UNIVERSITI PUTRA MALAYSIA

CHANNEL-AWARE DOWNLINK SCHEDULING FOR QUALITY OF SERVICE IN LONG TERM EVOLUTION NETWORK

ALAA OMER NAJIM

FSKTM 2018 2

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By

ALAA OMER NAJIM

Thesis Submitted to the School of Graduate Studies, Universiti Putra Malaysia, in Fulfilment of the Requirements for the Degree of Master of Science

January 2018

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DEDICATIONS

I would like to dedicate this thesis to my beloved motherland "IRAQ".

To the spirit of my father and mother".

&

To All whom I love.

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Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfilment of the requirement for the degree of Master of Science

CHANNEL-AWARE DOWNLINK SCHEDULING FOR QUALITY OF SERVICE IN LONG TERM EVOLUTION NETWORK

By

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January 2018

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Long Term Evolution (LTE) is a recently evolving technology proposed by the Third Generation Partnership Project to provide a smooth migration toward the Fourth Generation of cellular networks. Radio Resource Management (RRM) is one of the core modules in LTE network architecture which includes functions to manage and handle involved system users who are communicating with their resources sites. In this thesis, Packet Scheduling is defined as one of the main RRM functions, and it is responsible for the intelligent selections of users and transmissions of their packets such that radio resources are efficiently utilized, and user's Quality of Service (QoS) requirements are satisfied. The emphasis of this research is on the radio resource scheduling of LTE downlink. For flows with different volumes, delay has been defined as a major challenging issue that restricts the delivered network performance to subscribed users.

In this thesis, a Delay-oriented Resource Allocation (DoRA) scheduler is proposed to provide an efficient allocation of wireless resources across users of different traffic volumes to minimize delay. Initially, a range of constraints was defined based on a recent algorithm from the literature, namely Delay Based Weighted Proportional Fair (DBWPF). These constraints comprise the use of an inefficient method to determine delay by the buffer size. In the proposed algorithm we, utilize Head of Line delay with channel-related parameters such as user data rate in addition to several pre-defined QoS tunable parameters to formulate a rule that prioritizes different user flows assigned with channel resources in order to improve delay.

The proposed algorithm using system-level simulation experiments with perfor-

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mance comparison with DBWPF in terms of end-to-end delay, fairness, system throughput, Packet Loss Ratio (PLR), and spectral efficiency was evaluated. The output results indicate that the proposed DoRA scheduling algorithm outperforms DBWPF in providing a minimum level of end-to-end delay.

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Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia
sebagai memenuhi keperluan untuk ijazah Master Sains

PENJADUALAN PAUTAN TURUN SALURAN-SEDAR UNTUK KUALITI PERKHIDMATAN DALAM JARINGAN EVOLUSI JANGKA PANJANG

Oleh

ALAA OMER NAJIM

Januari 2018

Pengerusi: Nor Asilah Wati Abdul Hamid, PhD
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Evolusi Jangka Panjang (LTE) adalah teknologi yang baru-baru ini berkembang dan dicadangkan oleh Projek Perkongsian Generasi Ketiga untuk menyediakan migrasi yang lancar ke arah rangkaian selular Generasi Keempat. Pengurusan Sumber Radio (RRM) merupakan salah satu modul teras dalam seni bina rangkaian LTE yang merangkumi fungsi untuk mengurus dan mengendalikan pengguna sistem yang terlibat yang berkomunikasi dengan laman sumber masing-masing. Di dalamnya, Penjadualan Packet dianggap sebagai salah satu fungsi RRM utama dan ia bertanggungjawab untuk pemilihan pengguna pintar dan penghantaran paket mereka supaya sumber radio digunakan dengan cekap dan keperluan Kualiti Perkhidmatan (QoS) pengguna dipenuhi. Penekanan kajian ini adalah penjadualan sumber radio LTE pautan tutun. Untuk aliran dengan jumlah yang berlainan, kelewatan telah disenaraikan sebagai isu utama yang membataskan prestasi jaringan yang disampaikan kepada pengguna yang dilanggan. Dalam tesis ini, Penjadualan Peruntukan Sumber Berorientasikan Kelewatan (DoRA) dicadangkan untuk menyediakan peruntukan sumber tanpa wayar yang cekap menanggani masalah jumlah kesesakan pengguna yang berbeza dan meminimumkan kelewatan. Pada mulanya, pelbagai kekangan telah ditakrifkan pada algoritma yang sebelumnya, iaitu Kelewatan Berasaskan Pemberat Berpatutan Adil (DBWPF). Kekangan-kekangan ini merangkumi penggunaan kaedah yang tidak ketara untuk menentukan penangguhan oleh saiz penampan. Dalam algoritma yang dicadangkan, kami menggunakan Ketua Talian Kelewatan dengan parameter yang berkaitan dengan saluran seperti kadar data pengguna sebagai tambahan kepada beberapa parameter yang boleh dimodelkan QoS yang telah ditetapkan untuk merumuskan peraturan yang mengutamakan aliran pengguna yang berbeza untuk ditugaskan dengan sumber saluran untuk meningkatkan kelewatan.

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Kami menilai algoritma yang dicadangkan menggunakan eksperimen simulasi paras sistem dengan perbandingan prestasi dengan DBWPF dari segi kelewatan akhir, keadilan, beban sistem, Nisbah Kehilangan Paket (PLR), dan kecekapan spektrum. Keputusan output menunjukkan bahawa algoritma penjadualan DoRA yang dicadangkan mengatasi DBWPF dalam memberikan kelewatan akhir dari hujung ke hujung.

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ACKNOWLEDGEMENTS

First and foremost, I would like to express my sincere gratitude to my supervisor Dr. Nor Asilah Wati Abdul-Hamid for the continuous support of my study and research, for his 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, Dr. Zurina Mohd Hanapi, and Dr. Idawati Ahmad 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 Master.

I am very grateful to my family, my brothers, and my sisters 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.

Last but not least, it gives me immense pleasure to express my deepest gratitude to my friends, colleagues and lab mates for their unlimited support and encouragement.

Finally, 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.

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TABLE OF CONTENTS

	Page
ABSTRACT	i
ABSTRAK	iii
ACKNOWLEDGEMENTS	v
APPROVAL	vi
DECLARATION	viii
LIST OF TABLES	xii
LIST OF FIGURES	xiii
CHAPTER	
1 INTRODUCTION	1
1.1 Problem Statement	2
1.2 Motivation	3
1.3 Research Objective	3
1.4 Research Scope	4
1.5 Research Contribution	4
1.6 Thesis Organization	4
2 LITERATURE REVIEW	7
2.1 Evolution of Mobile Communication	7
2.2 Overview of LTE Network	8
2.3 LTE Network Architecture	9
2.4 LTE Radio Protocol Architecture	11
2.5 Radio Resource Management	14
2.6 QoS and Bearers	16
2.7 Radio Resource Scheduling in LTE Systems	17
2.8 Classification of Downlink Scheduling Algorithms in LTE Systems	19
2.8.1 Channel-unaware Scheduling Algorithms	19
2.8.2 Channel-aware Scheduling Algorithms	21
2.8.3 QoS-aware Scheduling Algorithms	25
3 RESEARCH METHODOLOGY	28
3.1 Notations and Definitions	28
3.2 Research Framework	29
3.2.1 Problem Formulation	29
3.2.2 Previous Works Implementation	29
3.2.3 The Proposed Scheme	31
3.2.4 Conducting Simulation Experiment	31
3.2.5 Evaluation of Performance Metrics	31

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3.3 Experiment Environment 31
3.3.1 Computer Resources 32
3.3.2 Simulation Model 32
3.4 DBWPF Algorithm 34
3.4.1 Delay Weighted Mechanism 35
3.5 Performance Metrics 36
3.5.1 Mean End-to-End Delay 37
3.5.2 Fairness Index 37
3.5.3 Throughput 38
3.5.4 PLR 38
3.5.5 Spectral Efficiency 38
3.6 Performance Analysis 39
3.7 Simulation Validation 40
3.8 Summary 42

4 DELAY-ORIENTED RESOURCE ALLOCATION FOR DIFFERENT TRAFFIC VOLUMES IN LTE DOWNLINK 43
4.1 Introduction 43
4.2 The proposed DoRA Algorithm 43
4.2.1 Limitation of DBWPF Algorithm 44
4.2.2 The Proposed DoRA Scheduling Algorithm 44
4.2.3 Impact of Tunable Parameters 50
4.3 Performance Evaluation 51
4.3.1 Simulation Scenario 51
4.3.2 Results and Discussions 51
4.4 Summary 58

5 CONCLUSION AND FUTURE WORKS 59
5.1 Conclusion 59
5.2 Future Works 60

REFERENCES 61
APPENDICES
Appendix A 66
BIODATA OF STUDENT 68
LIST OF PUBLICATIONS 69

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LIST OF TABLES

Table		Page
2.1	Standard QoS Class Identifier (QCI) for LTE (Ali-Yahiya, 2011)	17
2.2	Comparative Summary of Downlink Scheduling Algorithm in LTE	26
3.1	Notations used in the equations	29
3.2	Simulation Parameters (Liu et al., 2015)	34
3.3	Main Component of the LTE-Sim	40

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LIST OF FIGURES

Figure		Page
1.1	Downlink System Architecture	2
1.2	Thesis Modules	5
2.1	Generation of Mobile Systems	8
2.2	The Network Architecture of LTE Network	10
2.3	LTE Protocol Layer	11
2.4	U-Plane protocol stack	13
2.5	C-Plane protocol stack	13
2.6	Time-Frequency radio resources grid (Ragaleux et al., 2016)	15
2.7	Packet Scheduler Model	19
3.1	Research Framework	30
3.2	Simulation Network topology for packet scheduling (19 Cell)	33
3.3	Simulation Scenario	33
3.4	DBWPF Algorithm Flowchart	36
3.5	Protocol stack implemented in LTE-Sim	39
3.6	Example of Output Trace	40
3.7	Delay Fairness	41
3.8	Aggregate Throughput	42
4.1	DoRA Algorithm Flowchart	45
4.2	Resource Allocation Process in DoRA	48
4.3	Illustration of queue delay	49
4.4	Delay Term in DoRA Algorithm	49

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4.5 Impact of Tunable Parameters on the Delay Term 50

4.6 Average Delay Time at 30 km/h 52

4.7 Average Delay Time at 120 km/h 52

4.8 Fairness Index at 30 km/h 53

4.9 Fairness Index at 120 km/h 53

4.10 Aggregated Throughput at 30 km/h 54

4.11 Aggregated Throughput at 120 km/h 55

4.12 Packet Loss Ratio at 30 km/h 56

4.13 Packet Loss Ratio at 120 km/h 56

4.14 Spectral Efficiency at 30 km/h 57

4.15 Spectral Efficiency at 120 km/h 58

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CHAPTER 1

INTRODUCTION

Mobile communication has recently received increasing approbation worldwide due to the rapid increase in the number of User Equipment (UE), the rate of mobile data and the demand for wireless multimedia applications. The expected increase in the rate of mobile data has become an evolutionary driving force that led to new mobile communication technologies. Although several mobile communication technologies are used in wireless networks, this research ocused on technologies that centered on the Long-Term Evolution (LTE) standard. The LTE standard was launched by the Third Generation Partnership Project (3GPP) and was defined as a step to the Fourth Generation (4G) mobile platform (Astély et al., 2009). The LTE architecture is characterized as flat and Internet Protocol (IP)-based, and the performance of multimedia services is thus expected to take a step further in mobile communication such as achieving high data rates, low latency and increased level of Spectral Efficiency (SE) (Zyren and McCoy, 2007). The LTE can provide a better user experience in delivering multimedia and Internet applications even in high-mobility scenarios. In fact, the LTE achieves a high performance level due to the adoption of Orthogonal Frequency Division Multiple Access (OFDMA) technology in the Downlink (DL) system. This adoption has allowed the DL channel to boost up the system capacity by transmitting traffic with high data rate and low latency values to different users who are multiplexed in time and frequency domains (Shah, 2008). Ensuring satisfaction towards the high system performance of the LTE telecommunication technology has created many challenges related to radio base station capabilities in bandwidth management (Markoulidakis et al., 1997). For instance, satisfaction is affected by the limited bandwidth that constrains user's requests to be provided with diverse services (Prasad et al., 2000). The base station is responsible for all the procedures related to user traffic management in DL and Uplink (UL) directions that are handled by a resource scheduler. This study investigated the effective resource-scheduling strategies designed for DL communication in LTE networks in order to achieve the required performance and a high satisfaction level of end users.(Ahmadi, 2013).

Figure 1.1 demonstrates a typical LTE DL system model. The scheduler at the base station manages and controls data transmission in both channel directions by assigning sufficient resources to the involved UEs in Medium Access Control (MAC) layer. All flows from different applications are assigned to different bearers, each with specific QoS requirements. A bearer is defined as a logical connection, which is established between UE and Eevolved NodeB (eNB). When user data are scheduled by MAC policy, they are mapped to a number of physical resources with particular frequencies. This process is performed by deciding a proper Modulation and Coding Scheme (MCS) from the given Signal-to-Interference-plus Noise Ratio (SINR) values of each UE channel in the physical layer (Capozzi et al., 2013).

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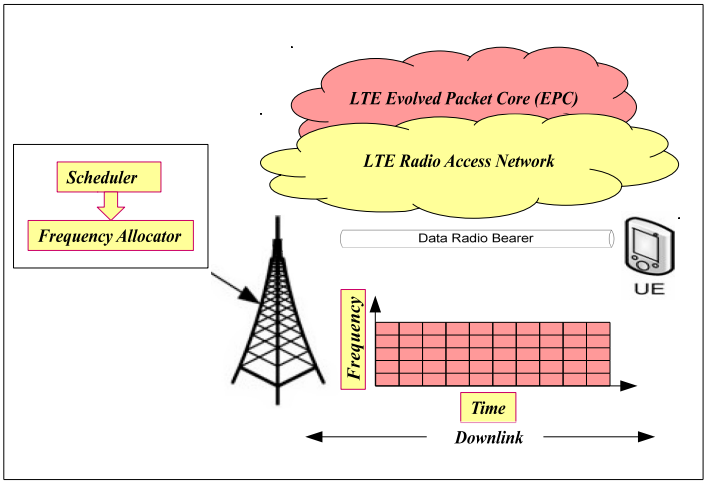

Figure 1.1: Downlink System Architecture

1.1 Problem Statement

The 3GPP standard leaves open the design and implementation of radio resource scheduling. Consequently, numerous studies (Lau, 2002) (Holtzman, 2001); (Kim et al., 2004); (Pramudito and Alsusa, 2014); (Schwarz et al., 2011); (Liu et al., 2015) proposed ways to solve issues related to resource allocation in the LTE channel to improve system throughput and service fairness of the involved user data. Nevertheless, these proposals lack solutions that emphasize the awareness of satisfying traffic QoS in terms of delay in addition to the guaranteed service rate. The essence of studying network latency becomes a major issue, considering that the recent LTE networks are rich with user applications that are run at different traffic attributes.

A recent proposal that addresses the delay issue is the DBWPF algorithm (Liu et al., 2015). The approach triggers a scheduling decision by considering a delay weight that is determined on the basis of buffer size and previous and current buffer delay states. This approach influences the scheduler to emphasize delay balancing rather than guaranteeing low delay values. With this behavior, flows with different volumes suffer a high delay as the variations among flow sizes become significant.

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1.2 Motivation

LTE networks are among the mobile communication network technologies that support high data rates, large convergence, and QoS for various applications. The current mobile communication technologies maintain a set of performance quality level according to the demand of end users for new telecommunication applications such as multimedia streaming, music and video download, mobile gaming and Internet browsing. These end-user applications should be able to run with an enhanced service utilization so that these applications can be on instantly, all the time and anywhere. Thus, resource allocation has become important in ensuring and maintaining the QoS and performance quality level of the networks due to the scarcity of resources in LTE networks.

Radio resource algorithm or scheduling algorithm is the fundamental component to guarantee QoS of various applications, which provides a major contribution towards the network performance as a whole. This is achieved basically by allocating the scarce wireless channel resources among UEs and determining their transmission order. This research focused primarily on DL scheduling in which users simultaneously run different traffic volumes that may require more channel resources. The scarcity of these resources has led to increased packet loss, delay and poor fairness index which has consequently affected the QoS and performance quality level of the network. This research intended to mitigate this problem by proposing an algorithm that schedules varying traffic volumes while ensuring both the QoS and performance level quality are sufficiently maintained. To this end, a motivated research objective was considered and discussed, followed by an outline of the contribution and organization of this study.

1.3 Research Objective

In this study, the emphasize was on scheduling data traffic with minimum delay time and maintaining a service level which are defined as among the key challenges for the QoS concept in 4G and beyond. Therefore, the main objective of this study is to propose an efficient LTE downlink scheduling algorithm in which a delay-based weight is calculated on flows of different volumes to prioritize radio resources allocation such that QoS is satisfied with the minimal delay.

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1.4 Research Scope

This study focuses on the scheduling strategies in MAC layer for LTE DL transmission. The scheduling strategies can be classified in terms of the key design aspects such as channel-unaware, channel-aware, and QoS-aware. It is also focused on the channel-aware technique, which is likely to be suitable for wireless environments. Simulation tools were employed to verify the performance of the proposed algorithm, and all the measures were considered in a multi-cell environment. Figure 1.2 illustrates the flow scope of the thesis, where the shapes with bold lines show the scope followed by the thesis while the others show those that are outside the scope of the thesis.

1.5 Research Contribution

A DoRA for LTE downlink scheduling is proposed by considering the state of the variable traffic volumes. The proposed algorithm adopts a priority-based approach, which utilizes a delay-based information to affect the scheduling rule directly. The algorithm selects the flows of different data volumes with delay that is high and tends to expire. The significance of this scheduling approach is that it exponentially tunes the scheduler behaviour to depend on delay during high stages of traffic loads while maintaining an acceptable level of QoS directions by configuring some performance parameters to control the scheduler behaviour.

1.6 Thesis Organization

This study presents a new DL scheduling mechanism for LTE networks. The rest of this paper is organized as follows.

Chapter 2 presents the evolution of mobile communication, followed by an overview of the LTE network, LTE network architecture, LTE radio protocol architecture and radio bearer management. RRM at the MAC and physical layers is briefly described. Scheduling and related works on DL scheduling techniques that addresses the LTE performance metrics are also shown. Analysis of different scheduling schemes and some resource management issues are also discussed.

Chapter 3 identifies the definition and theme used throughout the development of the research work. This chapter presents the thesis framework and explains the stages in detail. Experimental setup and topologies, as well as the perfor-

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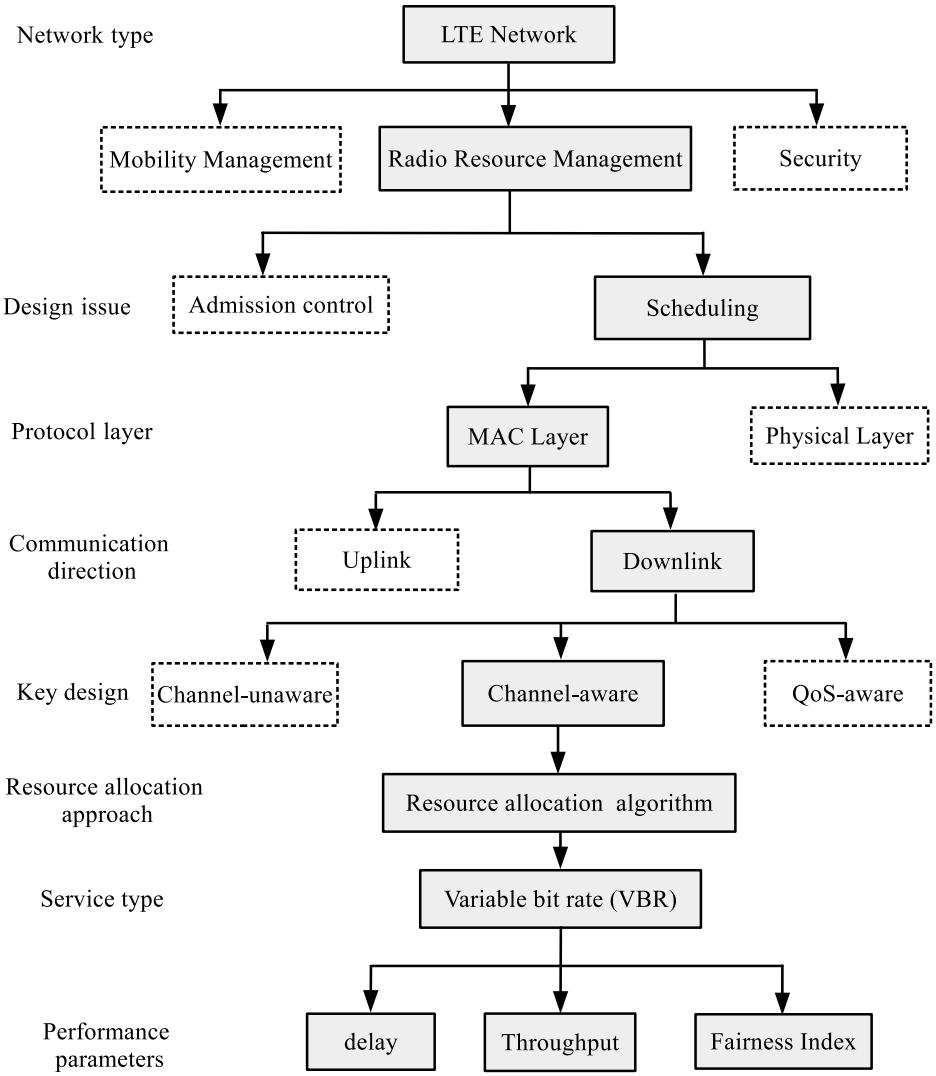

Figure 1.2: Thesis Modules

mance metrics and their evaluation methods are also provided.

Chapter 4 presents an efficient resource scheduling mechanism known as DoRA algorithm that provides a delay enhancement performance target. The

DoRA algorithm is described and evaluated in terms of delay, fairness Index, throughput, PLR, and spectral efficiency.

Chapter 5 concludes the work and recommends some promising directions for future research.

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REFERENCES

Ahmadi, S. 2013. *LTE-Advanced: a practical systems approach to understanding 3GPP LTE releases 10 and 11 radio access technologies*. Academic Press.

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.

Ali, I., Casati, A., Chowdhury, K., Nishida, K., Parsons, E., Schmid, S. and Vaidya, R. 2009. Network-based mobility management in the evolved 3GPP core network. *IEEE Communications Magazine* 47 (2): 58–66.

Ali-Yahiya, T. 2011. *Understanding LTE and its Performance*. Springer Science & Business Media.

Alouini, M.-S. and Goldsmith, A. J. 1999. Area spectral efficiency of cellular mobile radio systems. *IEEE Transactions on vehicular technology* 48 (4): 1047–1066.

Aniba, G. and Aissa, S. 2004. Adaptive proportional fairness for packet scheduling in HSDPA. In *Global Telecommunications Conference, 2004. GLOBECOM'04. IEEE*, 4033–4037. IEEE.

Astély, D., Dahlman, E., Furuskär, A., Jading, Y., Lindström, M. and Parkvall, S. 2009. LTE: the evolution of mobile broadband. *IEEE Communications magazine* 47 (4).

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* .

Bechir, N., Nasreddine, M., Mahmoud, A., Walid, H. and Sofien, M. 2014. Novel Scheduling Algorithm for 3GPP Downlink LTE Cellular Network. *Procedia Computer Science* 40: 116–122.

Brehm, M. and Prakash, R. 2013. Overload-state downlink resource allocation in LTE MAC layer. *Wireless networks* 19 (5): 913–931.

Capozzi, F., Laselva, D., Frederiksen, F., Wigard, J., Kovacs, I. Z. and Mogensen, P. E. 2009. UTRAN LTE downlink system performance under realistic control channel constraints. In *Vehicular Technology Conference Fall (VTC 2009-Fall), 2009 IEEE 70th*, 1–5. IEEE.

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.

Cheng, Y.-H., Su, W.-C., Feng, K.-T. and Wang, L.-C. 2017. QoS-Guaranteed Channel-Aware Scheduling and Resource Grouping under Non-Full Buffer Traffic for LTE-A Networks. In *Wireless Communications and Networking Conference (WCNC), 2017 IEEE*, 1–6. IEEE.

© COPYRIGHT UPM

Choi, J.-G. and Bahk, S. 2007. Cell-throughput analysis of the proportional fair scheduler in the single-cell environment. *IEEE Transactions on Vehicular Technology* 56 (2): 766–778.

Coetzee, L. and Eksteen, J. 2011. The Internet of Things-promise for the future? An introduction. In *IST-Africa Conference Proceedings, 2011*, 1–9. IEEE.

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.

Djouama, A. and Lim, M.-S. 2015. Reduction of the feedback delay effect on a proportional fair scheduler in LTE downlink using nonlinear support vector machine prediction. *AEU-International Journal of Electronics and Communications* 69 (10): 1393–1402.

Ekstrom, H. 2009. QoS control in the 3GPP evolved packet system. *IEEE Communications Magazine* 47 (2): 76–83.

Elhadad, M. I., El-Rabaie, E.-S. M. and Abd-Elnaby, M. 2016. Resource allocation for Real-Time services using Earliest Due Date mechanism in LTE networks. In *Electronics, Communications and Computers (JEC-ECC), 2016 Fourth International Japan-Egypt Conference on*, 9–12. IEEE.

Elnashar, A., El-saidny, M. A. and Sherif, M. R. 2014. LTE Network Architecture and Protocols. *Design, Deployment and Performance of 4G-LTE Networks: A Practical Approach* 1–45.

Ferdosian, N., Othman, M., Ali, B. M. and Lun, K. Y. 2016. Greedy–knapsack algorithm for optimal downlink resource allocation in LTE networks. *Wireless Networks* 22 (5): 1427–1440.

Goldsmith, A. 2005. *Wireless communications*. Cambridge university press.

Holma, H. and Toskala, A. 2007. *HSDPA/HSUPA for UMTS: high speed radio access for mobile communications*. John Wiley & Sons.

Holma, H. and Toskala, A. 2009. *LTE for UMTS-OFDMA and SC-FDMA based radio access*. John Wiley & Sons.

Holma, H. and Toskala, A. 2011. *LTE for UMTS: Evolution to LTE-advanced*. John Wiley & Sons.

Holtzman, J. M. 2001. Asymptotic analysis of proportional fair algorithm. In *Personal, Indoor and Mobile Radio Communications, 2001 12th IEEE International Symposium on*, F–F. IEEE.

Jain, R. 1990. *The art of computer systems performance analysis: techniques for experimental design, measurement, simulation, and modeling*. John Wiley & Sons.

Jochen, S. 2003. Mobile communications .

© COPYRIGHT UPM

Kela, P., Puttonen, J., Kolehmainen, N., Ristaniemi, T., Henttonen, T. and Moisio, M. 2008. Dynamic packet scheduling performance in UTRA long term evolution downlink. In *Wireless Pervasive Computing, 2008. ISWPC 2008. 3rd International Symposium on*, 308–313. IEEE.

Khan, F. 2009. *LTE for 4G mobile broadband: air interface technologies and performance*. Cambridge University Press.

Kim, H., Kim, K., Han, Y. and Yun, S. 2004. A proportional fair scheduling for multicarrier transmission systems. In *Vehicular Technology Conference, 2004. VTC2004-Fall. 2004 IEEE 60th*, 409–413. IEEE.

Kolehmainen, N., Puttonen, J., Kela, P., Ristaniemi, T., Henttonen, T. and Moisio, M. 2008. Channel quality indication reporting schemes for UTRAN long term evolution downlink. In *Vehicular Technology Conference, 2008. VTC Spring 2008. IEEE*, 2522–2526. IEEE.

Kreher, R. and Gaenger, K. 2010. *LTE signaling: troubleshooting and optimization*. John Wiley & Sons.

Kuhne, A. and Klein, A. 2008. Throughput analysis of multi-user OFDMA-systems using imperfect CQI feedback and diversity techniques. *IEEE Journal on Selected Areas in Communications* 26 (8).

Kulkarni, P., Chin, W. H. and Farnham, T. 2010. Radio resource management considerations for LTE femto cells. *ACM SIGCOMM Computer Communication Review* 40 (1): 26–30.

Kwan, R. and Leung, C. 2010. A survey of scheduling and interference mitigation in LTE. *Journal of Electrical and Computer Engineering* 2010: 1.

Lau, V. K. 2002. Proportional fair spatial scheduling for wireless access point with multiple antenna-reverse link with scalar feedback. In *Global Telecommunications Conference, 2002. GLOBECOM'02. IEEE*, 763–767. IEEE.

Lee, J., Han, J.-K. and Zhang, J. C. 2009. MIMO technologies in 3GPP LTE and LTE-advanced. *EURASIP Journal on Wireless Communications and Networking* 2009 (1): 302092.

Lin, L.-x., Liu, Y.-a., Fang, L., Gang, X., LIU, K.-m. and Ge, X.-Y. 2012. Resource scheduling in downlink LTE-Advanced system with carrier aggregation. *The Journal of China Universities of Posts and Telecommunications* 19 (1): 44123–49.

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*, 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.

© COPYRIGHT UPM

Madhow, U. 2008. *Fundamentals of digital communication*. Cambridge University Press.

Markoulidakis, J. G., Lyberopoulos, G. L., Tsirkas, D. F. and Sykas, E. D. 1997. Mobility modeling in third-generation mobile telecommunications systems. *IEEE personal communications* 4 (4): 41–56.

Nguyen, D.-H., Nguyen, H. and Renault, E. 2016. A new channel-and qos-aware scheduling scheme for real-time services in lte network. *International Journal of Applied Information Systems* 11 (4): 8.

Nossenson, R. 2009. Long-term evolution network architecture. In *Microwaves, Communications, Antennas and Electronics Systems, 2009. COMCAS 2009. IEEE International Conference on*, 1–4. IEEE.

Pedersen, K. I., Kolding, T. E., Frederiksen, F., Kovács, I. Z., Laselva, D. and Mogensen, P. E. 2009. An overview of downlink radio resource management for UTRAN long-term evolution. *IEEE Communications Magazine* 47 (7).

Piro, G., Grieco, L. A., Boggia, G., Fortuna, R. and Camarda, P. 2011. Two-level downlink scheduling for real-time multimedia services in LTE networks. *IEEE Transactions on Multimedia* 13 (5): 1052–1065.

Pramudito, W. and Alsusa, E. 2014. Confederation based RRM with proportional fairness for soft frequency reuse LTE networks. *IEEE Transactions on Wireless Communications* 13 (3): 1703–1715.

Prasad, R., Mohr, W. and Konhauser, W. 2000. *Third generation mobile communication systems*. Artech House, Inc.

Ragaleux, A., Baey, S. and Gueguen, C. 2016. Adaptive and generic scheduling scheme for lte/lte-a mobile networks. *Wireless Networks* 22 (8): 2753–2771.

Schwarz, S., Mehlfuhrer, C. and Rupp, M. 2011. Throughput maximizing multiuser scheduling with adjustable fairness. In *Communications (ICC), 2011 IEEE International Conference on*, 1–5. IEEE.

Sesia, S., Baker, M. and Toufik, I. 2011. *LTE-the UMTS long term evolution: from theory to practice*. John Wiley & Sons.

Shah, S. I. 2008. Umts: High speed packet access (hspa) technology. In *Networking and Communications Conference, 2008. INCC 2008. IEEE International*, 2–2. IEEE.

Sulthana, S. F. and Nakkeeran, R. 2014. Study of Downlink Scheduling Algorithms in LTE Networks. *JNW* 9 (12): 3381–3391.

Tan, L. and Wang, N. 2010. Future internet: The internet of things. In *Advanced Computer Theory and Engineering (ICACTE), 2010 3rd International Conference on*, V5–376. IEEE.

Tran, T.-T., Shin, Y. and Shin, O.-S. 2012. Overview of enabling technologies for 3GPP LTE-advanced. *EURASIP Journal on Wireless Communications and Networking* 2012 (1): 54.

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Unknown, A. 2010. 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* 36.

Wang, C. and Huang, Y.-C. 2014. Delay-scheduler coupled throughput-fairness resource allocation algorithm in the long-term evolution wireless networks. *IET Communications* 8 (17): 3105–3112.

Wang, C., Liu, J., Li, B., Sohraby, K. and Hou, Y. T. 2007. LRED: a robust and responsive AQM algorithm using packet loss ratio measurement. *IEEE Transactions on Parallel and Distributed Systems* 18 (1): 29–43.

Zhou, W., Chen, W., Tan, Z., Chen, S. and Zhang, Y. 2011. A modified RR scheduling scheme based CoMP in LTE-A system .

Zyren, J. and McCoy, W. 2007. Overview of the 3GPP long term evolution physical layer. *Freescale Semiconductor, Inc., white paper* .

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