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HYPERGRAPH-BASED RESOURCE ALLOCATION IN WIRELESS MESH NETWORKS

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By

BASHAR KHUDHAIR ABBAS

Thesis submitted to the School of Graduate Studies, Universiti Putra Malaysia in fulfillment of the Requirements for the degree of Master of Science

December 2017

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DEDICATION

This thesis is dedicated to

All those I love

Especially

My dearest parents

My family

My brothers and sisters

For their endless encouragement, patience, and support and for being a great source of motivation and inspiration

And to all my friends

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

HYPERGRAPH-BASED RESOURCE ALLOCATION IN WIRELESS MESH NETWORKS

By

BASHAR KHUDHAIR ABBAS AL-ZEYADI

December 2017

Chairman : Professor Nor Kamariah bt Noordin, PhD
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The success of wireless mesh networks (WMNs) is highly contingent on effective radio resource management. In conventional wireless networks with heterogeneous traffic, system throughput, quality of service (QoS), fairness and complexity are usually common performance metrics. Orthogonal Frequency Division Multiplexing Access (OFDMA) is the most known modulation technique in wireless networks which are largely dependent on the mechanism of resource allocation. Limited spectrum resources necessitate that these resources be optimally employed in such a way as to satisfy the requirements of WMN users. Therefore, the task of resource allocation in this technology should be formulated as a task of allocating resource blocks (RBs) to the network stations according to the required traffic demands and QoS parameters and should also take into account the interference among them. By considering these features in mathematical models using a hypergraph and Koenig graphs, we can obtain an accurate description of the network. This enables us to fully describe all possible configurations of a mesh network and its individual elements, and takes into account the limitations of spectrum resources and interference between the network stations.

The proposed mathematical model was aimed at improving the performance of a mesh network as a whole by balancing the number of resource blocks allocated to individual stations. Thus, our algorithm was developed such that the throughput was maximised as long as the QoS was guaranteed with low complexity. Finally, a hypergraph-based resource allocation in a wireless mesh network with a balanced technique (BA-HBRA) was developed for OFDMA downlink RBs allocation to further enhance the system performance by satisfying the traffic demands with the least number of RBs and simultaneously ensuring the QoS. Algorithms, OFDMA-based channel-width adaptation in a wireless mesh network (OBCWA) and QoS-aware channel-width

adaptation (QACWA), were compared. The results of simulations showed that the throughput of BA-HBRA outperformed OBCWA by 13%, 12%, 8%, 8%, 7% and 10%, respectively, in six cases with different numbers of RBs. In terms of QoS provision with low traffic demands, our algorithm achieved the same results as QACWA and it could guarantee the QoS. When the traffic demands increased with different services, BA-HBRA throughput achieved about 12%-25% more than QACWA, and was close to satisfying the traffic demands in most cases. When the traffic was relatively high, QACWA could not satisfy the traffic demands. Finally, in terms of complexity, we found that the processing level of our algorithm was the same as QACWA. Although they were at the same level of processing, BA-HBRA achieved a remarkable improvement over QACWA in terms of time consumption, where BA-HBRA took about 82%, 66% and 40% less time than QACWA did. At the same time, it also outperformed OBCWA with about 87%, 78% and 63% for three sets of nodes (10, 20 and 30, respectively). From the above simulations, we can conclude that our proposed algorithm is more suitable for WMNs, especially those with limited-resource scenarios

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

PERUNTUKAN SUMBER BERASASKAN HYPERGRAPH DALAM JEJARING TANPA WAYAR

Oleh

BASHAR KHUDHAIR ABBAS

Disember 2017

Pengerusi : Profesor Nor Kamariah bt. Noordin, PhD
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Kejayaan rangkaian jaringan tanpa wayar (WMNs) sangat bergantung pada pengurusan sumber radio berkesan. Dalam rangkaian tanpa wayar konvensional dengan trafik heterogen, sistem pemprosesan, kualiti perkhidmatan (QoS), keadilan dan kerumitan adalah persembahan metrik biasa.Pembahagian Akses Berganda Frekuensi Ortogon (OFDMA) adalah teknik modulasi yang paling terkenal dalam rangkaian wayarles dimana sebahagian besarnya bergantung kepada mekanisma pengagihan sumber. Oleh itu, mekanisma pengagihan sumber dalam teknologi ini perlu diwujudkan sebagai tugas memperuntukkan blok sumber (RBs) kepada stesen rangkaian mengikut bandwidth yang diperlukan dan parameter QoS.Pertimbangan ciri-ciri ini dalam model matematik menggunakan hypergraph dan graf Koenig, memberikan gambaran yang tepat tentang rangkaian ini. Ini membolehkan penyedian keperluan bagi mereka bentuk sepenuhnya semua konfigurasi bagi jaringan rangkaian dan elemen-elemen individu, mengambil kira perbatasan sumber spektrum dan gangguan antara stesen rangkaian. Model matematik yang dicadangkan bertujuan untuk meningkatkan prestasi jaringan rangkaian secara keseluruhan dengan menyeimbangkan bilangan blok sumber diperuntukkan kepada stesen individu.Oleh itu, algoritma yang dibangunkan kelajuan muat turun tetap makzimum selagi kerumitan sistem QoS masih rendah.Akhirnya, peruntukan sumber berdasarkan hypergraph masuk rangkaian jaringan tanpa wayar dengan teknik-kira (BA-HBRA) dibangunkan untuk OFDMA RBS pautan muat turun untuk meningkatkan lagi prestasi sistem. Algoritma, berdasarkan penyesuian OFDMA saluran-lebar dalam jaringan rangkaian mesh tanpa wayar (OBCWA) dan QoS adalah bersesuian dengan saluran-lebar (QACWA) untuk tujuan perbandingan. Keputusan simulasi menunjukkan bahawa, kelajuan muat turun BA-HBRA mengatasi setiap satu OBCWA sebanyak 13%, 12%, 8%, 8%, 7% dan 10%, dan dalam enam kes nombor RBs yang berbeza. Bagi peruntukan QoS dengan keperluan trafik yang rendah, algoritma ini mampu mencapai keputusan yang sama seperti QACWA dengan prestasi QoS terjamin.

Apabila permintaan trafik meningkat dengan perkhidmatan yang berbeza, BA-HBRA pemprosesan mencapai kira-kira 12% -25% lebih daripada QCWA, dan hampir memenuhi permintaan trafik dalam kebanyakan kes. Di dalam situasi trafik yang agak tinggi QACWA tidak mampu untuk memenuhi permintaan trafik. Akhir sekali, dari segi kerumitan, didapati bahawa, tahap pemprosesan algoritma adalah sama seperti QACWA.Walaupun, pada tahap yang sama pemprosesan, BA-HBRA mencapai peningkatan yang luar biasa ke atas QACWA dalam jangka masa yang lama, di mana ia adalah kira-kira 82%, 66% dan 40% lebih rendah. Pada masa yang sama, OBCWA mencapai kira-kira 87%, 78% dan 63% untuk tiga set nod 10, 20 dan 30 masing-masing. Dari simulasi di atas, dapat disimpulkan bahawa algoritma yang dicadangkan adalah lebih sesuai untuk WMNs terutamanya, dengan senario sumber terhad.

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I certify that a Thesis Examination Committee has met on 22 December 2017 to conduct the final examination of Bashar Khudhair Abbas on his thesis entitled "Hypergraph-Based Resource Allocation in Wireless Mesh 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 Master of Science.

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Signature:	______________________
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LIST OF ABBREVIATIONS

BA-HBRA	Balance Hypergraph-Based Resource Allocation
BCH	Broadcast Channel
CA	Cannel Assignment
CP	Cyclic Prefix
CSMA/CA	Carrier Sensing Multiple Access with Collision Avoidance
DL	Down Link
DL-SCH	Downlink Shared Channel
DwPTS	Downlink Pilot Time Slot
FDD	Frequency Division Duplex
FDMA	Frequency Division Multiple Access
GA	Genetic Algorithm
GP	Guard Period
HARQ	Hybrid Automatic Repeat Request
HBRA	Hypergraph-Based Resource Allocation
IFFT	Inverse Fourier Fast Transform
IMT	International Mobile Telecommunications
ISI	Inter Symbol Interference
LTE	Long Term Evolution
MAC	Medium Access Control
MBMS	Multimedia Broadcast Multicast Service
MC	Mesh Client
MCH	Multicast Channel

MICA	Minimum Interference Channel Assignment
MILP	Mixed Integer Linear Programming
MIMC	Multi Interference Multi Channel
MIMO	Multiple Input Multiple Output
MR	Mesh Router
MU-MIMO	Multi User MIMO
NP	Non Polynomial
OBCWA	OFDMA-Based Channel-Width Adaptation
OC	Overlapping Channel
OFDMA	Orthogonal Frequency Division Multiple Access
PAPR	Peak to Average Power Ratio
PBCH	Physical Broadcast Channel
PCFICH	Physical Control Format Indicator Channel
PCH	Paging Channel
PDCCH	Physical Downlink Control Channel
PDSCH	Physical Downlink Shared Channel
PHICH	Physical HARQ Indicator Channel
PMCH	Physical Multicast Channel
POC	Partially Overlapping Channel
QACWA	QoS-Aware Channel-Width Adaptation
QAM	Quadrature Amplitude Modulation
QoS	Quality of Service
QPSK	Quadrature Phase Shift Key
RB	Resource Block

RBG	Resource Block Groups
RE	Resource Elements
SC-FDMA	Single Carrier Frequency Division Multiple Access
SINR	Signal to Interference Noise Ratio
TDD	Time Division Duplex
TR	Transmission Reception
UE	User Equipment
UL	Up Link
UMTS	Universal Mobile Telecommunications System
UpPTS	Uplink Pilot Time Slot
WMN	Wireless Mesh Network

CHAPTER 1

INTRODUCTION

1.1 Background

The advent of cost-effective wireless mesh networks (WMN) based on Orthogonal Frequency Division Multiple Access (OFDMA) technology [1], [2] has significantly changed the process of organization of both wireless access networks and traffic radio networks. The mesh mode allows the user equipment (UE) to communicate not only via the base station (eNodeB) but also directly with each other. As a result, the UE that is located at a considerable distance from the eNodeB can be connected by multiple hops via other user equipment. Figure 1.1 represents a typical WMN, which consists of a group of different user equipment (UEs) connected to one or more base stations (eNodeB) by wireless connections [3]. Most of the users are connected to each other where they are located in the same channel frequency area or perhaps they share two or more channels. These connections provide multi-links and enable the user to send and receive data through any other neighbouring link in case of a link failure [4]. Most networks suffer from a limited number of links because of spectral limited resources which are reflected in low network performance and user dissatisfaction. In order to guarantee user satisfaction with limited spectrum resources, resource allocation must be done using an efficient method which enhances the network performance and Quality of Service (QoS). Channel information must be considered in the trade-off among these parameters during the transmitting stage. Optimisation of the throughput, QoS and complexity are key parameters in the evaluation of any resource allocation algorithm in frequency and time domain. The mathematical solution of frequency and time resources (Resource Block) is considered as a low-cost solution as it can be done using simulation. Therefore, we set forth to design a mathematical solution to solve the problem of allocating RBs.

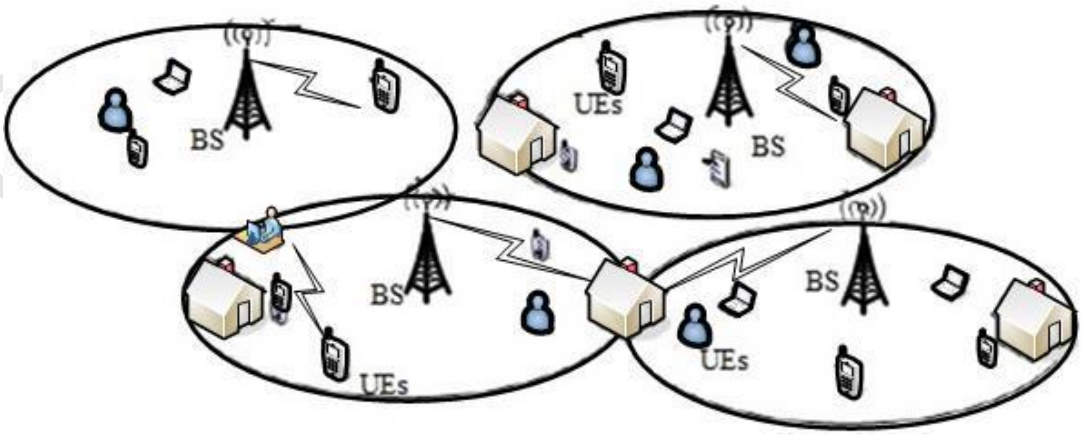

Figure 1.1 : Wireless Mesh Network

1.2 Problem Statement

Among the various requirements for WMN, the main one is to provide high performance (throughput) and to ensure the quality of service (QoS) of the network as a whole with low complexity. Our Problem Statement is depicted in Figure 1.1 above, where every node in WMN is equipped with one or more radios that are assigned channels which are overlapping or orthogonal in nature. Therefore, we have to counter this issue by developing a new approach to distribute and allocate the frequency-time resources and interference mitigation using hypergraph representation, which enables us to save frequency resources as compared with frequency channels allocation. The issue of frequency planning can be presented as a problem of resource blocks allocation in the OFDMA technology (WiMAX, LTE) mesh network. On the basis of the requirements, an RBs distribution model of one frequency channel is proposed. The proposed model is aimed at improving the performance of mesh networks as a whole by improving the performance of each station, that is, balancing the RBs number allocated to individual stations. This, in turn, should help to create a wireless network with no "bottlenecks", that is, a network that requires minimum bandwidth and gives maximum performance to ensure QoS. Thus, the OFDMA technology mesh-network simulation will use more efficient ways to present mesh networks using hypergraph, allowing us to produce a theoretical description of the RBs allocation problem.

1.3 Aim and Objectives

1. To design a theoretical mathematical model of resource blocks (RBs) allocation in LTE wireless mesh network, based on hypergraph representation.
2. To satisfy the traffic demands requirements in terms of throughput, Quality of Service (QoS) and complexity with least-number of RBs as well as balancing these RBs among the stations.

1.4 Scope of Thesis

Furthermore, this research focuses on a theoretical mathematical solution where it is inexpensive. So, the present study offers an algorithm of a mathematical model of the optimal solution to satisfy the traffic demands with least-number of RBs as well as balancing these RBs among the stations.

The study is based on the following assumptions: -

1. All nodes in topologies are fixed.
2. The base station eNodeB was considered as an interface to the radio frequency.
3. Omni-antenna was considered where the transmission/reception would be in all directions.
4. Random topology was employed.
5. The interference occurs among the nodes.
6. Different bandwidth and traffic demands were applied.
7. Different services (voice, live streaming, real-time and video) are investigated.

It is important to state that, the scenario above is carried out by Matlab (R2015a) simulator in perfect conditions, where the channel state information (CSI) is excellent. In a practical implementation, CSI must be considered in such a way that the improper channels must be neglected and the algorithm will be applied to the perfect channels.

The scope of this research concentrates on the distribution of spectrum resources to the WMN stations (nodes) by means of RBs allocation in OFDMA technology. The management of the distribution of these RBs can be done in the media access control (MAC) layer which is concerned with RBs allocation. In addition, a physical layer translates logical communications requests from the media access control (MAC) sublayer into hardware-specific operations to cause transmission or reception of signals

1.5 Motivation

The high performance of WMN can be achieved by improving the relevant network mechanisms responsible for the resources allocation. Further, the use of OFDMA allows for the management of the frequency and time resources[5]. Thus, RBs can be used as the time-frequency resource [5][6]. Furthermore, in OFDMA networks, one radio can support multiple links at the same time where the spectrum band is not consecutive. In the joint management of the frequency and time resources, resource blocks (RBs) are used as control elements, which motivated us to adopt a new approach for the time-frequency resources allocation to reduce interference and increase the throughput of WMNs in order to satisfy the various requirements to achieve the conditions of a good quality of service (QoS), improved mesh-network performance as a whole, and low complexity. Thus, we assumed a mathematical model of WMNs, where all decisions are computed to optimize the best configuration to reduce the computation complexity burden but with high performance of the network configuration and cost of implementation. There is a fairly wide range of approaches [7-11] for increasing performance and ensuring QoS by addressing the issues of both frequency and time-resource allocation. They primarily focus on the dynamic nature of frequency and time-resources allocation, maximizing networks, and other indicators of performance in order to ensure better QoS. The use of a distributed or centralized resource management mode minimises the impact of primary and secondary interference among the user equipment of the WMN. The coordinated addressing of radio channel allocations between mesh-stations and assigning sub-channels focuses on the use of efficient routing protocols. Considerations of the technological features of the network involve communications range, the intensity of the user traffic received by the network, the volume of used frequency and time resources, the number of supported transceivers at WMN stations, channel width, and a number of sub-channels, among others. In most cases, incomplete consideration of these factors in mathematical descriptions results in complications in implementing the protocols. All these issues led us to design a model of resource assignment that further assumes increased interference.

1.6 Thesis Organisation

This thesis shows how to design and develop a model of resource allocation in WMNs mathematically with the consideration of interference. The organization of this thesis is as follows:

In Chapter 1, we give an introduction to the RBs allocation issue in OFDMA- WMNs and its challenges, the problem statement and the contributions. Chapter 2 introduces the literature review. We first provide a broad overview regarding wireless mesh networks. Then we describe in detail the WMN architecture and its corresponding structure, followed by the LTE-OFDMA structure and modulation and its characteristics. Next, we introduce interference and RBs assignment and their effects on WMN and also show how to represent these using a graph and hypergraph model. Lastly, we introduce the related work models and show how our work is distinguished from the others.

Chapter 3 introduces our methodology in developing a mathematical model of resource allocation that considers interference, and we test it. Next, we apply the algorithm in order to enhance the performance of the network and ensure the QoS by maximizing user bandwidth and minimizing interference in addition to evaluating complexity. In Chapter 4, we present our results and analysis with the proper diagrams. Chapter 5 introduces our conclusion as well as implementations for future study.

REFERENCES

[1] H. Y. Wei, J. Rykowski, and S. Dixit, *WiFi, WiMAX, and LTE Multi-Hop Mesh Networks: Basic Communication Protocols and Application Areas*. 2013.

[2] Y. Y, K. Papagiannaki, S. Ci, and S. Shen, *Wireless Mesh Networks: Applications, Architectures, and Protocols*, vol. 22, no. 1. 2008.

[3] I. F. Akyildiz, X. Wang, and W. Wang, “Wireless mesh networks: A survey,” *Computer Networks*, vol. 47, no. 4. pp. 445–487, 2005.

[4] P. Pathak and R. Dutta, “A Survey of Network Design Problems and Joint Design Approaches in Wireless Mesh Networks,” *IEEE Commun. Surv. Tutorials*, pp. 1–33, 2010.

[5] Ghosh A., J. Zhang, R. Muhammed, Andrews J. Cr. Fundamentals of LTE., Prentice Hall, USA, 2010. – 464 p.

[6] 3GPP TS 36.211. 3rd Generation Partnership Project; Technical Specification Group Radio Access Network; Evolved Universal Terrestrial Radio Access (E-UTRA); Physical Channels and Modulation (Release 11). – Valbonne, France: Sophia Antipolis, 2012. – 108 p.

[7] S. V. Garkusha, “The model of time and frequency resource scheduling in downlink LTE,” *2013 Int. Sib. Conf. Control Commun. SIBCON 2013 - Proc.*, pp. 13–16, 2013.

[8] Garkusha S., AI-Dulaimi A. and AI-Janabi H. "Result Research Model of Scheduling Block Allocation in Downlink LTE", Modern Problems of Radio Engineering, Telecommunications, and Computer Science proceedings of the XII International Conference (TCSET'2014), Slavske, Ukraine, 2014, P. 498-500

[9] Garkusha Sergiy, “Results of development of model for bandwidth management in LTE downlink with Resource Allocation Type 1, The Experience of Designing and Application of CAD Systems in Microelectronics ”, Lviv, Ukraine, 2015.

[10] S. Garkusha, A. M. K. Al-Dulaimi, and H. D. Al-Janabi, “Model of resource allocation type 1 for LTE downlink,” *2015 Int. Conf. Antenna Theory Tech. Dedic. to 95 Year Jubil. Prof. Yakov S. Shifrin, ICATT 2015 - Proc.*, pp. 1–3, 2015.

[11] O. Iosif and I. Banica, “On the Analysis of Packet Scheduling in Downlink 3GPP LTE System,” *Fourth Int. Conf. Commun. Theory, Reliab. Qual. Serv.*, no. c, pp. 99–102, 2011.

[12] B. Ko and D. Rubenstein, “Distributed Channel Assignment in Multi-Radio,”, Wireless Communications and Networking Conference, IEEE Wcnc, 2007.

[13] H. Liu, H. Yu, X. Liu, C. Chen-Nee, and P. Mohapatra, “Scheduling multiple partially overlapped channels in wireless mesh networks,” *IEEE Int. Conf. Commun.*, vol. 2, no. 2, pp. 3817–3822, 2007.

[14] M. Seyedzadegan, M. Othman, B. M. Ali, and S. Subramaniam, “Wireless Mesh Networks : WMN Overview , WMN Architecture,” *Int. Conf. Commun. Eng. Networks, IACSIT Press*, vol. 19, pp. 12–18, 2011.

[15] H. G. Myung, J. Lim, and D. J. Goodman, “Single carrier FDMA for uplink wireless transmission,” *IEEE Veh. Technol. Mag.*, vol. 1, no. 3, pp. 30–38, 2006.

[16] D. Wing, K. Ng, E. S. Lo, and R. Schober, “Wireless Information and Power Transfer : Energy Efficiency Optimization in OFDMA Systems,” vol. 12, no. 12, pp. 6352–6370, 2013.

[17] M. Jahanshahi and A. Talebi Barmi, “Multicast routing protocols in wireless mesh networks: a survey,” *Computing*, vol. 96, no. 11, pp. 1029–1057, 2014.

[18] J. Loo, J. L. Mauri, and J. H. Ortiz, “Mobile ad hoc networks: current status and future trends,”, CRC Press, p. 538, 2016.

[19] C. Cox, An Introduction to LTE: LTE, LTE-Advanced, SAE, VoLTE and 4G Mobile Communications: Second Edition. 2014.

[20] 3GPP, “3Gpp Tr 25.913,” Requir., Evolved Universal Terrestrial Radio Access (UTRA) Evolved UTRAN (E-UTRAN)(Release 7), vol. 0, 2007.

[21] S. B. Weinstein and P. M. Ebert, “Data Transmission by Frequency-Division Multiplexing Using the Discrete Fourier Transform,” *IEEE Trans. Commun. Technol.*, vol. 19, no. 5, pp. 628–634, 1971.

[22] J. A. C. Bingham, “Multicarrier Modulation for Data Transmission: An Idea Whose Time Has Come,” *IEEE Commun. Mag.*, vol. 28, no. 5, pp. 5–14, 1990.

[23] H. Sari, Y. Levy, and G. Karam, “An analysis of orthogonal frequency-division multiple access,” *GLOBECOM 97. IEEE Glob. Telecommun. Conf. Conf. Rec.*, vol. 3, no. l, pp. 1635–1639, 1997.

[24] Taewon Hwang, Chenyang Yang, Gang Wu, Shaoqian Li, and G. Ye Li, “OFDM and Its Wireless Applications: A Survey,” *IEEE Trans. Veh. Technol.*, vol. 58, no. 4, pp. 1673–1694, 2009.

[25] C. Ciochina and H. Sari, “A review of OFDMA and single-carrier FDMA,” *2010 Eur. Wirel. Conf. EW 2010*, no. 1, pp. 706–710, 2010.

[26] C. Cox, *AN INTRODUCTION TO LTE: LTE, LTE-Advance, SAE and 4G Mobile Communicatios*. 2012.

[27] S. C. Yang, *OFDMA System Analysis and Design*. British Library Cataloguing in Publication Data, 2010.

[28] "Feasibility study for evolved Universal Terrestrial Radio Access (UTRA) and Universal Terrestrial Radio Access Network (UTRAN) (3GPP TR 25.912 version 9.0.0 Release 9)", European Telecommunications Standards Institute 2009.

[29] A. Ghosh and R. Ratasuk, *Essentials of LTE and LTE-A.*, Cambridge University Press, 2011.

[30] V. Bukkapatanam, A. A. Franklin, and C. S. R. Murthy, "Using partially overlapped channels for end-to-end flow allocation and channel assignment in wireless Mesh Networks," in *IEEE International Conference on Communications*, 2009.

[31] Z. Feng and Y. Yang, "Characterizing the Impact of Partially Overlapped Channel on the Performance of Wireless Networks," in *IEEE GLOBECOM 2008 - 2008 IEEE Global Telecommunications Conference*, 2008, pp. 1–6.

[32] H. Wei, S. Ganguly, and R. Izmailov, "Interference-Aware IEEE 802 . 16 WiMax Mesh Networks," *Ieee Veh. Technol. Conf.*, vol. 0, no. c, 2005.

[33] D. Chafekar, V. S. . Kumart, M. V Marathe, S. Parthasarathy, and A. Srinivasan, "Approximation Algorithms for Computing Capacity of Wireless Networks with SINR Constraints," no. i, pp. 1166–1174, 2008.

[34] S. A. Makram and M. Gunes, "Distributed channel assignment for multi-radio wireless mesh networks," *IEEE Symp. Comput. Commun.*, pp. 272–277, 2008.

[35] D. Benyamina, A. Hafid, and M. Gendreau, "Wireless Mesh Networks Design A Survey," *IEEE Commun. Surv. Tutorials*, vol. 14, no. 2, pp. 299–310, 2012.

[36] Y. Liu, R. Venkatesan, and C. Li, "Load-aware channel assignment exploiting partially overlapping channels for wireless mesh networks," *GLOBECOM - IEEE Glob. Telecommun. Conf.*, pp. 7–11, 2010.

[37] J. F. Kurose and K. W. Ross, "*Computer Networking A Top-Down Approach*", Addison-Wesley no. 5. 2013.

[38] C. Berge, "Graphs and Hypergraphs," *North-holl. Math. Libr.*, vol. 6, pp. 3–528, 1973.

[39] J. Gao, Q. Zhao, W. Ren, A. Swami, R. Ramanathan, and A. Bar-Noy, "Dynamic Shortest Path Algorithms for Hypergraphs," *IEEE/ACM Trans. Netw.*, vol. 23, no. 6, pp. 1805–1817, 2015.

[40] C. Berge, "Hypergraphs: The Theory of Finite Sets", Amisterdam, Netherland: North Holand, 1989. 256P

[41] V. I. Voloshin, "Introduction to graph and hypergraph theory", New York, NY : Nova Science Publ., 2009, 303P.

[42] Sergii Harkusha, Olena Harkusha, and Marina Ievdokymenko, "Hypergrapg Representations of Topological model Mesh-Network IEEE 802.11,"TCSET vol. 6, pp. 7–9, 2016.

[43] J. A. Bondy and U. S. R. Murty, "Graph theory with applications," *Operational Research Quarterly 19701977*, vol. 290. p. 270, 1976.

[44] A. N. Al-Khwildi, S. Khan, K. K. Loo, and H. S. Al-Raweshidy, "Adaptive link-weight routing protocol using cross-layer communication for MANET," *WSEAS Trans. Commun.*, vol. 6, no. 11, pp. 833–839, 2007.

[45] O. Hynčica, F. Zezulka, and P. Fiedler, "Wireless standards for mobile platform," *WSEAS Transactions and Communications*, vol. 4, no. 5. pp. 199–210, 2005.

[46] Q. Li and R. Negi, "Maximal scheduling in wireless Ad Hoc networks with hypergraph interference models," *IEEE Trans. Veh. Technol.*, vol. 61, no. 1, pp. 297–310, 2012.

[47] P. B. F. Duarte, Z. M. Fadlullah, K. Hashimoto, and N. Kato, "Partially Overlapped Channel Assignment on Wireless Mesh Network Backbone," *GLOBECOM 2010, 2010 IEEE Glob. Telecommun. Conf.*, pp. 0–4, 2010.

[48] L.-H. Yen, K.-W. Huang, and V. C. M. Leung, "Link-preserving interference-minimization channel assignment in multi-radio wireless mesh networks," *2012 IEEE Int. Conf. Commun.*, no. June, pp. 642–647, 2012.

[49] X. Liu and J. Luo, "Joint channel assignment and link scheduling for wireless mesh networks: Revisiting the Partially Overlapped Channels," in *21st Annual IEEE International Symposium on Personal, Indoor and Mobile Radio Communications*, 2010, pp. 2063–2068.

[50] M. A. Hoque, X. Hong, and F. Afroz, "Multiple radio channel assignement utilizing partially overlapped channels," in *GLOBECOM - IEEE Global Telecommunications Conference*, 2009.

[51] S. M. Allen, I. M. Cooper, and R. M. Whitaker, "Optimising multi-rate link scheduling for wireless mesh networks," *Comput. Commun.*, vol. 35, no. 16, pp. 2014–2024, 2012.

[52] B. He, B. Xie, and D. P. Agrawal, "Optimizing the internet gateway deployment in a wireless mesh network," in *2007 IEEE Internatonal Conference on Mobile Adhoc and Sensor Systems, MASS*, 2007.

[53] H. Skalli, S. Ghosh, S. Das, and L. Lenzini, "Channel Assignment Strategies for Multiradio Wireless Mesh Networks: Issues and Solutions," *IEEE Commun. Mag.*, vol. 45, no. 11, pp. 86–95, 2007.

[54] Y.-Y. Chen, S.-C. Liu, and C. Chen, "WLC30-2: Channel Assignment and Routing for Multi-Channel Wireless Mesh Networks Using Simulated Annealing," *IEEE Globecom 2006*, pp. 1–5, 2006.

[55] a. K. Das, H. M. K. Alazemi, R. Vijayakumar, and S. Roy, "Optimization models for fixed channel assignment in wireless mesh networks with multiple radios," *2005 Second Annu. IEEE Commun. Soc. Conf. Sens. Ad Hoc Commun. Networks, 2005. IEEE SECON 2005.*, pp. 463–474, 2005.

[56] I. Katzela and M. Naghshineh, "Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive survey," *IEEE Pers. Commun.*, vol. 3, no. 3, pp. 10–31, 1996.

[57] A. H. Mohsenian-Rad and V. W. S. Wong, "Joint logical topology design, interface assignment, channel allocation, and routing for multi-channel wireless mesh networks," *IEEE Trans. Wirel. Commun.*, vol. 6, no. 12, pp. 4432–4440, 2007.

[58] A. P. Subramanian, "Minimum Interference Channel Assignment in Multi-Radio Wireless Mesh Networks," vol. 7, no. 12, pp. 1459–1473, 2006.

[59] H. Yin and H. Liu, "An efficient multiuser loading algorithm for OFDM-based broadband\nwireless systems," *Globecom '00 - IEEE. Glob. Telecommun. Conf. Conf. Rec. (Cat. No.00CH37137)*, vol. 1, no. 2, pp. 103–107, 2000.

[60] W. Rhee and J. M. Cioffi, "Increase in Capacity of Multiuser OFDM System Using Dynamic Subchannel Allocation," *Vtc 2000*, pp. 1085–1089, 2000.

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

[62] G. Pei, S. Parthasarathy, A. Srinivasan, and A. K. S. Vullikanti, "Approximation Algorithms for Throughput Maximization in Wireless Networks," vol. 21, no. 6, pp. 1988–2000, 2013.

[63] Z. Beheshtifard and M. R. Meybodi, "Online Channel Assignment in Multi-Radio Wireless Mesh Networks Using Learning Automata," *arXiv Prepr. arXiv1405.3448*, 2014.

[64] S. Pediaditaki, P. Arrieta, and M. K. Marina, "A learning-based approach for distributed multi-radio channel allocation in wireless mesh networks," *2009 17th IEEE Int. Conf. Netw. Protoc.*, pp. 31–41, 2009.

[65] G. Monghal, K. I. Pedersen, I. Z. Kov??cs, and P. E. Mogensen, "QoS oriented time and frequency domain packet schedulers for the UTRAN long term evolution," in *IEEE Vehicular Technology Conference*, 2008, pp. 2532–2536.

[66] M. Andrews, K. Kumaran, K. Ramanan, A. Stolyar, P. Whiting, and R. Vijayakumar, "Providing quality of service over a shared wireless link," *IEEE Commun. Mag.*, vol. 39, no. 2, pp. 150–154, 2001.

[67] G. Piro, L. A. Grieco, G. Boggia, R. Fortuna, and P. Camarda, "Two-level downlink scheduling for real-time multimedia services in LTE networks," *IEEE Trans. Multimed.*, vol. 13, no. 5, pp. 1052–1065, 2011.

[68] D. Julian, D. O'Neill, and S. Boyd, "QoS and fairness constrained convex optimization of resource allocation for wireless cellular and ad hoc networks," in *Proceedings.Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies*, 2002, vol. 2, pp. 477–486.

[69] J. Jang, S. Member, and K. B. Lee, "Transmit Power Adaptation for Multiuser OFDM Systems," *IEEE J. Sel. Areas Commun.*, vol. 21, no. 2, pp. 171–178, 2003.

[70] L. Gao and S. Cui, "Efficient subcarrier, power, and rate allocation with fairness consideration for OFDMA uplink," *IEEE Trans. Wirel. Commun.*, vol. 7, no. 5, pp. 1507–1511, 2008.

[71] C. Y. Ng and C. W. Sung, "Low complexity subcarrier and power allocation for utility maximization in uplink OFDMA systems," *IEEE Trans. Wirel. Commun.*, vol. 7, no. 5, pp. 1667–1675, 2008.

[72] J. Shi and A. Hu, "Maximum utility-based resource allocation algorithm in the IEEE 802.16 OFDMA system," *IEEE Int. Conf. Commun.*, pp. 311–316, 2008.

[73] S. Xinghua, H. Zhiqiang, N. Kai, and W. Weiling, "A Hierarchical Resource Allocation for OFDMA Distributed Wireless Communication Systems," *Commun. Soc.*, pp. 5195–5199, 2007.

[74] I. Ahmed, A. Mohammed, and H. Alnuweiri, "On the fairness of resource allocation in wireless mesh networks: A survey," *Wireless Networks*, vol. 19, no. 6. pp. 1451–1468, 2013.

[75] L. Qin and D. Zhao, "Channel time allocations and handoff management for fair throughput in wireless mesh networks," *IEEE Trans. Veh. Technol.*, vol. 64, no. 1, pp. 315–326, 2015.

[76] C. Papadimitriou and K. Steiglitz, "Combinatorial optimization: algorithms and complexity," Courier Corporation, 1998.

[77] M. K. R. Al-juaifari and B. P. Rani, "Engineering Wireless Mesh Networks : Joint Scheduling , Routing , Power control and Rate Adaptation Networks with Bottleneck Algorithm," vol. 3, no. 9, pp. 1–5, 2012.

[78] Y. Chen and C. Chen, "Interface Constraint Aware Modeling in Wireless Mesh Networks Using Mixed Hypergraph,", Wireless Communications and Networking Conference (WCNC), IEEE, pp. 2032–2037, 2015.

[79] R. Seibel, S. Taheri, K. Wang, and D. Hogrefe, "Minimizing Intra-Flow Interference in Multi-Channel Mesh Networks : An Optimization Approach", Performance Computing and Communications Conference (IPCCC), IEEE 35th International, 2016.

[80] A. Adya, P. Bahl, J. Padhye, A. Wolman, and L. Zhou, "A multi-radio unification protocol for IEEE 802.11 wireless networks," *Proc. - First Int. Conf. Broadband Networks, BroadNets 2004*, pp. 344–354, 2004.

[81] R. Draves, J. Padhye, and B. Zill, "Routing in multi-radio, multi-hop wireless mesh networks," *Proc. 10th Annu. Int. Conf. Mob. Comput. Netw. - MobiCom '04*, pp. 114–128, 2004.

[82] H. L. N. and U. T. Nguyen, "Minimum Interference Channel Assignment for Multicast in Multi-Radio Wireless Mesh Networks", Wireless Communications and Mobile Computing Conference, IWCMC International, pp. 1–6, 2008.

[83] A. Gamst and K. Ralf, "Computational Complexity of Some Interference Graph Calculations," *IEEE Trans. Veh. Technol.*, vol. 39, no. 2, pp. 140–149, 1990.

[84] M. M. Halldorsson and T. Tonoyan, "How Well Can Graphs Represent Wireless Interference?," *Proc. 47th Annu. ACM Symp. Theory Comput. - STOC '15*, pp. 635–644, 2015.

[85] G. Parissidis, M. Karaliopoulos, M. May, T. Spyropoulos, and B. Plattner, "Interference in wireless multihop networks: A model and its experimental evaluation," *2008 Int. Symp. a World Wireless, Mob. Multimed. Networks*, pp. 1–12, 2008.

[86] J. Yang, S. C. Draper, and R. Nowak, "Learning the Interference Graph of a Wireless Network," *IEEE Trans. Signal Inf. Process. over Networks*, pp. 1–1, 2016.

[87] R. Van Nee and R. Prasad, OFDM for wireless multimedia communications, Artech House, Inc. Norwood, MA, USA vol. 3, 2000.

[88] M. Alicherry, R. Bhatia, and L. (Erran) Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks," *Proc. 11th Annu. Int. Conf. Mob. Comput. Netw. - MobiCom '05*, p. 58, 2005.

[89] K. Jain, J. Padhye, V. N. Padmanabhan, and L. Qiu, "Impact of interference on multi-hop wireless network performance," in *Wireless Networks*, 2005, vol. 11, no. 4, pp. 471–487.

[90] M. Kodialam and T. Nandagopal, "Characterizing the capacity region in multi-radio multi-channel wireless mesh networks," *Proc. 11th Annu. Int. Conf. Mob. Comput. Netw. - MobiCom '05*, p. 73, 2005.

[91] X. Wang, P. Huang, J. Xie, and M. Li, "OFDMA-based channel-width adaptation in wireless mesh networks," *IEEE Trans. Veh. Technol.*, vol. 63, no. 8, pp. 4039–4052, 2014.

[92] H. Li, J. Zhang, Q. Hong, H. Zheng, Y. Wang, and J. Zhang, "QoS-aware channel-width adaptation in wireless mesh networks," *2016 IEEE Int. Conf. Commun. ICC 2016*, pp. 2–7, 2016.

[93] D. Whitley, "A genetic algorithm tutorial," Stat. Comput., vol. 4, no. 2, pp. 65–85, 1994.

[94] K. Deb, A. Pratap, S. Agarwal, and T. Meyarivan, "A fast and elitist multiobjective genetic algorithm: NSGA-II," IEEE Trans. Evol. Comput., vol. 6, no. 2, pp. 182–197, 2002.

[95] B. Shahi, S. Dahal, A. Mishra, S. B. V. Kumar, and C. P. Kumar, "A Review Over Genetic Algorithm and Application of Wireless Network Systems," Procedia Comput. Sci., vol. 78, pp. 431–438, 2016.

[96] F. Brah, L. Vandendorpe, and J. Louveaux, "OFDMA constrained resource allocation with imperfect channel knowledge," in *2007 14th IEEE Symposium on Communications and Vehicular Technology in the Benelux, SCVT*, 2007.

[97] F. Brah, L. Vandendorpe, and J. Louveaux, "Constrained resource allocation in OFDMA downlink systems with partial CSIT," in *IEEE International Conference on Communications*, 2008, pp. 4144–4148.

[98] M. Priesler (Moreno) and A. Reichman "Resource Allocation in Wireless Mesh Networks," Ruppin Academic Center, Emek Hefer, 40250, 2016.

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