10) × 1*</td>
<td>(4.69/18) × 6, (5.21/20) × 1</td>
<td>(4.69/36) × 6, (5.21/40) × 1</td>
<td>(4.69/72) × 6, (5.21/80) × 1</td>
<td>(4.69/108) × 6, (5.21/120) × 1</td>
<td>(4.69/144) × 6, (5.21/160) × 1</td>
</tr>
</tbody>
</table>

Figure 2.3 LTE downlink physical resource based on OFDM.
It should be noted that regardless of the transmission bandwidth, sub-carrier spacing is always constant. To achieve an expected data rate, the operations of LTE transmission in differently sized spectrum allocations, is enhanced by varying the number of OFDM sub-carriers, this eventually dynamically varies the transmission bandwidth.

### 2.2.2. Transmitter Structure

The block diagram in Figure 2.4 [27] and Figure 2.5 [28] describes the LTE Transmitter and Receiver respectively.

![Figure 2.4 LTE eNodeB Transmitter signal chain](image1)

![Figure 2.5 LTE UE Receiver signal chain](image2)
2.2.3. LTE Downlink Channels

In the downlink there are three main physical channels used in LTE transmission [5].

- Physical Downlink Shared Channel (PDSCH) is used for all the data transmitted. Supported modulation formats on the PDSCH are QPSK, 16QAM and 64QAM.
- Physical Multicast Channel (PMCH) is used for broadcast transmission using a Single Frequency Network.
- Physical Broadcast Channel (PBCH) is used to send most important system information within the cell.

Control information and data transmission are time multiplexed within each downlink TTI are reserved for transmission of the related downlink control channels such as the physical downlink control channel (PDCCH) as well as the physical control format indicator channel (PCFICH). The PCFICH carries information on the time duration of the control channel (1-3 OFDM symbols), while the PDCCH carries the dynamic scheduling grants for both downlink and uplink.

The remaining OFDM symbols within the TTI are used for transmission of user data and common/dedicated reference signals. The information carried on the PDCCH includes the indication of the user’s frequency domain allocation, the used modulation and coding scheme, and so on. The allocated resources combined with modulation and coding scheme are used to define the used transport block size. This information enables the user to demodulate and decode the transport blocks transmitted by the eNodeB.

2.2.4. LTE Uplink Modulation Scheme and Channels

In the uplink LTE uses a pre-coded version of OFDM called Single Carrier Frequency Division Multiple Access (SC-FDMA). This is to compensate for a drawback with normal OFDM, which has a very high PAPR. High PAPR requires expensive and inefficient power terminal and drains the battery faster. SC-FDMA solves this problem by grouping together the resource blocks in a way that reduces the need for linearity, and so power consumption, in the power amplifier. A low PAPR also improves
coverage and the cell-edge performance. The uplink has three main physical channels. While the Physical Random Access Channel (PRACH) is only used for initial access and when the UE is not uplink synchronized all the data is sent on the Physical Uplink Shared Channel (PUSCH) [4].

2.2.5. Multiple Input Multiple Output (MIMO) Antennas

LTE air interface uses more than one antenna at both the transmitter and the receiver. The use of multiple antennas by communicating entities in LTE system offers significant possibilities of high data throughput, without a need for a corresponding increase in bandwidth or transmits power. When the system uses more antennas an extra spatial dimension is open to signal pre-coding and detection. There are various classification of MIMO operations based on the availability of these antennas, these include:

**Single Input Multiple Output (SIMO)**

The transmitter uses one antenna while the receiver has two or more antennas. This forms a technique called receive diversity.

- **Receive Diversity**: receiver can combine several copies of the received signal to get a better reception.

**Multiple Input Single Output (MISO)**

The transmitter utilizes more than one antenna to transmit data to a receiver.

- **Beam forming**: This involves pointing the antenna beam towards a specific user by using different phase shifts on the additional antennas.
- **Transmit Diversity**: It is a process of transmitting more copies of the same data using different delays to get artificial time dispersion.

**Single User MIMO (SU-MIMO)**

One UE has multiple antennas both for transmit and receive from eNodeB.

**Multi User MIMO (MU-MIMO)**

Several UE’S can communicate with an eNodeB. For instance, in downlink MU-MIMO transmission mode, two users can be spatially multiplexed per TTI and per physical resource block.
- Spatial Multiplexing: This technique multiplexes different data streams and transmits the data streams simultaneously in parallel over two or more antennas.
- Spatial Diversity: It is used to increase the robustness of communication in fading channels by transmitting multiple replicas of the transmitted signal using different antennas.

2.3. FDD and TDD Frequency Bands

In LTE 3GPP specification, 15 different FDD frequency bands and 8 different TDD frequency bands have been defined for use as shown in Table 2.2. With FDD, downlink and uplink traffic is transmitted simultaneously in separate frequency bands. With TDD, transmission is discontinuous within the same frequency bands. This flexibility in spectrum allocation on LTE network will aid its deployment on multiple bands.

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency UL/DL (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1920 – 1980/2110 – 2170</td>
</tr>
<tr>
<td>3</td>
<td>1710 – 1785/1805 – 1880</td>
</tr>
<tr>
<td>4</td>
<td>1710 – 1755/2110 – 2155</td>
</tr>
<tr>
<td>5</td>
<td>824 – 849/869 – 894</td>
</tr>
<tr>
<td>6</td>
<td>830 – 840/875 – 885</td>
</tr>
<tr>
<td>7</td>
<td>2500 – 2570/2620 – 2690</td>
</tr>
<tr>
<td>8</td>
<td>885 – 915/925 – 960</td>
</tr>
<tr>
<td>9</td>
<td>1750 – 1805/1845 – 1880</td>
</tr>
<tr>
<td>10</td>
<td>1710 – 1770/2110 – 2170</td>
</tr>
<tr>
<td>11</td>
<td>1428 – 1453/1476 – 1501</td>
</tr>
<tr>
<td>12</td>
<td>698 – 716/728 – 746</td>
</tr>
<tr>
<td>13</td>
<td>777 – 783/794 – 756</td>
</tr>
<tr>
<td>14</td>
<td>768 – 798/758 – 768</td>
</tr>
<tr>
<td>15</td>
<td>704 – 716/734 – 746</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Band</th>
<th>Frequency UL/DL (MHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>33,34</td>
<td>1920 – 1980</td>
</tr>
<tr>
<td></td>
<td>2010 – 2025</td>
</tr>
<tr>
<td>35,36</td>
<td>1850 – 1910</td>
</tr>
<tr>
<td></td>
<td>1930 – 1990</td>
</tr>
<tr>
<td>37</td>
<td>1910 – 1930</td>
</tr>
<tr>
<td>38</td>
<td>2570 – 2620</td>
</tr>
<tr>
<td>39</td>
<td>1880 – 1920</td>
</tr>
<tr>
<td>40</td>
<td>2300 – 2400</td>
</tr>
</tbody>
</table>
Two radio frame structure (FS) are defined for LTE. These include the structure type 1, FS1 for FDD and the frame structure type 2, FS2 for TDD. A radio frame has duration of 10 ms. Figure 2.6 and Figure 2.7 show the two categories frame structures for one sub-frame.

Figure 2.6 Frame structure type 1 FDD [1]

![Frame structure type 1 FDD](image)

Figure 2.7 Frame structure type 2 TDD [1]

![Frame structure type 2 TDD](image)

2.4. Channel Bandwidth and Resource Allocation

A key characteristic of LTE that is worth noting is spectrum flexibility. This makes LTE to operate in different sized spectrum allocation from 1.4 MHz to 20 MHz, 3GPP base station radio transmission and reception specification document 36104 [9] defines the number of resources associated with each channel bandwidth. The knowledge of the number of available resources on the different bands of frequency is strategic to LTE performance since it determines the number of resources that can be allocated to users. Table 2.3 [14] highlights this relationship and shows the exact number of resource blocks.
Table 2.3 Transmission bandwidth configuration in EUTRAN

<table>
<thead>
<tr>
<th>Channel bandwidth [MHz]</th>
<th>1.4</th>
<th>3</th>
<th>5</th>
<th>10</th>
<th>15</th>
<th>20</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of resource blocks (N_{RB})</td>
<td>6</td>
<td>15</td>
<td>25</td>
<td>50</td>
<td>75</td>
<td>100</td>
</tr>
<tr>
<td>Number of occupied subcarriers</td>
<td>72</td>
<td>180</td>
<td>300</td>
<td>600</td>
<td>900</td>
<td>1200</td>
</tr>
<tr>
<td>IDFT (Tx) / DFT (Rx) size</td>
<td>128</td>
<td>256</td>
<td>512</td>
<td>1024</td>
<td>1536</td>
<td>2048</td>
</tr>
<tr>
<td>Sample rate [MHz]</td>
<td>1.92</td>
<td>3.84</td>
<td>7.68</td>
<td>15.36</td>
<td>23.04</td>
<td>30.72</td>
</tr>
<tr>
<td>Samples per slot</td>
<td>960</td>
<td>1920</td>
<td>3840</td>
<td>7680</td>
<td>11520</td>
<td>15360</td>
</tr>
</tbody>
</table>

The relationship between Channel bandwidth and the transmission bandwidth configuration relationship is expressed in Figure 2.8 [14]. The figure identifies channel edges of E-UTRAN system. Channel edges are defined as the lowest and highest frequencies of the carrier separated by the channel bandwidth.

![Figure 2.8](image-url)

Figure 2.8 Channel bandwidth definition and transmission bandwidth configuration for one E-UTRA carrier.
2.5. Radio Resource Management (RRM)

RRM involves allocating available radio resources efficiently to users. This forms a key part of network systems and operates in view of the fact that one of the main challenges of any broadband solution like LTE is to efficiently utilize available resources and to deliver high throughput, which is only achievable through optimal performance of RRM algorithms. Radio resource management involves exploring and fine-tuning RRM algorithms under different load and traffic conditions to improve the quality of service of packet switching in LTE optimized network.

LTE radio resource algorithm includes bearer admission control, multi-user time and frequency domain packet scheduling, fast link adaptation with dynamic switching on different transmission modes and hybrid automatic repeat request (HARQ) management. One of the added objectives of RRM algorithms is to maximize system capacity while serving all users according to their minimum QoS constraints. Therefore the role of RRM is essential to ensure that radio resources are efficiently utilized, taking advantage of the available adaptation techniques, and to serve users according to their QoS attributes.

An analysis of the performance of these protocols is strategic to understanding the intricacies of packet behavior using various RRA options, detecting errors and developing solutions in line with the cooperate goals of establishing LTE as a full packet switched optimized system. In this thesis we will investigate these radio resource management algorithms with emphasis on packet scheduling. It should be noted that having the RRM algorithms in the base station with easy access to air interface measurements and monitoring provides an attractive framework for cross-layer optimization.

2.6. Protocol Architecture

The basic protocol stack of the E-UTRAN air interface is represented in Figure 2.9 [15]. The radio link control (RLC) and medium access control (MAC) layers are responsible for segmentation of packets, retransmission and multiplexing of data flows. The
The physical layer has three major responsibilities: coding, modulation and antenna resources mapping. Data to be transmitted is turbo coded and modulated using any of these modulation schemes (QPSK, 16-QAM, or 64-QAM) followed by OFDM modulation. The subcarrier spacing $\Delta f$ is 15 kHz and a normal cyclic prefix value of 4.7 $\mu$s is used for most deployments. Two cyclic prefix lengths are supported for both uplink and downlink.

![Diagram of LTE protocol structures](image)

Figure 2.9 LTE protocol structures.

An extended cyclic prefix value of 16.7 $\mu$s can be used in an environment with heavy time dispersion. Table 2.4 displays a list of supported subcarrier spacing, cyclic prefix length and the equivalent symbols per slot.
Table 2.4 Cyclic Prefix Value

<table>
<thead>
<tr>
<th>Configuration (Δf)</th>
<th>CP length (µs)</th>
<th>Symbol per slot</th>
</tr>
</thead>
<tbody>
<tr>
<td>Normal 15 KHz</td>
<td>4.7 (1st CP is 5.2 µs)</td>
<td>7</td>
</tr>
<tr>
<td>Extended 15KHz</td>
<td>16.7</td>
<td>6</td>
</tr>
<tr>
<td>7.5KHz</td>
<td>33.3</td>
<td>3</td>
</tr>
</tbody>
</table>

Transmitted signal is organized into sub-frame of 1 ms duration on the time domain, consisting of 12 OFDM symbols on the frequency domain. The scheduler determines for each 1 ms sub-frame which user(s) are permitted to transmit and on what frequency resources the transmission will take place. Packet scheduling is one of the major RRM functions and it is responsible for intelligent selections of users and transmissions of their packets such that radio resources are efficiently utilized and user’s quality of service requirements can be satisfied. The radio resources available for user in both frequency and time domain is called resource block.

- 1 Resource Element (RE) = 1 subcarrier during 1 OFDM Symbol
- 12 OFDM symbol x 15 kHz = 180 kHz
- 180 kHz x 0.5 ms = 1 RB (resource block)
- 180 kHz x 1 ms = 2 RB (resource block)

Scheduling in LTE system is performed at 1 ms interval which is equivalent to one TTI and two consecutive RBs (in time domain) are assigned to a user for a TTI. It is worth noting that the downlink and uplink transmissions are controlled by the scheduler located in the base station. The scheduler is invariably a key element and can influence the performance of an LTE system. The instantaneous CQI feedback to the base station aid the downlink scheduler in the decision process to know which users to schedule. Other elements includes hybrid-automatic repeat request (HARQ) which handles occasional retransmission errors. It has a low overhead feedback and supports for soft combining with incremental redundancy to complement the automatic repeat request protocol.
2.7. Channel Capacity

The system capacity $C$ of an Additive White Gaussian Noise (AWGN) channel is calculated with Shannon–Hartley theorem as is (2.1).

$$C = B \log_2(1 + \text{SNR})$$

(2.1)

Where $C$ is channel capacity in bits per second (b/s), $B$ is bandwidth of channel in hertz (Hz) and SNR refers to Signal to Noise Ratio (dB).

The transmission of an OFDM signal requires the transmission of a cyclic prefix (CP) to avoid inter-symbol interference and the reference symbols for channel estimation [21]. Therefore, some arrangements are made on the Shannon in (2.1) by the factor $F$ in equation (2.2). This factor $F$ accounts the inherent system losses and is calculated as in (2.3).

$$C = F B \log_2(1 + \text{SNR})$$

(2.2)

$$F = \frac{T_{\text{frame}} - T_{\text{CP}}}{T_{\text{frame}}} \cdot \frac{N_{\text{sc}} \cdot N_s/2 - 4}{N_{\text{sc}} \cdot N_s/2}$$

Reference symbol loss

(2.3)

In Equation (2.3) $T_{\text{frame}}$ is the fixed frame duration of 10 ms, $T_{\text{CP}}$ is the total CP time of all OFDM symbols within one frame. Where $N_{\text{sc}}$ is the number of subcarriers in one RB and $N_s$ is the number of OFDM symbols in one subframe [21]. $N_s$ depend on the cyclic prefix length. With normal cyclic prefix length, TCP 5.2 µs for the first symbol and 4.7µs for the remaining 6 symbols. This refers to $N_s$ as 7 symbols. For extended cyclic prefix with in 15 kHz sub-carrier spacing, $T_{\text{CP-E}}$ is 16.7µs and contains $N_s$ is 6 OFDM symbols. For 7.5 kHz sub-carrier spacing, the generic frame structure with extended cyclic prefix of $T_{\text{CP-E}}$ is 33.3µs. It contains 3 symbols.

The Channel capacity for different bandwidths with respect to SNR changes are figured in Figure 2.10.
2.8. **RRM Algorithms on Protocol stack**

As introduced above an LTE radio access network is composed of three layers namely layer 1, layer 2 and layer 3 for both the user and control planes. Figure 2.11 [13] depicts the block diagram of related RRM functions.

![Channel Capacity Graph](image-url)

Figure 2.10 Channel capacity for different bandwidths in SISO.
Figure 2.11 Mapping of the primary RRM functionalities to the different layers [13].

The physical layer (layer 1) transmits the binary information from the transmitter to receiver through a radio channel. This layer engages different layer 1 algorithms to ensure robustness of the system against signal distortions which can be caused by interference conditions of the channel. The system can achieve varying transmission qualities and spectral efficiencies depending on the algorithm that is used, which also has a dependency of the channel conditions (i.e. based on channel conditions the physical layer uses certain algorithms to achieve a pre-determined transmission quality) [6]. CQI manager is a key algorithm and controller of the physical layer. The layer 1 provides data transport services to the higher layers using transport channels. Other functions of physical layer include Error detection on the transport channels and encoding/decoding of the transport channels.

Layer 2 is called the data link layer and its main function is to allocate radio resources to users and also control their QoS. It comprises of MAC and RLC protocols. The MAC layer performs mapping between the transport and logical channels while the RLC provides sequenced delivery of data units to higher layers. The radio resources available to users include frequency subcarriers, time slots, spectrum spreading code and multi-antennas diversity scheme. Data link layer is designed to control the use of these radio resources based on the QoS requirements of network users. The following are considered key quality of service requirement of any network user: latency, error rates and throughput.
2.9. Channel Quality Indicator– CQI

Channel Quality Indicator is 5 bit information which an active UE sends as feedback to the eNodeB at regular interval. The CQI is reported every 5 TTI with a delay of 2 time to live (TTL). UE reports CQI value to eNodeB via two methods. Periodically by using physical uplink control channel (PUCCH) or physical uplink shared channel (PUSCH) and a-periodically by using PUSCH channels.

CQI is calculated at the UE based on the SNR of the received common pilot which indicates the highest modulation and the code rate at which the block error rate (BLER) of the channel analyzed does not exceed a threshold. CQI includes information not only about instantaneous channel quality but information necessary to determine the appropriate antenna processing in case of spatial multiplexing [1]. In the 3GPP Technical specification 36.213 reference [7], CQIs index are specified. The index ranges up to 15. Each numbered index relates to a modulation scheme and an equivalent channel coding rate. These values are listed in Table 2.5.

<table>
<thead>
<tr>
<th>CQI Index</th>
<th>Modulation</th>
<th>Code rate x 1024</th>
<th>Efficiency</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>Out of range</td>
<td></td>
<td></td>
</tr>
<tr>
<td>1</td>
<td>QPSK</td>
<td>78</td>
<td>0.1523</td>
</tr>
<tr>
<td>2</td>
<td>QPSK</td>
<td>120</td>
<td>0.2344</td>
</tr>
<tr>
<td>3</td>
<td>QPSK</td>
<td>193</td>
<td>0.3770</td>
</tr>
<tr>
<td>4</td>
<td>QPSK</td>
<td>308</td>
<td>0.6016</td>
</tr>
<tr>
<td>5</td>
<td>QPSK</td>
<td>449</td>
<td>0.8770</td>
</tr>
<tr>
<td>6</td>
<td>QPSK</td>
<td>602</td>
<td>1.158</td>
</tr>
<tr>
<td>7</td>
<td>16QAM</td>
<td>378</td>
<td>1.4766</td>
</tr>
<tr>
<td>8</td>
<td>16QAM</td>
<td>490</td>
<td>1.9141</td>
</tr>
<tr>
<td>9</td>
<td>16QAM</td>
<td>616</td>
<td>2.4063</td>
</tr>
<tr>
<td>10</td>
<td>64QAM</td>
<td>466</td>
<td>2.7305</td>
</tr>
<tr>
<td>11</td>
<td>64QAM</td>
<td>567</td>
<td>3.3223</td>
</tr>
<tr>
<td>12</td>
<td>64QAM</td>
<td>666</td>
<td>3.9023</td>
</tr>
<tr>
<td>13</td>
<td>64QAM</td>
<td>772</td>
<td>4.5234</td>
</tr>
<tr>
<td>14</td>
<td>64QAM</td>
<td>873</td>
<td>5.1152</td>
</tr>
<tr>
<td>15</td>
<td>64QAM</td>
<td>948</td>
<td>5.5547</td>
</tr>
</tbody>
</table>
Table 2.5 displays an implementation of three modulation schemes including QPSK, 16QAM and 64QAM. The use of higher order modulation such like 16QAM and 64QAM provides the possibility for higher bandwidth utilization and subsequently higher data rate, within a particular bandwidth. Higher order modulation schemes achieve higher data rates by using alternative signaling modulation alphabet been extended and thus allowing for more bits of information to be communicated per modulation symbol. However this does not go without an effect on the received signal having a reduced robustness to noise and interference. A reduced robustness of received signal to noise and interference will cause an increase in the probability of error rate and a necessity for a corresponding increase in the $E_b/N_o$ [26] [1]. Analysis has been done to reduce this effect and the corresponding increase of $E_b/N_o$ of the received signal, by the introduction of a channel coding factor. The combination of channel coding and the higher-order modulation will give a more efficient solution for a received signal.
CHAPTER 3

SCHEDULING ALGORITHMS

Scheduling is simply allocating or reserving resources to users in a communication system to maximize throughput and system efficiency. Scheduling in LTE downlink takes advantage of various factors including channel variations by allocating frequency and time resources to a user with transiently better channel conditions. The quality of service requirement in a multi-user communication system varies therefore the choice of a scheduling algorithm critically impacts the system performance.

Packet scheduling is one of the RRM functions and it is responsible for intelligent selections of users and transmissions of their packet. PS is located directly in the eNodeB and is performed on minimum allocation unit of 1 ms TTI basis in order for the system to adapt to fast channel variation and therefore benefit from multi-user diversity gain. The scheduler controls, for each time instant, to which users the shared resources should be assigned. It also determines the data rate to be used for each link, a function executes with Link adaptation. The scheduler is also responsible for selecting the transport-block size, the modulation scheme, and the antenna mapping. The overall system performance in the downlink is based on how efficient the scheduler is.

In LTE downlink the flexibility of allocating available resource block on the physical layer is an inherent function of a user diversity system that depends on the various techniques adopted by the scheduling algorithm. These techniques are evaluated on the basis of quality of service requirement of a user, and in terms of the maximum benefit the system can derive from it using metrics of fairness, system throughput and most especially service level agreement.

Although the scheduling strategy is implementation specific and not specified by 3GPP, the overall goal of most scheduler is satisfy the system and users requirement. A good scheduling algorithm therefore has two main objectives: First to maximize the
throughput and second to achieve fairness between users. To achieve this goal, there are many algorithms developed for wireless system, such as maximum rate scheduling, round robin (RR), best CQI and proportional fair (PF). An evaluation of the performance of these algorithms in an LTE system using known radio conditions are important to making an informed observation about the factors that contribute to realizing the LTE objectives. In this study we investigated round robin and best CQI using the pedestrian B (PedB) ITU channel model conditions and we propose an empirical algorithm scheduling method, which achieves a good throughput and satisfying fairness of each user.

3.1. Dynamic Scheduling

IEEE 802.16 and 3GPP HSDPA implements a semi-persistent scheduling for a deterministic data flow services. The principle is to assign certain transmission resources for a particular user. The time pattern for scheduling a UE in semi-persistent method is pre-configured via resource control (RRC) protocol [22]. Although the UE can be semi-persistently scheduled for real time services in LTE downlink, however eNodeB can override the decision using a dynamic scenario. One good advantage of semi-persistent is that there is good reduction of the downlink control signalling overhead.

The Packet scheduler at layer 2 in the LTE protocol stack performs scheduling decision every TTI dynamically by allocating physical resource block to UE. The scheduling decision is done on a per UE basis. During one TTI, the packet scheduler must decide between sending a new transmission or a pending hybrid ARQ retransmission. Given a certain scheduled transport block size for a UE, the MAC protocol decides what size of data is sent. The types of data flow for any UE is either a control plane data flow for RRC protocol or multiple user plane data flow. Packet scheduler in E-UTRAN LTE can be decomposed into a time-domain and frequency-domain scheduling approach.
3.2. Generalized Scheduling Model

The generalized model for packet scheduling algorithm is given in Figure 3.1 [23]. The model implements a traditional queuing system approach for LTE system, and a first in first out (FIFO) scheduling mechanism is used. The method works by accepting packets from all UE’s, en-queue the inputs on a first come first serve basis into a stack memory (or buffer) and then allocate resources in the order of arrival at the input. The figure describes a process of user’s packet arriving into an eNodeB and assigned a buffer, these packets are time stamped and queued for transmission based on FIFO.

![Figure 3.1 Generalized scheduling model](image)

In a multi user mobile communication environment the generalized model is seldom implemented except it fulfils specific quality of service requirements for our modelled network. When evaluating packet scheduling performance in a typical LTE downlink key performance indicators are system throughput and fairness.

3.3. Round Robin

Round Robin is one of the fundamental and widely used scheduling algorithms. Its running process is very simple and easy to implement. Round robin algorithm uses a principle of sharing resources on an equal time slots basis and does not consider the
channel quality information from participating user equipments [12]. Each active UE in a cell have equal access to resources and services at equal amount of time slots hence round robin algorithm is not a channel-dependent scheduling algorithm. A simple flow chart of round robin scheduling process is displayed in Figure 3.2.

![Flowchart of Round Robin Scheduling](image)

**Figure 3.2 Flowchart of RR schedule algorithm**

RR scheduler behavior for two users with different average channel quality is illustrated in Figure 3.3[1]. The figure illustrates the process of assigning resource cyclically to users. This may seems fair in the sense that same amount of radio resources is given each communication link but it is not fair in the sense of providing the same service quality to all communication links. Since RR does not take the instantaneous channel conditions into account during the scheduling process, it will result in lower overall system performance.
3.4. Best CQI

The CQI feedback values sent from UE to eNodeB as shown in Figure 3.4[3] are used to adapt the modulation and coding for appropriate UEs. The CQI value can be expressed as a recommended transport-block size instead of expressing it as a received signal quality. It can be used for the scheduling. Best CQI scheduling algorithm uses these values as a reference for making decision of scheduling. Flow chart of the scheduling algorithm is shown in Figure 3.5.
The idea is to transfer the data to the UE which has the highest CQI value which is illustrated in Figure 3.6 [1]. When the transmitter power is kept constant, data rate will vary and its variation is depending on channel quality as shown in Figure 3.7 [3].
3.5. Empirical Scheduling Algorithm

The aim of designing the algorithm is to test a low complex solution for the scheduling function of the eNodeB and to ensure a balance between fairness and throughput for UE resource allocation in an LTE downlink system. As a validation of the algorithm, we considered a multi-user environment with a minimum of three user equipments and we assumed the users have varying CQI value due to different instantaneous SNR value of the received signal from the transmitter. The strategy employed is to use an adaptive scheduling approach by tuning the system to allocate resource to a UE with the highest CQI value and make a fair allocation of remaining resources to the two other UE’s in a proportion that depends on a preset priority coefficient, D. The systems consideration for fairness may vary on resource allocation due to this priority coefficient, D and this is considered vendor specific, as there is no strict rule or standard that guide scheduling solution in 3GPP specification. Vendors will be guided by their offered quality of service level agreement and priority considerations for the resource scheduling. Previous research work has been experimented in solutions like the proportional fair algorithm although with a more complex approach. The systems consideration for fairness can be based on maintaining a balance between key priority factors for the user equipments, these include:

- Quality of Service parameters and measurements
- Payloads buffered in the eNodeB ready for scheduling
- Pending retransmissions,
CQI reports from the UE
- UE capabilities
- UE sleep cycles and measurement gaps/periods
- Latency of users applications

Due to time constraints and issues with reducing complexities in our simulation scenarios of LTE downlink we have used the UE’s CQI values as our metrics for evaluating fairness. A simple relationship can be drawn for the algorithm:

\[ D = \begin{cases} 
\arg \max(CQI_i) \leq CQI \quad i \in Z^+ & 0.5 \\
\text{otherwise} \quad \ldots & 0.3 \\
\arg \min(CQI_i) \geq CQI \quad i \in Z^+ & 0.2 
\end{cases} \]

The system assigns half of the RBs to UE which has highest CQI value. The other half the RBs are assigned between the remaining two UEs based on a scaling factor 0.3 and 0.2. A simple illustration of the algorithm is expressed in the flow chart Figure 3.8
Figure 3. 8 Flowchart of empirical scheduler algorithm
CHAPTER 4

SIMULATION

In this section we investigate the performance of LTE downlink scheduler algorithms with respect to different channel bandwidth. Test environment consist of one eNodeB (Base station) and three user equipment’s (UE’s). Each UE has its own individual CQI value and it is changed randomly by time. Pedestrian B (PedB) channel model is used as a channel type condition in the simulation.

4.1. Radio Propagation Environment and Channel conditions

A key characteristic of UTRAN LTE radio communication link is the rapid variation in channel conditions which is causes by fast multipath fading. A realistic channel model is essential for accurate evaluation of LTE system. The International Telecommunications Union (ITU) channel models were implemented in 3G radio access systems and various scenarios of channel propagation conditions were considered. These channel propagation scenario defined by ITU include indoor office, indoor-to-outdoor, pedestrian and vehicular radio environments [24]. Some of the unique factors that characterized each channel type are Path-loss, Fading characteristics and Propagating radio frequency [25].

Path Loss

In wireless communication transmission, signal disperses and attenuates with distance. This is referred to as path loss. Path loss may be due to many effects such as free-space loss, refraction, diffraction and reflection [25]. In line with ITU recommendation guidelines for evaluation of radio transmission technologies, a path loss rule of $R^{-4}$ is appropriate for PedB channel environment and the following path loss model is used [24]:

$$L = 40 \log_{10} R + 30 \log_{10} F + 49$$

Where:

$R$: Distance between base station and the user equipment (km)
$F$: Carrier frequency
Fading
Fading refers to the time variation of received signal power caused by changes in the transmission medium. In broadband wireless communication users experience different types of fading in transmission because the degradation on received signal power caused by the propagation environment.

Shadow Fading: Shadow fading is caused by movement of the transmitter or receiver. It is not deterministic but uses statistical parameters. Shadow fading and distance dependent path loss affects the received signal strength.

Multipath Fading: Multipath fading is experienced in a non-line of sight microwave radio channel. It is also referred to as a dispersive transmission medium or environment where propagation between transmitter and receiver takes place along several paths of different electrical lengths. Receivers thus sees weighted sum of delayed replicas of the transmitted signal from these multi-paths, interfering with each other constructively or destructively. The amplitude of the received signal varies with time. When the replicas arrive at the receiver in-phase, they reinforce each other but when they arrive in an anti-phase they cancel each other.

Frequency Selective Fading: Rapid and random variations in the channel attenuation. Due to the relatively long symbol time, OFDM provides a high degree to robustness against channel frequency selectivity. But corruption of signal due to frequency selective fading can in principle be handled by equalization at the receiver side.

4.2. ITU Channel Model
The ITU channel model The ITU channel model used to investigate the performance of packet scheduling algorithm in this thesis is the Pedestrian B (PedB) channel type. Each UE establishes a signaling connection with the eNodeB with the high overall path gain. The PedB channel in ITU models is displayed in Table 4.1.
Table 4. 1 ITU Pedestrian B [25]

<table>
<thead>
<tr>
<th>Tap Number</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
<th>5</th>
<th>6</th>
</tr>
</thead>
<tbody>
<tr>
<td>Delay Relative delay (ns)</td>
<td>0</td>
<td>200</td>
<td>800</td>
<td>1200</td>
<td>2300</td>
<td>3700</td>
</tr>
<tr>
<td>Mean Power (dB)</td>
<td>0</td>
<td>-0.9</td>
<td>-4.9</td>
<td>-8.0</td>
<td>-7.8</td>
<td>-23.9</td>
</tr>
</tbody>
</table>

4.3. Simulation Assumptions

It is assumed that all user equipments on the average will experience similar variations in the instantaneous channel conditions, this is due to fast multipath fading a standard characteristic of broadband wireless communication systems. Although UE are expected to experience differences in received signal strength and data throughput due to distance between UE and eNodeB.

It is also assumed that UE report an error free and delay free instantaneous downlink SNR values on each RB and at each TTI to the serving eNodeB. The reported SNR values are calculated based on sub-carrier located at the center frequency of each RB. It is expected that all sub-carriers are used for data transmission and the eNodeB use dynamic rate control link adaptation technique, while the transmitting power is kept constant data rate is dynamically adjusted to compensate for the varying channel conditions.

Pathloss, shadow fading and multi-path fading are used to determine the channel gain and hence the instantaneous downlink SNR value of each user on each RB. It is assumed in the simulation that pathloss and shadow fading values are fixed for each RB while the multipath values vary on each RB.

4.4. Scenario 1 – Multi-User SISO

In this scenario we evaluate scheduling algorithms on a cell transmission network of SISO. There are three different types of scheduling algorithms and HARQ was not used. The transmission rates were tested for SNR range of 0 to 50 dB. In addition measurements were done for multiple bandwidth conditions.
<table>
<thead>
<tr>
<th>Simulation Type</th>
<th>Multi-User SISO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of User Equipments</td>
<td>3</td>
</tr>
<tr>
<td>Number of Base Stations</td>
<td>1</td>
</tr>
<tr>
<td>Channel Type</td>
<td>Pedestrian B</td>
</tr>
<tr>
<td>Number of transmit antennas</td>
<td>1</td>
</tr>
<tr>
<td>Number of receive antennas</td>
<td>1</td>
</tr>
<tr>
<td>Number of Iterations</td>
<td>500 sub-frames</td>
</tr>
<tr>
<td>SNR Range</td>
<td>0 to 50 dB</td>
</tr>
<tr>
<td>Scheduling Algorithms</td>
<td>Round Robin, Best CQI and Empirical scheduling</td>
</tr>
<tr>
<td>Bandwidths</td>
<td>1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz</td>
</tr>
</tbody>
</table>
4.5. Scenario 2 - Multi-User MIMO

In this scenario we evaluated scheduling algorithms on MIMO base cell transmission network. The rest of the all other settings are same as in MU-SISO scenario.

Table 4.3 Simulation Parameters of Multiple-Users MIMO Scenario

<table>
<thead>
<tr>
<th>Simulation Type</th>
<th>Multi-User MIMO</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of User Equipments</td>
<td>3</td>
</tr>
<tr>
<td>Number of Base Stations</td>
<td>1</td>
</tr>
<tr>
<td>Channel Type</td>
<td>Pedestrian B</td>
</tr>
<tr>
<td>Number of transmit antennas</td>
<td>2</td>
</tr>
<tr>
<td>Number of receive antennas</td>
<td>2</td>
</tr>
<tr>
<td>Number of Iterations</td>
<td>500 sub-frames</td>
</tr>
<tr>
<td>SNR Range</td>
<td>0 to 50 dB</td>
</tr>
<tr>
<td>Scheduling Algorithms</td>
<td>Round Robin, Best CQI and Empirical scheduling</td>
</tr>
<tr>
<td>Bandwidths</td>
<td>1.4 MHz, 3 MHz, 5 MHz, 10 MHz, 15 MHz, 20 MHz</td>
</tr>
</tbody>
</table>
CHAPTER 5

RESULTS and ANALYSIS

Figure 5.1 Throughput Graphs for (A) 1.4 MHz and (B) 3 MHz

(A) Throughput (MUSISO, 3 UEs, 1.4 MHz) (B) Throughput (MUSISO, 3 UEs, 3 MHz)

Figure 5.2 Throughput Graphs for (A) 5 MHz and (B) 10 MHz
It is observed that results from the MUSISO graph at various bandwidth in Figure 5.1-5.3 shows that RR and Empirical have higher throughput at low SNR than the best algorithm. It is expected that at a high SNR value Best has a higher throughput since it allocates resources based on higher SNR value. However Empirical has a steady and average throughput from low SNR to higher SNR values which suggest an inherent stability of low rate delivery.

Best one rises sharply at about 5 dB SNR with the throughput achieving an almost exponential rise from 0 to 3 Mbps when at SNR varying from 5-25 dB. The peak throughput is achieved at about 3.3 Mbps compared to the peak throughput of about 2.2 Mbps for Empirical and 1.2 Mbps for RR. The initial throughputs however are better at low SNR for both RR and Empirical.

RR algorithm suggests an under utilization of the system capability of delivering a high throughput. The result form the MUSISO graph indicate that the highest throughput RR could deliver was about 23Mbps at a bandwidth frequency of 20 Mhz. Although RR uses a very fair approach of allocating equal amount of resources to users but the result of the throughput value even at high SNR suggest RR may not be a good scheduling approach at certain circumstances.
The empirical result seems to be a good choice because it suggests an approach that is fair to the users and to the system resources since the same SNR value is guaranteed a constant throughput. The summary of results is similar at 3 MHz, 5 MHz, 10 MHz, 15 MHz and 20 MHz respectively. The bandwidth size may not have had any impact on the throughput/SNR performances for these algorithms.

Figure 5.4 BLER Graphs for (A) 1.4 MHz and (B) 3 MHz
The BLER result for the best algorithm is very commendable at 1.4 MHz (3UEs, MUSISO) because its about $E^{-3}$ at 50dB SNR compared to same value ($E^{-3}$) at 22dB SNR and about 30dB for both RR and Empirical respectively. However, in Fig 5.4b, we can now observe the impact...
of increased bandwidth as Best seems to suffer reduced SNR at the same value of E-3 because SNR is now at about 25dB.

The RR produces similar BLER for same SNR value at increased bandwidth but Best’s SNR actually toggles down at increased bandwidth. This suggests that Best produces excellent results of BLER/SNR ratio at lower bandwidth sizes.

The empirical solution has a better performance than RR and BestCQI with a lower BLER at average SNR ratio for both SUMIMO and MUMIMO even at high bandwidth.

The results of MUMIMO indicates similar trends.

(A) Throughput (MUMIMO, 3 UEs, 1.4 MHz)
(B) Throughput (MUMIMO, 3 UEs, 3 MHz)

Figure 5.7 Throughput Graphs for (A) 1.4 MHz and (B) 3 MHz
Figure 5.8 Throughput Graphs for (A) 15 MHz and (B) 20 MHz

Figure 5.9 Throughput Graphs for (A) 15 MHz and (B) 20 MHz
Figure 5.10 BLER Graphs for (A) 1.4 MHz and (B) 3 MHz

Figure 5.11 BLER Graphs for (A) 5 MHz and (B) 10 MHz
Figure 5.12 Throughput Graphs for (A) 15 MHz and (B) 20 MHz
SUMMARY OF SIMULATION RESULTS

The analysis of the simulation graphs generally show that Best CQI scheduler had highest throughput values at higher SNR values. But at low SNRs values Round Robin scheduler performed better efficiency than other scheduler algorithms, except the bandwidth of 15MHz and 20 MHz MIMO systems. At these two bandwidth systems empirical algorithm had agreeable throughput at low SNRs (up to 15dB). At some of the bandwidth Best CQI and empirical schedulers start with slow phase (up to 10dB). If we want just high throughput; the best CQI schedulers will be a good choice for the system. But if fairness and an average throughput is a major consideration in the service requirement of the system then the empirical idea will be a better choice. It is also worth noting that the difference in the throughput results of the BestCQI and Empirical is not low and cannot be used to justify the argument for BestCQI as a better algorithm.
References

[1] Erik Dahlman, Stefan Parkvall, Johan Skold and Per Beming. 3G Evolution HSPA and LTE for Mobile Broadband.


