UNIVERSITI PUTRA MALAYSIA

DOWNLINK RADIO RESOURCE MANAGEMENT TO ENHANCE QOS OF MULTIMEDIA SERVICES IN LTE NETWORKS

NADIM K M MADI

FSKTM 2018 70

DOWNLINK RADIO RESOURCE MANAGEMENT TO ENHANCE QOS OF MULTIMEDIA SERVICES IN LTE NETWORKS

By

NADIM K M MADI

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

September 2018

DEDICATIONS

I would like to dedicate this thesis to my Family

&

To All whom I love.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the degree of Doctor of Philosophy

DOWNLINK RADIO RESOURCE MANAGEMENT TO ENHANCE QOS OF MULTIMEDIA SERVICES IN LTE NETWORKS

By

NADIM K M MADI

September 2018

Chairman: Zurina Mohd Hanapi, PhD
Faculty: Computer Science and Information Technology

Long Term Evolution (LTE) has become the most dominant Fourth Generation (4G) mobile broadband network. The Radio Access Network (RAN) in LTE is designed to deliver a high trend of Quality of Service (QoS) over diverse user applications and several network scenarios. Therein, the functions of Radio Resource Management (RRM) features which span over the LTE protocol stack should be carefully developed to address related challenges, such as bandwidth utilization, resources scheduling, and physical channel's power allocation. In upper level of downlink Medium Access Control (MAC) layer, the bandwidth distribution function is resided to manage the channel bandwidth over the offered user traffic to guarantee fair service. The performance of this function presents weaknesses when schemes such as Packet Prediction Mechanism (PPM) are adopted, hence the bandwidth is distributed in a linear and greedy fashion. Furthermore, flows scheduling with on-time transmissions is essential in Real-Time (RT) applications. PPM seems to guarantee a stable low delay for kinds of burst applications, other RT traffic are severely compromised though due to the aggressive data dropping procedures in high network overload states. From another aspect, recent QoS profiles count for energy-efficient transmissions as a core dimension. However, this aim still seeks a margin of enhancements with respect to the relevant power allocation schemes as seen in Piro and Lee schemes to focus on controlling the transmission power beside the system capacity maximization in order to maintain a long-term energy-efficient transmissions.

This study figures out managing radio resources over different users for a particular purpose. The first proposal considers the issue of downlink channel resource distribution among different multimedia applications which lead to

unfair service. Therefore, a "Frame-based Game Theory (FGT)" bandwidth distribution scheme is proposed for the MAC layer in the downlink LTE channel. In FGT, bandwidth is shared based on the data rate requirements of each traffic flow over the entire LTE frame. Simulation results reveal that FGT enhances the service fairness up to 25% with respect to the existing reference scheme and maintain a high data rate for different users.

The second proposal considers the issue of flows scheduling for different RT flows. Therefore, Delay-based and QoS Aware Scheduling (DQAS) scheme is introduced to assign channel resources to delay sensitive flows based on QoS-derived rules for different flow types in a way to guarantee low latency and maintain a good data rate. Simulation results show that the efficient delay control in DQAS allows RT flows transmission with 55% minimum delay time compared to existing schemes and guarantees a reasonable throughput level for non-real time flows.

Finally, the issue of surplus power allocation at the base station which degrades the system energy efficiency is discussed thoroughly. Accordingly, Link-adaptive Power Control and Allocation (LaPCA) scheme is proposed to tune the allowable power for the base station and adhere distributes this determined power among the utilized subchannels to transmit users' data. The performance evaluation results indicate that LaPCA guarantees a high trend of energy-efficiency at the base station up to 23% with respect to existing works and keeps an outperforming level of network downlink transmissions.

The findings of this study conceive several significant enhancements that are realized by the proposed RRM schemes. These enhancements include: a guaranteed fair bandwidth sharing among multi-traffic transmitted in unified LTE channel by introducing FGT scheme; stable and low delay for RT flows by introducing DQAS scheme; and finally, energy-efficient downlink transmissions with maximized system capacity by introducing LaPCA. Applying these proposed RRM-schemes in the current protocol stack of LTE radio access network persistently supports a high QoS level for communicating multimedia services in urban-like scenarios. Whereby, network utility and energy-efficient transmissions are significantly returned. This indeed allows more agility for network operators to define their QoS profiles which consequently maintain a long-term network service continuity within the kinds of highly dense environments.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

PENGURUSAN SUMBER RADIO LALUAN MENURUN UNTUK MENINGKATKAN QOS PERKHIDMATAN MULTIMEDIA DI DALAM RANGKAIN LTE

Oleh

NADIM K M MADI

September 2018

Pengerusi: Zurina Mohd Hanapi, PhD
Fakulti: Sains Komputer dan Teknolologi Maklumat

Evolusi Jangkaan Panjang (LTE) adalah perkhidmatan jalur lebar mudah alih selular Generasi Keempat (4G) yang terunggul. Rangkaian Capaian Radio (RAN) direka bentuk untuk menawarkan kualiti perkhimatan (QoS) yang tinggi untuk pelbagai jenis aplikasi di dalam pelbagai senario rangkaian. Pengurusan Sumber Radio (RRM) yang terdiri dari pelbagai lapisan protokol LTE dan direka bentuk untuk menyelesaikan pelbagai masalah seperti penggunaan jalur lebar, penjadualan sumber dan peruntukan kuasa untuk saluean fizikal. Pembahagian saluran jaluran yang terletak di dalam lapisan teratas MAC berfungsi untuk melayan pengguna dengan lebih adil. Terdapat kelemahan di dalam fungsi Mekanisma Ramalan Paket (PPM) yang menyebabkan jalur lebar dibahagikan secara linear dan tidak saksama. Penjadualan aliran dalam penghantaran data yang tepat pada waktunya amat penting di dalam aplikasi masa sebenar. PPM dapat menjanjikan lengah yang rendah untuk aplikasi masa sebenar yang berat. Sebaliknya, trafik letus yang lain terjejas akibat daripada prosedur membuang data apabila bebanan rangkaian adalah tinggi. Dari perspektif yang lain, penggunaan tenaga yang cekap menjadi satu ukuran yang penting untuk pemancaran. Walaubagaimanapon, kajian ini berusaha untuk meningkatkan mekanisme peruntukan kuasa seperti digunakan oleh skim Piro dan Lee yang lebih tertumpu kepada pengawalaan kuasa pemancaran dan memaksimunkan kapasiti sistem.

Kajian ini mengenalpasti pengurusan sumber radio untuk pelbagai pengguna untuk tujuan tertentu. Cadangan pertama adalah untuk menyelesaikan isu pembahagian sumber yang tidak adil di saluran laluan menurun untuk pelbagai aplikasi multimedia. Oleh itu, penggunaan Teori Permainan di dalam Bingkai

Data (FGT) telah dicadangkan sebagai fungsi pembahagian saluran jalur lebar untuk laluan menurun laluan di lapisan MAC. Dalam FGT jalur lebar dikongsi mengikut keperluan kadar kelajuan data untuk setiap aliran trafik bagi keseluruhan bingkai data LTE. Keputusan menunjukkan peningkatan sebanyak 25% untuk FGT jika dibandingkan mekasnime tanda aras dan mengekalkan kadar data pada tahap maksimum untuk pelbagai pengguna.

Cadangan kedua adalah mengambil kira isu pembahagian sumber kepada beberapa jenis lengah saluran yang sensitif. Oleh itu, Skim Penjadualan yang Peka kepada Lengah dan Servis Kualiti (DQAS) diperkenalkan untuk pembahagian saluran sumber yang cekap untuk aliran lengah yang sensitif berdasarkan rumus-rumus yang diperolehi daripada kualiti servis untuk setiap aliran bagi menjamin nilai lengah yang rendah dan mengekalkan kelajuan kadar data yang optimum untuk aliran yang berasaskan kadar penghantaran. Penilaian simulasi menunjukkan DQAS boleh menjadualkan dengan kadar 55% lebih rendah jika dibandingkan dengan skim tanda aras.

Cadangan terakhir adalah membincangkan dengan teliti tentang isu pengagihan kuasa berlebihan di stesen pangkalan yang menyebabkan penggunaan sistem kuasa yang tidak cekap. Skim Perhubungan Mudah Suai Kawalan Kuasa dan Pengagihan (LaPCA) dicadangkan untuk menala kadar kuasa yang dibenarkan bagi stesen pangkalan dan mematuhi pengagihan kuasa yang telah dikenalpasti di antara sub saluran yang digunakan untuk penghantaran data. Penilaian prestasi menunjukkan LaPCA memberi jaminan kecekapan tenaga sebanyak 23% dan mengekalkan prestasi yang tinggi untuk rangkaian saluran laluan menurun.

Hasil kajian yang menggunakan skim RRM menghasilkan beberapa penambahbaikan seperti berikut: Skim FGT menghasilkan perkongsian jalur lebar yang lebih saksama dan terjamin untuk kepelbagaian trafik dipancar oleh saluran bersatu LTE; skim DQAS memastikan lengah adalah rendah dan stabil untuk saluran RT dan LaPCA memperkenalkan saluran laluan menurun yang mempunyai kecekapan tenaga dan memaksimunkan kapasiti sistem. Skim RMM yang digunakan di lapisan protokol rangkaian capaian radio dapat menyokong tahap QoS yang lebih tinggi untuk servis multimedia di dalam senario bandar. Oleh itu, penggunaan rangkaian dan kecekapan tenaga pancaran dapat diperbaiki dengan baik. Ini memudahkan para operator rangkaian membuat takrifan ke atas profail QoS supaya dapat mengekalkan servis untuk jangka masa panjang di dalam kawasan kepadatan yang tinggi.

ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my supervisor Assoc. Prof. Dr. Zurina Mohd Hanapi for the continuous support of my study and research, for her patience, motivation, enthusiasm, and immense knowledge. Her guidance helped me in all the time of research and writing of this thesis. Her encouragement and help made me feel confident to overcome every difficulty I encountered in all the stages of this research. What I really learned from Her, however, is her attitude to work and life - always aiming for excellence.

I would like to extend my gratitude and thanks to the distinguished committee member, Professor Dr. Mohamed Othman , and Professor Dr. Shamala Subramaniam for their encouragement and insightful comments.

I am very grateful to the Faculty of Computer Science and Information Technology and the staff of Postgraduate office, School of Graduate Studies, Library and Universiti Putra Malaysia, for providing me excellent research environment. Thanks to every person who has supported me to pursue and finish my Ph.D.

I am very grateful to my family, my father Kamal Madi, the pure souls of my mother Laila Madi and my martyr sister Nada, as well as the rest of my brother, sisters, and my step-mother for their unflagging love and support throughout my life. I have no suitable words that can fully describe my everlasting love to them except, I love you all.

Words fail me to express my appreciation to my lovely wife Noor Madi whose dedication, love and persistent confidence in me, has taken the load off my shoulder. I owe her for being unselfishly let her intelligence, passions, and ambitions collide with mine. Special thank goes to my lovely son Yamen, and the little princess Nada, you are my joy and my guiding lights. Thanks for giving me your valuable time through all this long process. I promise I will never let you alone any more.

Besides, it gives me immense pleasure to express my deepest gratitude to my friends, colleagues and lab mates for their unlimited support and encouragement.

Last but not least, I would like to thank everybody who was important to the successful realization of this thesis, as well as I express my apology that I could not mention you all personally.

I certify that a Thesis Examination Committee has met on 3 September 2018 to conduct the final examination of Nadim K M Madi on his thesis entitled "Downlink Radio Resource Management to Enhance QoS of Multimedia Services in LTE Networks" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

Members of the Thesis Examination Committee were as follows:

Azizol b Hj Abdullah, PhD
Senior Lecturer
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Chairman)

Zuriati bt Ahmad Zukarnain, PhD
Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Internal Examiner)

Abdullah bin Muhammed, PhD
Senior Lecturer
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Internal Examiner)

Irfan Awan, PhD
Professor
University of Bradford
United Kingdom
(External Examiner)

RUSLI HAJI ABDULLAH, PhD
Professor and Deputy Dean
School of Graduate Studies
Universiti Putra Malaysia

Date: 31 October 2018

This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfilment of the requirement for the degree of Doctor of Philosophy.

The members of the Supervisory Committee were as follows:

Zurina Mohd Hanapi, PhD
Associate Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Chairman)

Mohamed Othman, PhD
Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Member)

Shamala Subramaniam, PhD
Professor
Faculty of Computer Science and Information Technology
Universiti Putra Malaysia
(Member)

ROBIAH BINTI YUNUS, PhD
Professor and Dean
School of Graduate Studies
Universiti Putra Malaysia

Date:

Declaration by graduate student

I hereby confirm that:

- this thesis is my original work;
- quotations, illustrations and citations have been duly referenced;
- this thesis has not been submitted previously or concurrently for any other degree at any other institutions;
- intellectual property from the thesis and copyright of thesis are fully-owned by Universiti Putra Malaysia, as according to the Universiti Putra Malaysia (Research) Rules 2012;
- written permission must be obtained from supervisor and the office of Deputy Vice-Chancellor (Research and Innovation) before thesis is published (in the form of written, printed or in electronic form) including books, journals, modules, proceedings, popular writings, seminar papers, manuscripts, posters, reports, lecture notes, learning modules or any other materials as stated in the Universiti Putra Malaysia (Research) Rules 2012;
- there is no plagiarism or data falsification/fabrication in the thesis, and scholarly integrity is upheld as according to the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) and the Universiti Putra Malaysia (Research) Rules 2012. The thesis has undergone plagiarism detection software.

Signature: _____ Date: _____

Name and Matric No.: Nadim K M Madi (GS35243)

Declaration by Members of Supervisory Committee

This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

Signature: _____
Name of
Chairman of
Supervisory
Committee: _____

Signature: _____
Name of
Member of
Supervisory
Committee: _____

Signature: _____
Name of
Member of
Supervisory
Committee: _____

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

2G	Second Generation
3G	Third Generation
3GPP	Third Generation Partnership Project
4G	Fourth Generation
5G	Fifth Generation
AMC	Adaptive Modulation and Coding
AQM	Active Queue Management
ARQ	Automatic Retransmission Request
AWGN	Additive White Gaussian Noise
BER	Bit Error Rate
CA	Carrier Aggregation
CBR	Constant Bit Rate
CC	Component Carrier
CDMA	Code Division Multiple Access
CQI	Channel Quality Indicator
CSI	Channel State Information
DL	Downlink
DQAS	Delay–based and QoS Aware Scheduling
DTX	Discontinuous Transmission
E-UTRAN	Evolved UMTS Terrestrial Radio Access Network
EDC	Efficient Delay Control
EDF	Earliest Deadline First
EE	Energy Efficiency
eNB	evolved NodeB
EPC	Evolved Packet Core
EV-DO	Evolution–Data Optimized
EXP-PF	EXPonential-Proportional Fairness
EXP-Rule	EXPonential–Rule
FCFS	First Come First Serve
FD	Frequency Domain
FFR	Fractional Frequency Reuse
FGT	Frame-based Game Theory
FTP	File Transfer Protocol
GBR	Guaranteed Bit Rate
GPRS	General Packet Radio Service
GSM	Global Systems for Mobile Communications
HARQ	Hybrid Automatic Repeated Request
HoL	Head of Line
HSPA	High Speed Packet access
ICI	Inter–Cell Interference
IMS	IP Multimedia Subsystem
IoT	Internet of Things
KKT	Karush–Kuhn–Tucker

LaPCA	Link-adaptive Power Control and Allocation
LDI	Least Delay Increase
LTE	Long–Term Evolution
LTE-A	Long–Term Evolution–Advanced
LTE-U	Long–Term Evolution-Unlicensed
M-LWDF	Modified-Largest Weighted Delay First
MAC	Medium Access Control
MCS	Modulation and Coding Scheme
MIMO	Multiple-Input and Multiple-Output
MME	Mobility Management Entity
MTC	Machine Type Communications
NRT	Non–Real Time
OFDM	Orthogonal Frequency Division Multiplexing
OFDMA	Orthogonal Frequency Division Multiple Access
P-GW	Packet Gate Way
PC	Power Control
PDCCH	Physical Downlink Control Channel
PDF	Probability Density Function
PDSCH	Physical Downlink Shared Channel
PDU	Packet Data Unit
PF	Proportional Fairness
PLR	Packet Loss Ratio
PPM	Packet Prediction Mechanism
PRB	Physical Resource Block
PUCCH	Physical Uplink Control Channel
QCI	QoS Class Identifier
QoS	Quality of Service
RAN	Radio Access Network
RB	Resource Block
RLC	Radio Link Control
RR	Round Robin
RRM	Radio Resource Management
RT	Real Time
S-GW	Serving Gate Way
SAE	System Architecture Evolution
SC	System Capacity
SC-FDMA	Single Carrier– Frequency Division Multiple Access
SDMA	Space Division Multiple Access
SINR	Signal–to–Interference–plus-Noise–Ratio
SLNR	Signal–to– Leakage–plus–Noise–Ratio
TCP	Transmission Control Protocol
TD	Time Domain
TDMA	Time Division Multiple Access
TTI	Time Transmission Interval

UE	User Equipment
UMTS	Universal Mobile Telecommunications Service
VBR	Variable Bit Rate
VoIP	Voice over Internet Protocol
W-CDMA	Wideband Code Division Multiple Access
Wi-Fi	Wireless Fidelity

CHAPTER 1

INTRODUCTION

1.1 Background

The era of mobile broadband communication is rapidly and tremendously evolved hence multimedia technology vision and looking forward to the near–zero latency with data rates up to tens of Gigabits per second throughout the wireless channel (Li et al., 2018; Huawei Technologies, 2017). Based on a current study by Cisco Systems (2017), it is estimated that the number of mobile users will be as high as 11.6 billion by 2021. It is also reported by the same source that the volume of transferred data over mobile networks reached up to 63% by the end of 2016. These statistical figures reveal that System Capacity and QoS have been considered as a major driven key in the technology advancement, starting from the Fourth Generation (4G) to the current Fifth Generation (5G) mobile systems.

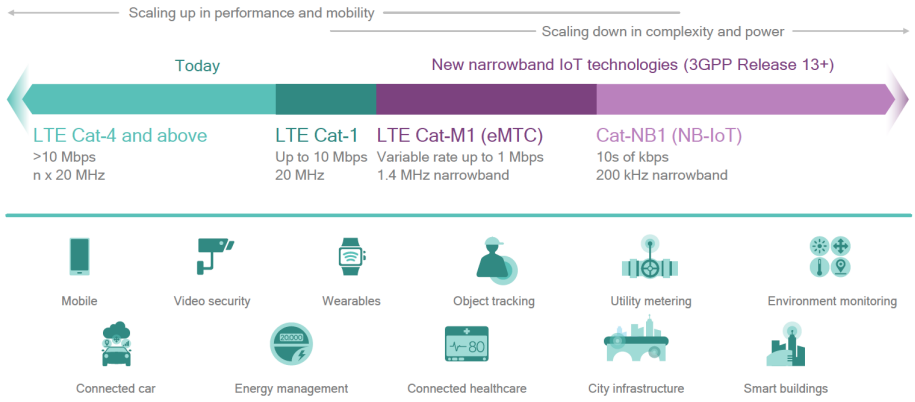

Figure 1.1: Applications of Modern LTE Networks for Smart Cities.
(Source: Leverege (2017))

The Long Term Evolution (LTE) mobile network by Third Generation Partnership Project (3GPP) [1] has been evolved as an example of the dominant 4G and beyond mobile platform that vigorously thrives in multimedia communication advancements on different scenarios. Recently, Internet of Things (IoT) has been protruded to redefine the modern ecosystem of smart life by realizing a mesh-like connected world (Wang et al., 2017). This, in fact, has substantially driven more advancements in the design of LTE Radio Access Network (RAN) within its current releases to suite such a novel communication paradigm in tangible and real scenarios as presented in Figure 1.1.

[1] http://www.3gpp.org/

In Radio Access Network (RAN), Radio Resource Management (RRM) is defined among the premier operations in LTE system. Therein, different users can be dynamically managed and administered to access the respective Internet applications with a high QoS level. RRM has been comprehensively extended in downlink transmissions due to the multiuser diversity in wireless scenarios. In spite of the collaborative efforts paid on this side, Quality of Service (QoS) performance is still hindered by the scares amount of channel resources shared among different involved applications. Symptoms of this situation is presented in different perspectives such as unfair bandwidth sharing, transmissions with violated delay bounds for RT applications, and excessive dissipated power.

Basically, in the user-plane LTE protocol stack, the MAC layer handles most of the RRM functions. *Bandwidth distribution* occurs as an upper level process at the MAC scheduler wherein traffic applications are granted an access to use the channel resources (Alasti et al., 2010). Ideally, MAC scheduler should invoke sophisticated manners to control the bandwidth utilization volume, particularly when different application types are transmitted in the LTE channel. The essence of this component in MAC scheduler is obviously seen from the new emerging types of traffic. Therein, burst traffic application usually tends to dominate the bandwidth causing a starvation on small flows with higher priority like VoIP.

Aside from that, ensuring fair traffic service implies that a high data rate is possible to be guaranteed, however, RT traffic may have their QoS compromised in terms of delay. The early Third Generation (3G) LTE networks allow a relaxed delay tolerance of multimedia applications since the aim was mainly to boost the network capacity (Dahlman et al., 2010). However, with the integration of IoT– and Machine Type Communications (MTC)–based scenarios in LTE mobile networks, latency is yet defined as the major QoS criteria for most of the existing applications (Nikaein and Krea, 2011). A mutual observation by most of the carried out research studies states that queuing delay at MAC scheduler is the key contributor to the overall network latency (Capozzi et al., 2013). Therefore, most of the contributions in MAC *flows scheduling* function have been attempting to figure out the issue of delay in this part of the network over specific scenarios. Nonetheless, the hurdle here remains to guarantee low delay while provisioning other QoS indices.

It is commonly known that the steady increase in System Capacity (SC) directly leads to high power consumption (Wu et al., 2017). In the evolving paradigm of 4G and beyond, the issue of *power management* at the base station has been actively discussed in twofold. From network performance aspect, the excessive dissipated transmission power increases the interference that is caused by either other neighboring cells or mobile users (Boudreau et al., 2009). This eventually imposes a high signal deterioration and thereby low QoS performance. Furthermore, from economic and environmental aspects, deploying a base station with a constant power volume is no longer applicable at the era of green communications, or the economical predictive. According to Oh et al.

(2011), technologies of renewable energy sources are intensively considered in the recent mobile systems in order to operate network communication with low costs. Therefore, research efforts present a vast volume of solutions to reduce the transmission power of the base station (Hasan et al., 2011; Kanwal et al., 2017). Nevertheless, the compromise between cell capacity and low power consumption is still debatable, especially in urban-like network scenarios.

In this thesis, we propose three RRM schemes for downlink system in LTE network. The first scheme is deployed at the upper level of MAC layer and emphasizes on the "fair service" property of the channel bandwidth. QoS profiles of different multimedia traffic are leveraged to enhance the throughput fairness and the network performance. In the lower level of MAC layer, the second scheme is designed to concentrate on satisfying the "delay-sensitivity" trait of RT applications. Heterogeneous flows are analyzed based on their delay characteristics to minimize the overall latency. Finally, the physical layer is enhanced with an energy-wise scheme which ensures high efficiency on the transmitted bits over every power unit under network impediments. The global aim of the thesis is to enhance QoS for different multimedia applications such that common trade-offs between the performance metrics are at a reasonable level. This indeed remains to be a debatable area in the research as the mobile communication paradigm is evolved.

1.2 Research Problems

The multiuser diversity as well as the applications heterogeneity turned the QoS provisioning in the recent LTE network to a major challenge. Therefore, in the literature, several RRM methods have been introduced to maintain the desired QoS level. Among the recent works, Packet Prediction Mechanism (PPM) by Lai and Tang (2013) is introduced to handle the RRM functions at the downlink MAC layer. PPM employs a lightweight method for bandwidth distribution function in upper-level of MAC layer. Whereby, the channel bandwidth is shared in a greedy fashion; based on the behavior of incoming traffic. This behavior may provide a fair service for kinds of burst traffic to some extent under light network loads. Besides, PPM also adopts a comprehensive method for flows scheduling function in the lower-level of MAC layer to maintain low delay for RT flows. It employing a detailed queue analysis to predict the behaviour of the incoming traffic based on the current buffer sizes. This allow predefining the probable expired flows and adhere, invoke a dropping procedure based on a calculated threshold to maintain a steady and low delay for RT traffic.

On the other hand, in the downlink physical layer, "Piro scheme" (Piro et al., 2011a) and "Lee scheme" (Lee et al., 2016a) are two recent power allocation schemes in LTE network. Piro scheme employs an equivalent power distribution among the subchannels to ensure fair QoS for all users with different channel conditions and thereby maintained level of energy efficiency. Besides, Lee

scheme adopts a non-linear optimization method to benefit from the maximum base station transmission power in increase the system capacity, and thereby enhance the energy efficiency.

In spite of the notable significance of these existing RRM schemes, limitations are still observed in maintaining the desired performance on scenarios of heterogeneous traffic during network overload states. These drawbacks include:

- The PPM scheme at the downlink MAC layer combines the function of bandwidth distribution to control and manage the amount of channel data that can be scheduled from different traffic sources. Unfortunately, a low service fairness on high priority traffic classes occurs due to the linear and greedy fashion of the channel bandwidth assignment. This results in a starvation on small-sized flows as the burst traffic is overtaking the available bandwidth during the network overload states which eventually degrades the fairness index.

- In PPM scheme, the downlink flows scheduling process occurs by prioritizing the variously available flows to be transmitted via the Physical Resource Block (PRB)s. However, the delay is observed to be compromised in different RT flows at the overload network states. This is due to the utilization of delay threshold (for defining future expired traffic) which causes an excessive dropping procedure with frequent retransmission against traffic flows to flush the queue during congestion states and thereby leads to high delay.

- In Piro and Lee power allocation schemes, The LTE Physical layer accommodates a power allocation model in which the subchannels are able to claim a portion of the power to transmit the payload of scheduled users. The system's energy efficiency is nonetheless compromised under congested network states and limited transmission power profiles. This is because, the transmission power at the base station is either extensively utilized up to the maximum level or equivalently distributed among all the subchannels disregarding the required power. This eventually leads to a high level of dissipated power and thereby deteriorating the system Energy Efficiency (EE).

1.3 Research Objectives

The global objective of this research is to propose different downlink RRM–based schemes to ensure a long–term QoS on various multimedia applications over LTE network. In details, this can be described throughout the following objectives:

1. To propose a bandwidth distribution scheme in the downlink MAC which efficiently determines the portion of channel bandwidth over the LTE frame to be utilized by different RT and NRT applications according to their bit rate share by using cooperative game theory in order to enhance the service fairness of the various flows.

2. To propose a flows scheduling scheme in the downlink MAC layer scheduler by developing different heuristic delay–based rules for RT (burst and light–weight) traffic which prioritize the available flows according to their delay bounds, and simultaneously, adopting a throughput-based procedure for low priority flows in order to minimizes the delay on different RT flows while maintaining QoS on burst and NRT flows.

3. To propose a link–adaptive power control and allocation scheme for the downlink LTE channel by using an adaptive transmission power determining for base station in a first phase, and non–linear optimization mechanism for subchannels power distribution in a second phase to enhance the system energy efficiency during the network overload states.

1.4 Research Scope

This research concentrates on QoS–oriented downlink radio resource schemes with the promise to provide a long-term QoS provisioning for multimedia applications in LTE networks. Each of these proposed schemes is basically developed to target a specific QoS criterion in order to fulfill the desired objective while being aware of not compromising other QoS indices. In this context, the introduced RRM schemes are circled around channel bandwidth control, flows scheduling, and power management in MAC and Physical layers of the LTE protocol architecture in Releases 9 and 10. In order to ensure a realistic design of the RRM schemes, LTE 3GPP standards which declare the details of traffic QoS and the various rules and constraints in functions of MAC and Physical layers have been followed. Figure 1.2 conceives an obvious and comprehensive description of the research scope.

The proposed downlink RRM schemes share a common trait of harnessing a lightweight computational algorithms; this allows an agile performance in heterogeneous traffic scenarios, for example in IoT paradigm. Furthermore, one side of this study emphases on managing the downlink channel bandwidth over multi-traffic classes for the seek of fair service. On another hand, by realizing the essence of delay-sensitivity in most of multimedia applications, the QoS-based investigation is handled on MAC scheduler to ensure transmissions with minimal delay budgets. Dwelling further, the last part of the study, figures out the issue of power management at the base station with the ultimate goal of enabling downlink transmissions with the a high energy efficiency in network

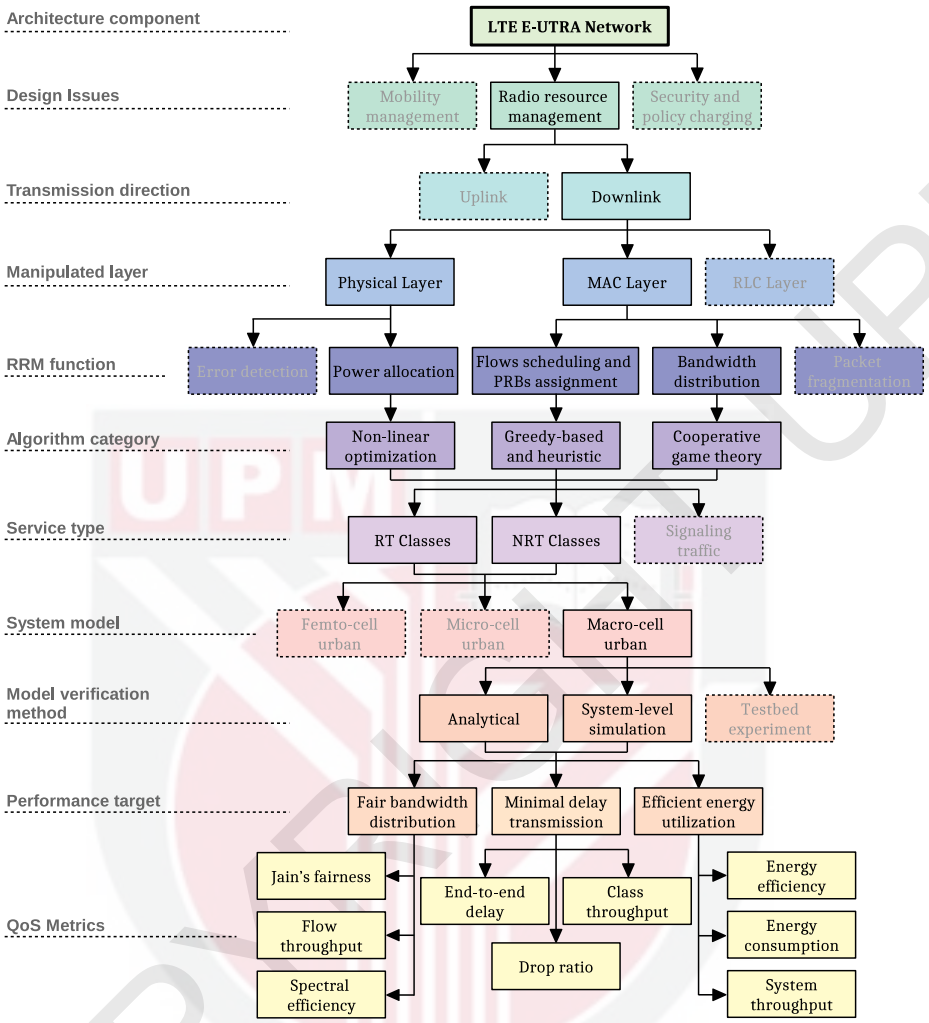

Figure 1.2: Thesis Research Scope.

overload states.

For performance evaluation, comprehensive system–level simulation with various scenarios are conducted for the proposed schemes. Numerical results of specific QoS parameters are then discussed with respect to benchmarking schemes.

1.5 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 2 – presents the literature review. It starts with an overview of the LTE networks architecture with more laid focus on RRM functions. Then the related work od the different RRM schemes are discussed and analyzed accordingly.

Chapter 3 – conceives the overall research methodology. The research framework is presented in the first place, then the experimental setups, the simulation environment are described in details. In addition, results of the benchmark as well as the involved QoS metrics are defined.

Chapter 4 – explores the design and evaluation of the proposed scheme for bandwidth distribution function, namely, FGT, which is adopted to ensure high fairness index among the different multimedia flows.

Chapter 5 – describes the proposed scheme for the flows scheduling and PRBs allocation, namely DQAS. The evaluation of DQAS is also demonstrated with respect to relevant benchmarking schemes over different user mobility scenarios.

Chapter 6 – defines the problem of power allocation in LTE base stations and accordingly introduces the LaPCA scheme which operates over two phases. Performance evaluation with respect to relevant reference schemes is provided thereafter.

Chapter 7 – concludes the work and recommends some promising directions for future research.

REFERENCES

3GPP (2011a). 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) radio transmission and reception (Release 10). *Technical Specification*, 10.2.0(ETSI TS 36.101):1–208.

3GPP (2011b). 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; FDD Base Station (BS) classification (Release 10). *Technical Specification*, 10.0.0(3GPP TR 25.951):1–63.

Abdelhadi, A., Khawar, A., and Clancy, T. C. (2015). Optimal Downlink Power Allocation in Cellular Networks. *Physical Communication*, 17:1–14.

Adesh, N. and Renuka, A. (2018). Adaptive Downlink Packet Scheduling in LTE Networks Based on Queue Monitoring. *Wireless Networks*, pp. 1–18.

Afroz, F., Barua, S., and Sandrasegaran, K. (2014). Performance Analysis of FLS, EXP, LOG AND M-LWDF Packet Scheduling Algorithms in Downlink 3GPP LTE System. *International Journal of Wireless & Mobile Networks*, 5(6):77–91.

Akyildiz, I. F., Gutierrez-Estevez, D. M., and Reyes, E. C. (2010). The Evolution to 4G Cellular Systems: LTE-Advanced. *Physical communication*, 3(4):217–244.

Alasti, M., Neekzad, B., Hui, J., and Vannithamby, R. (2010). Quality of service in WiMAX and LTE networks [Topics in Wireless Communications]. *IEEE Communications Magazine*, 48(5):104–111.

Ali, A. A., Nordin, R., Ismail, M., and Abdullah, H. (2016). An Efficient Scheduling Scheme for OFDMA Resource Blocks with Joint User Scheduling based on Earliest Deadline First with Carrier Aggregation (CA) in LTE-A System. *Wireless Personal Communications*, 88(2):173–183.

Ali, S., Zeeshan, M., and Naveed, A. (2013). A Capacity and Minimum Guarantee-Based Service Class-Oriented Scheduler for LTE Networks. *EURASIP Journal on Wireless Communications and Networking*, 2013(1):67.

Ali-Yahiya, T. (2011a). Cross-Layer Multiservice Scheduling for LTE Networks. In *Understanding LTE and its Performance*, pp. 181–197. Springer.

Ali-Yahiya, T. (2011b). *Introduction to Mobile Broadband Wireless*, pp. 3–15. Springer New York, New York, NY.

Andrews, M., Kumaran, K., Ramanan, K., Stolyar, A., Vijayakumar, R., and Whiting, P. (2000). CDMA Data QoS Scheduling on the Forward Link with Variable Channel Conditions. Report, Bell Labs Technical Memorandum.

Ang, E. M., Wee, K. K., Pang, Y. H., and Lau, S. H. (2014). Two-Level Scheduling Framework with Frame Level Scheduling and Exponential Rule in Wireless Network. In *Information Science and Applications (ICISA), 2014 International Conference on*, pp. 1–4. IEEE.

Asadollahi, F. and Dehdasht-Heydari, R. (2018). Introduction of a Novel Hybrid Weighted Exponential Logarithm-Maximum Throughput (HWEL-MT) Scheduler for QoS Improvement of LTE/4G Cellular Networks. *Wireless Personal Communications*, 98(1):91–104.

Astely, D., Dahlman, E., Furuskar, A., Jading, Y., Lindstrom, M., and Parkvall, S. (2009). LTE: the evolution of mobile broadband. *IEEE Communications Magazine*, 47(4):44–51.

Asvial, M., Dewandaru, G., and Rachman, A. N. (2015). Modification of Round Robin and Best CQI Scheduling Method for 3GPP LTE Downlink. *International Journal of Technology*, 6(2):130–138.

Bae, S. J., Choi, B.-G., and Chung, M. Y. (2011). Delay-Aware Packet Scheduling Algorithm for Multiple Traffic Classes in 3GPP LTE System. In *Communications (APCC), 2011 17th Asia-Pacific Conference on*, pp. 33–37. IEEE.

Bentley, J. L. (1975). Multidimensional Binary Search Trees Used for Associative Searching. *Communications of the ACM*, 18(9):509–517.

Biernacki, A. and Tutschku, K. (2014). Comparative Performance Study of LTE Downlink Schedulers. *Wireless Personal Communications*, 74(2):585–599.

Bojovic, B. and Baldo, N. (2014). A New Channel and Qos Aware Scheduler to Enhance the Capacity of Voice over LTE Systems. In *Systems, Signals & Devices (SSD), 2014 11th International Multi-Conference on*, pp. 1–6. IEEE.

Bonnefoi, R., Moy, C., Farès, H., and Palicot, J. (2017). Power Allocation for Minimizing Energy Consumption of OFDMA Downlink with Cell DTx. In *24th International Conference on Telecommunications (ICT), ICT 2017 proceedings*, pp. 1–6. IEEE.

Bossy, B., Kryszkiewicz, P., and Bogucka, H. (2017). Optimization of Energy Efficiency in the Downlink LTE Transmission. In *2017 IEEE International Conference on Communications (ICC)*, pp. 1–6. IEEE.

Boudreau, G., Panicker, J., Guo, N., Chang, R., Wang, N., and Vrzic, S. (2009). Interference Coordination and Cancellation for 4G Networks. *IEEE Communications Magazine*, 47(4).

Brehm, M. and Prakash, R. (2013). Overload-State Downlink Resource Allocation in LTE MAC Layer. *Wireless networks*, 19(5):913–931.

Camp, T., Boleng, J., and Davies, V. (2002). A Survey of Mobility Models for Ad Hoc Network Research. *Wireless communications and mobile computing*, 2(5):483–502.

Capozzi, F., Piro, G., Grieco, L. A., Boggia, G., and Camarda, P. (2013). Downlink Packet Scheduling In LTE Cellular Networks: Key Design Issues and a Survey. *IEEE Communications Surveys & Tutorials*, 15(2):678–700.

Chadchan, S. and Akki, C. (2010). 3GPP LTE/SAE: An Overview. *International Journal of Computer and Electrical Engineering*, 2(5):806–814.

Chang, B.-J., Chang, P.-Y., and Liang, Y.-H. (2017). Adaptive Packet Scheduling and Radio RB Allocation for LTE-A Toward 5G Relaying Communications. In *Information Technology, Electronics and Mobile Communication Conference (IEMCON), 2017 8th IEEE Annual*, pp. 358–364. IEEE.

Chayon, H. R., Dimyati, K. B., Ramiah, H., and Reza, A. W. (2017). Enhanced Quality of Service of Cell-Edge User by Extending Modified Largest Weighted Delay First Algorithm in LTE Networks. *Symmetry*, 9(6):81.

Chen, S., Yuan, Z., and Muntean, G.-M. (2013). An Energy-Aware Multipath-TCP-Based Content Delivery Scheme in Heterogeneous Wireless Networks. In *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, pp. 1291–1296. IEEE.

Chen, Y., Zheng, Z., Li, Y., and Li, Y. (2015). Energy-Efficient Resource Allocation in Multiuser OFDM Systems with Proportional Rate Constraints. *Electronics Letters*, 51(20):1611–1613.

Chetto, H. and Chetto, M. (1989). Some Results of the Earliest Deadline Scheduling Algorithm. *IEEE Transactions on software engineering*, 15(10):1261–1269.

Chiang, M., Hande, P., Lan, T., Tan, C. W., et al. (2008). Power Control in Wireless Cellular Networks. *Foundations and Trends® in Networking*, 2(4):381–533.

Chuah, C.-N. and Katz, R. H. (2002). Characterizing Packet Audio Streams from Internet Multimedia Applications. In *Communications, 2002. ICC 2002. IEEE International Conference on*, volume 2, pp. 1199–1203. IEEE.

Cisco Systems, I. (Feb. 2017). Cisco Visual Networking Index: Global Mobile Data Traffic Forecast Update, 2016-2021. *White Paper Cisco Systems, Inc., San Jose, CA, USA*, (1454457600805266).

Coskun, C. C., Davaslioglu, K., and Ayanoglu, E. (2017). Three-Stage Resource Allocation Algorithm for Energy-Efficient Heterogeneous Networks. *IEEE Transactions on Vehicular Technology*.

Cox, C. (2012). *System Architecture Evolution*, pp. 21–46. John Wiley & Sons, Ltd.

Dahlman, E., Parkvall, S., and Skold, J. (2013). Chapter8 - Radio-Interface Architecture. In *4G LTE/LTE-Advanced for Mobile Broadband*, pp. 109–126. Academic Press.

Dahlman, E., Parkvall, S., Skold, J., and Beming, P. (2010). *3G Evolution: HSPA and LTE for Mobile Broadband*. Academic press.

Dardouri, S. and Bouallegue, R. (2015). Comparative Study of Downlink Packet Scheduling for LTE Networks. *Wireless Personal Communications*, 82(3):1405–1418.

Deng, H., Wu, C., and Wang, Y. (2017). A Cognitive Gateway-Based Spectrum Sharing Method in Downlink Round Robin Scheduling of LTE System . *Modern Physics Letters B*, 31(19-21):1740070–1740076.

Destounis, A., Paschos, G. S., and Gesbert, D. (2018). Selective Fair Scheduling over Fading Channels. *arXiv preprint arXiv:1801.01793*, pp. 1–10.

Dinkelbach, W. (1967). On Nonlinear Fractional Programming. *Management science*, 13(7):492–498.

Elsayed, K. M. and Khattab, A. K. (2006). Channel-Aware Earliest Deadline due Fair Scheduling For Wireless Multimedia Networks. *Wireless Personal Communications*, 38(2):233–252.

ETSI (2012a). Digital Cellular Telecommunications System (Phase 2+); Universal Mobile Telecommunications System (UMTS); LTE; Quality of Service (QoS) concept and architecture. *ETSI 3GPP 4G LTE TS 123 107 v12.0.0*, pp. 1–44.

ETSI (2014). Digital Cellular Telecommunications System (Phase 2+); Universal Mobile Telecommunications System (UMTS); LTE; Policy and charging control architecture. *ETSI 3GPP TS 23.203 version 12.6.0 Release 12*, pp. 1–221.

ETSI (2015). LTE; Evolved Universal Terrestrial Radio Access (E-UTRA) and Evolved Universal Terrestrial Radio Access Network (E-UTRAN); Overall description. *ETSI 3GPP TS 36.300 version 10.12.0 Release 10*, pp. 1–212.

ETSI, T. (2011a). 136 211 V10. 0.0 (2011-01) LTE; Technical Specification; Physical Channels and Modulation. *ETSI 3GPP 4G LTE, TS 136 211 v10.0.0*, pp. 1–105.

ETSI, T. (2011b). LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); User Equipment (UE) Radio Transmission and Reception. *ETSI 3GPP 136 101 V10.3.0*, pp. 1–236.

ETSI, T. (2012b). LTE; Evolved Universal Terrestrial Radio Access (E-UTRA); Radio Frequency (RF) System Scenarios. *3GPP ETSI TR 36.942 10.2.0*, 10:1–109.

Giuliano, R., Mazzenga, F., and Petracca, M. (2014). Power Consumption Analysis and Dimensioning of UMTS-LTE with Relays. *Procedia Computer Science*, 40:74–83.

González, D., García-Lozano, M., Ruiz, S., and Lee, D. S. (2014). A Metaheuristic-Based Downlink Power Allocation for LTE/LTE-A Cellular Deployments. *Wireless Networks*, 20(6):1369–1386.

Gotsis, A. G., Lioumpas, A. S., and Alexiou, A. (2012). M2M Scheduling over LTE: Challenges and New Perspectives. *IEEE Vehicular Technology Magazine*, 7(3):34–39.

Hahne, E. L. (1991). Round-Robin Scheduling for Max-Min Fairness in Data Networks. *IEEE Journal on Selected Areas in communications*, 9(7):1024–1039.

Hahne, E. L. and Robert, G. (1986). Round Robin Scheduling for Fair Flow Control in Data Communication Networks. *NASA STI/Recon Technical Report N*, 86.

Hamed, M. M., Shukry, S., El-Mahallawy, M. S., and El-Ramly, S. H. (2014). Modified Earliest Deadline First Scheduling with Channel Quality Indicator for Downlink Real-time Traffic in LTE Networks. In *e-Technologies and Networks for Development (ICeND), 2014 Third International Conference on*, pp. 8–12. IEEE.

Han, Z. (2012). *Game Theory in Wireless and Communication Networks: Theory, Models, and Applications*. Cambridge University Press.

Hasan, Z., Boostanimehr, H., and Bhargava, V. K. (2011). Green Cellular Networks: A survey, some research issues and challenges. *IEEE Communications surveys & tutorials*, 13(4):524–540.

He, C., Li, G. Y., Zheng, F.-C., and You, X. (2014). Energy-Efficient Resource Allocation in OFDM Systems with Distributed Antennas. *IEEE Transactions on Vehicular Technology*, 63(3):1223–1231.

He, H., Shan, H., Huang, A., Cai, L. X., and Quek, T. Q. (2017). Proportional Fairness-based Resource Allocation for LTE-U Coexisting with Wi-Fi. *IEEE Access*, 5:4720–4731.

Holt, C. C. (2004). Forecasting Seasonals and Trends By Exponentially Weighted Moving Averages. *International journal of forecasting*, 20(1):5–10.

Holtkamp, H., Auer, G., Bazzi, S., and Haas, H. (2014). Minimizing Base Station Power Consumption. *IEEE Journal on Selected Areas in Communications*, 32(2):297–306.

Huang, X., Ge, X., Wang, Y., Li, F. Y., and Zhang, J. (2012). Energy-Efficient Binary Power Control with Bit Error Rate Constraint in MIMO-OFDM Wireless Communication Systems. In *2012 IEEE Vehicular Technology Conference (VTC Fall)*, pp. 1–5. IEEE.

Huawei Technologies, I. (March. 2017). 5G Network Architecture: A High-Level Perspective. *White Paper, Huawei Technologies*, pp. 1–21.

Iturralde, M., Wei, A., Ali-Yahiya, T., and Beylot, A.-L. (2013). Resource Allocation for Real Time Services In LTE Networks: Resource Allocation Using Cooperative Game Theory and Virtual Token Mechanism. *Wireless personal communications*, 72(2):1415–1435.

Iturralde, M., Yahiya, T. A., Wei, A., and Beylot, A.-L. (2011). Resource allocation using Shapley value in LTE networks. In *Personal Indoor and Mobile Radio Communications (PIMRC), 2011 IEEE 22nd International Symposium on*, pp. 31–35. IEEE.

Iturralde, M., Yahiya, T. A., Wei, A., and Beylot, A.-L. (2012). Interference Mitigation by Dynamic Self-Power Control in Femtocell Scenarios in LTE Networks. In *2012 IEEE Global Communications Conference (GLOBECOM)*, pp. 4810–4815. IEEE.

Jain, R., Chiu, D.-M., and Hawe, W. R. (1984). *A Quantitative Measure of Fairness and Discrimination for Resource Allocation in Shared Computer System*, volume 38. Eastern Research Laboratory, Digital Equipment Corporation Hudson, MA.

Jakes, W. C. and Cox, D. C. (1994). *Microwave Mobile Communications*. Wiley-IEEE Press.

Kachroo, A., Ozdemir, M. K., and Tekiner-Mogulkoc, H. (2016). Optimization of LTE Radio Resource Block Allocation for Maritime Channels. In *Sarnoff Symposium, 2016 IEEE 37th*, pp. 88–93. IEEE.

Kanwal, K., Safdar, G. A., Ur-Rehman, M., and Yang, X. (2017). Energy Management in LTE Networks. *IEEE Access*, 5:4264–4284.

Kayali, M. O., Shmeiss, Z., Safa, H., and El-Hajj, W. (2017). Downlink Scheduling in LTE: Challenges, Improvement, and Analysis. In *Wireless Communications and Mobile Computing Conference (IWCMC), 2017 13th International*, pp. 323–328. IEEE.

Kazmi, M. (2011). *Radio Resource Management*, pp. 503–530. John Wiley & Sons, Ltd.

Kela, P., Costa, M., Turkka, J., Koivisto, M., Werner, J., Hakkarainen, A., Valkama, M., Jantti, R., and Leppanen, K. (2016). Location Based Beamforming in 5G Ultra-Dense Networks. In *2016 IEEE 84th Vehicular Technology Conference (VTC-Fall)*, pp. 1–7. IEEE.

Kelly, F. (1997). Charging and Rate Control for Elastic Traffic. *Transactions on Emerging Telecommunications Technologies*, 8(1):33–37.

Khorov, E., Krasilov, A., and Malyshev, A. (2017). Reliable Low Latency Communications in LTE Networks. In *Black Sea Conference on Communications and Networking (BlackSeaCom), 2017 IEEE International*, pp. 1–5. IEEE.

Kim, Y. and Sichitiu, M. L. (2011). Optimal Resource Allocation in Multihop Relay-Enhanced WiMAX Networks. In *Wireless Communications and Networking Conference (WCNC), 2011 IEEE*, pp. 737–742. IEEE.

Krishna, M. B. and Mauri, J. L. (2016). *Advances in Mobile Computing and Communications: Perspectives and Emerging Trends in 5G Networks*. CRC Press.

Kumar, S., Sarkar, A., Sriram, S., and Sur, A. (2015). A Three Level LTE Downlink Scheduling Framework for RT VBR Traffic. *Computer Networks*, 91:654–674.

Lai, W. K. and Tang, C.-L. (2013). Qos-Aware Downlink Packet Scheduling for LTE Networks. *Computer Networks*, 57(7):1689–1698.

Law, A. M., Kelton, W. D., and Kelton, W. D. (2014). *Simulation Modeling and Analysis*. McGraw-Hill New York, Fifth Ed. edition.

Lee, T.-H., Lin, J.-C., Su, Y. T., et al. (1995). Downlink Power-Control Algorithms for Cellular Radio Systems. *IEEE Transactions on Vehicular Technology*, 44(1):89–94.

Lee, Y. L., Chuah, T. C., Loo, J., and Vinel, A. (2014). Recent Advances in Radio Resource Management for Heterogeneous LTE/LTE-A Networks. *IEEE Communications Surveys & Tutorials*, 16(4):2142–2180.

Lee, Y. L., Loo, J., and Chuah, T. C. (2016a). Dynamic Resource Management for LTE-Based Hybrid Access Femtocell Systems. *IEEE Systems Journal*.

Lee, Y. L., Loo, J., Chuah, T. C., and El-Saleh, A. A. (2016b). Fair Resource Allocation with Interference Mitigation and Resource Reuse for LTE/LTE-A Femtocell Networks. *IEEE Transactions on Vehicular Technology*, 65(10):8203–8217.

Lee, Y. L., Loo, J., Chuah, T. C., and El-Saleh, A. A. (2017). Multi-Objective Resource Allocation for LTE/LTE-A Femtocell/HeNB Networks Using Ant Colony Optimization. *Wireless Personal Communications*, 92(2):565–586.

Leverege (2017). White paper: PA Primer on Cellular IoT. Technical report, Leverege LLC.

Li, S., Da Xu, L., and Zhao, S. (2018). 5G Internet of Things: A Survey. *Journal of Industrial Information Integration*, 10:1–9.

Li, Y., Sheng, M., Tan, C. W., Zhang, Y., Sun, Y., Wang, X., Shi, Y., and Li, J. (2015). Energy-Efficient Subcarrier Assignment and Power Allocation in OFDMA Systems with Max-Min Fairness Guarantees. *IEEE Transactions on Communications*, 63(9):3183–3195.

Liao, H.-S., Chen, P.-Y., and Chen, W.-T. (2014). An Efficient Downlink Radio Resource Allocation with Carrier Aggregation in LTE-advanced Networks. *IEEE Transactions on Mobile Computing*, 13(10):2229–2239.

Liu, B., Tian, H., and Xu, L. (2013). An Efficient Downlink Packet Scheduling Algorithm for Real Time Traffics in LTE Systems. In *Consumer communications and networking conference (CCNC), 2013 IEEE*, pp. 364–369. IEEE.

Liu, D. and Lee, Y.-H. (2005). An Efficient Scheduling Discipline for Packet Switching Networks Using Earliest Deadline First Round Robin. *Telecommunication Systems*, 28(3-4):453–474.

Liu, S., Zhang, C., Zhou, Y., and Zhang, Y. (2015). Delay-Based Weighted Proportional Fair Algorithm for LTE Downlink Packet Scheduling. *Wireless Personal Communications*, 82(3):1955–1965.

Lohani, S., Hossain, E., and Bhargava, V. K. (2018). Joint Resource Allocation and Dynamic Activation of Energy Harvesting Small Cells in OFDMA HetNets. *IEEE TRANSACTIONS ON WIRELESS COMMUNICATIONS*, 17(3):1768–1783.

Masoudi, M., Zaefarani, H., Mohammadi, A., and Cavdar, C. (2018). Energy Efficient Resource Allocation in Two-Tier OFDMA Networks with QoS Guarantees. *Wireless Networks*, 24(5):1841–1855.

Mecozzi, A. and Essiambre, R.-J. (2012). Nonlinear Shannon Limit in Pseudo Linear Coherent Systems. *Journal of Lightwave Technology*, 30(12):2011–2024.

Mogensen, P., Na, W., Kovács, I. Z., Frederiksen, F., Pokhariyal, A., Pedersen, K. I., Kolding, T., Hugl, K., and Kuusela, M. (2007). LTE Capacity Compared to the Shannon Bound. In *Vehicular Technology Conference, 2007. VTC2007-Spring. IEEE 65th*, pp. 1234–1238. IEEE.

Nasralla, M. M., Razaak, M., Rehman, I. U., and Martini, M. G. (2018). Content-aware Packet Scheduling Strategy for Medical Ultrasound Videos over LTE Wireless Networks. *Computer Networks*, 140:126–137.

Nesterov, Y. (2013). *Introductory Lectures on Convex Optimization: A Basic Course*, volume 87. Springer Science & Business Media.

Ng, D. W. K., Lo, E. S., and Schober, R. (2013). Energy-Efficient Resource Allocation in Multiuser OFDM Systems with Wireless Information and Power Transfer. In *Wireless Communications and Networking Conference (WCNC), 2013 IEEE*, pp. 3823–3828. IEEE.

Nikaein, N. and Krea, S. (2011). Latency for Real-time Machine-to-machine Communication in LTE-based System Architecture. In *Wireless Conference 2011-Sustainable Wireless Technologies (European Wireless), 11th European*, pp. 1–6. VDE.

Noh, K. S. S. K. M., Ali, D. M., Rahman, A. A. A., Samingan, A. K., Yusuf, Y., and Yusuff, N. M. (2017). Performance Analysis of EXP-BET Algorithm. *Journal of Telecommunication, Electronic and Computer Engineering (JTEC)*, 9(1-4):15–19.

Nonchev, S. and Valkama, M. (2009). A New Fairness-Oriented Packet Scheduling Scheme with Reduced Channel Feedback for OFDMA Packet Radio Systems. *International Journal of Communications, Network and System Sciences*, 2(07):608–618.

Obaidat, M., Zarai, F., and Nicopolitidis, P. (2015). *Modeling and Simulation of Computer Networks and Systems: Methodologies and Applications*. Elsevier Science.

Oh, E., Krishnamachari, B., Liu, X., and Niu, Z. (2011). Toward Dynamic Energy-efficient Operation of Cellular Network Infrastructure. *IEEE Communications Magazine*, 49(6).

O'Neill, B. (1982). A Problem of Rights Arbitration from the Talmud. *Mathematical Social Sciences*, 2(4):345–371.

Pantisano, F. and Corvino, V. (2010). Position-Based Power Planning for Fair Resource Allocation in LTE-A. In *2010 IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, pp. 1493–1498. IEEE.

Partov, B. and Leith, D. J. (2017). Utility Fair Rate Allocation in LTE/802.11 Networks. *IEEE/ACM Transactions on Networking*, 25(2):1076–1088.

Paul, A. K., Kawakami, H., Tachibana, A., and Hasegawa, T. (2017). Effect of AQM-Based RLC Buffer Management on the eNB Scheduling Algorithm in LTE Network. *Technologies*, 5(3):59.

Piro, G., Grieco, L. A., Boggia, G., Capozzi, F., and Camarda, P. (2011a). Simulating LTE Cellular Systems: An Open-Source Framework. *IEEE transactions on vehicular technology*, 60(2):498–513.

Piro, G., Grieco, L. A., Boggia, G., Fortuna, R., and Camarda, P. (2011b). Two-Level Downlink Scheduling for Real-Time Multimedia Services in LTE Networks. *IEEE Transactions on Multimedia*, 13(5):1052–1065.

Priya, L. and Soundar, K. R. (2018). LTE: An Enhanced Hybrid Domain Downlink Scheduling. *Cognitive Systems Research*, 52:550–555.

Proebster, M., Mueller, C. M., and Bakker, H. (2010). Adaptive Fairness Control for a Proportional Fair LTE Scheduler. In *2010 IEEE 21st International Symposium on Personal Indoor and Mobile Radio Communications (PIMRC)*, pp. 1504–1509. IEEE.

Radhakrishnan, S., Neduncheliyan, S., and Thyagharajan, K. (2016). A Review of Downlink Packet Scheduling Algorithms for Real Time Traffic in LTE-advanced Networks. *Indian Journal of Science and technology*, 9(4).

Ramjee, T. B. L. E. L. R. (2006). Generalized Proportional Fair Scheduling in Third Generation Wireless Data Networks. In *Proc. IEEE Infocom 2006*.

Roodaki, M., Raahemifar, K., and Raahemi, B. (2014). Analysis of Quality of Services in LTE and Mobile WiMAX. *Computers & Electrical Engineering*, 40(5):1508–1523.

Sadeghi, M., Björnson, E., Larsson, E. G., Yuen, C., and Marzetta, T. L. (2018). Max–Min Fair Transmit Precoding for Multi-Group Multicasting in Massive MIMO. *IEEE Transactions on Wireless Communications*, 17(2):1358–1373.

Sadiq, B., Baek, S. J., and De Veciana, G. (2011). Delay-Optimal Opportunistic Scheduling and Approximations: The Log Rule. *IEEE/ACM Transactions on Networking (TON)*, 19(2):405–418.

Sadiq, B., Madan, R., and Sampath, A. (2009). Downlink Scheduling for Multiclass Traffic in LTE. *EURASIP Journal on Wireless Communications and Networking*, 2009(1):1–18.

Salami, R., Laflamme, C., Adoul, J.-P., Kataoka, A., Hayashi, S., Moriya, T., Lamblin, C., Massaloux, D., Proust, S., Kroon, P., et al. (1998). Design and Description of CS-ACELP: A Toll Quality 8 Kb/S Speech Coder. *IEEE transactions on Speech and Audio Processing*, 6(2):116–130.

Sargent, R. G. (2013). Verification and Validation of Simulation Models. *Journal of simulation*, 7(1):12–24.

Seeling, P. and Reisslein, M. (2012). Video Transport Evaluation with H. 264 Video Traces. *IEEE Communications Surveys & Tutorials*, 14(4):1142–1165.

Shakir, S. S. H. and Rajesh, A. (2017). Performance Analysis of Two Level Calendar Disc Scheduling in LTE Advanced System with Carrier Aggregation. *Wireless Personal Communications*, 95(3):2855–2871.

Shakkottai, S. and Stolyar, A. L. (2001). Scheduling Algorithms for a Mixture of Real-Time and Non-Real-Time Data in HDR. *Teletraffic Science and Engineering*, 4:793–804.

Shapley, L. S. (1953). A Value for N-Person Games. *Contributions to the Theory of Games*, 2(28):307–317.

Shi, H., Prasad, R. V., Onur, E., and Niemegeers, I. (2014). Fairness in Wireless Networks: Issues, Measures and Challenges. *IEEE Communications Surveys & Tutorials*, 16(1):5–24.

Sokun, H., Bedeer, E., Gohary, R., and Yanikomeroglu, H. (2017). Optimization of Discrete Power and Resource Block Allocation for Achieving Maximum Energy Efficiency in OFDMA Networks. *IEEE Access*.

Su, P., Sheng, Z., Weiwei, Z., and Tian, Y. (2016a). Power Optimization in MIMO-OFDM Systems with Mixed Orthogonal Frequency Division and Space Division Multiple Access Scheme. *Wireless Personal Communications*, 91(2):885–901.

Su, X., Liang, C., Choi, D., and Choi, C. (2016b). Power Allocation Scheme for Femto-to-Macro Downlink Interference Reduction for Smart Devices in Ambient Intelligence. *Mobile Information Systems*, 2016.

Su, X., Wang, Y., Choi, D., Kim, P., and Choi, C. (2017). Channel Allocation and Power Control Schemes for Cross-Tier 3GPP LTE Networks to Support Multimedia Applications. *Multimedia Tools and Applications*, pp. 1–17.

Sulthana, S. F. and Nakkeeran, R. (2015). Performance Analysis of Service Based Scheduler in LTE OFDMA System. *Wireless Personal Communications*, 83(2):841–854.

Taha, A.-E. M., Hassanein, H. S., and Ali, N. A. (2011). *Quality of Service and Bandwidth Reservation*, pp. 173–188. John Wiley & Sons, Ltd.

Tan, K., Wu, D., Chan, A. J., and Mohapatra, P. (2011). Comparing Simulation Tools and Experimental Testbeds for Wireless Mesh Networks. *Pervasive and Mobile Computing*, 7(4):434–448.

Tung, C.-T., Chung, Y.-L., and Tsai, Z. (2012). An Efficient Power-Saving Downlink Transmission Scheme in OFDM-Based Multiple Component Carrier Systems. In *2012 14th International Conference on Advanced Communication Technology (ICACT)*, pp. 116–120. IEEE.

Van Chien, T., Björnson, E., and Larsson, E. G. (2016). Downlink Power Control For Massive MIMO Cellular Systems with Optimal User Association. In *2016 IEEE International Conference on Communications (ICC)*, pp. 1–6. IEEE.

Venturino, L., Zappone, A., Risi, C., and Buzzi, S. (2015). Energy-Efficient Scheduling and Power Allocation in Downlink OFDMA Networks with Base Station Coordination. *IEEE transactions on wireless communications*, 14(1):1–14.

Wang, L.-C., Chiang, M.-C., Chen, L., Chang, C.-J., and Liao, C.-Y. (2003). Performance Comparisons of Power Allocation Mechanisms for Downlink Handoff in the WCDMA System with Microcellular Environments. In *Proceedings of the 6th ACM international workshop on Modeling analysis and simulation of wireless and mobile systems*, pp. 2–10. ACM.

Wang, R., Yan, S., Tian, X., Lv, C., and Liu, S. (2016a). Energy-Efficient Resource Allocation with Variable Fairness Threshold Based on BBO. In *Instrumentation & Measurement, Computer, Communication and Control (IMCCC), 2016 Sixth International Conference on*, pp. 78–81. IEEE.

Wang, X., Vasilakos, A. V., Chen, M., Liu, Y., and Kwon, T. T. (2012). A Survey of Green Mobile Networks: Opportunities and Challenges. *Mobile Networks and Applications*, 17(1):4–20.

Wang, Y., Abdelhadi, A., and Clancy, T. C. (2016b). Optimal Power Allocation for LTE Users with Different Modulations. In *2016 Annual IEEE Systems Conference (SysCon)*, pp. 1–5. IEEE.

Wang, Y.-P. E., Lin, X., Adhikary, A., Grovlen, A., Sui, Y., Blankenship, Y., Bergman, J., and Razaghi, H. S. (2017). A Primer on 3GPP Narrowband Internet of Things. *IEEE Communications Magazine*, 55(3):117–123.

Wengerter, C., Ohlhorst, J., and von Elbwart, A. G. E. (2005). Fairness and Throughput Analysis for Generalized Proportional Fair Frequency Scheduling in OFDMA. In *Vehicular Technology Conference, 2005. VTC 2005-Spring. 2005 IEEE 61st*, volume 3, pp. 1903–1907. IEEE.

Whitner, R. B. and Balci, O. (1989). Guidelines for Selecting and Using Simulation Model Verification Techniques. In *Proceedings of the 21st conference on Winter simulation*, pp. 559–568. ACM.

Wu, J., Qiao, X., Xia, Y., Yuen, C., and Chen, J. (2015). A Low-Latency Scheduling Approach for High-Definition Video Streaming In a Heterogeneous Wireless Network with Multihomed Clients. *Multimedia Systems*, 21(4):411–425.

Wu, Q., Li, G. Y., Chen, W., Ng, D. W. K., and Schober, R. (2017). An Overview of Sustainable Green 5G Networks. *IEEE Wireless Communications*, 24(4):72–80.

Xue, P., Gong, P., Park, J. H., Park, D., and Kim, D. K. (2009). Max-Min Fairness Based Radio Resource Management in Fourth Generation Heterogeneous Networks. In *Communications and Information Technology, 2009. ISCIT 2009. 9th International Symposium on*, pp. 208–213. IEEE.

Yassin, M., Lahoud, S., Ibrahim, M., and Khawam, K. (2014). A Downlink Power Control Heuristic Algorithm for LTE Networks. In *2014 21st International Conference on Telecommunications (ICT)*, pp. 323–327. IEEE.

Yu, W. and Lui, R. (2006). Dual Methods for Nonconvex Spectrum Optimization of Multicarrier Systems. *IEEE Transactions on Communications*, 54(7):1310–1322.

Zhang, H., Fang, F., Cheng, J., Long, K., Wang, W., and Leung, V. C. (2018). Energy-Efficient Resource Allocation in NOMA Heterogeneous Networks. *IEEE Wireless Communications*, 25(2):48–53.

Zhang, H., Jiang, C., Beaulieu, N. C., Chu, X., Wang, X., and Quek, T. Q. (2015). Resource Allocation for Cognitive Small Cell Networks: A Cooperative Bargaining Game Theoretic Approach. *IEEE Transactions on Wireless Communications*, 14(6):3481–3493.

Zhang, Y., Xiong, K., An, F., Di, X., and Su, J. (2016). Mobile-Service Based Max-Min Fairness Resource Scheduling for Heterogeneous Vehicular Networks. *arXiv preprint arXiv:1603.03645*.

Zhou, W., Chen, W., Tan, Z., Chen, S., and Zhang, Y. (2011). A modified RR scheduling scheme based CoMP in LTE-A system. In *IET International Conference on Communication Technology and Application (ICCTA 2011)*, pp. 176–180.

Zhou, Z., Ota, K., Dong, M., and Xu, C. (2017). Energy-efficient Matching for Resource Allocation in D2D Enabled Cellular Networks. *IEEE Transactions on Vehicular Technology*, 66(6):5256–5268.

Zolkaffli, N., Ibrahim, M., Yusof, M. I., and Ab Rahman, R. (2012). LTE Performance Evaluation of Scheduling Strategy in Various Environments. In *Wireless Technology and Applications (ISWTA), 2012 IEEE Symposium on*, pp. 327–331. IEEE.