CHANNEL ASSIGNMENTS USING CONSTRAINED GREEDY ALGORITHM, *T*-COLORING AND SIMULATED ANNEALING IN MESH AND CELLULAR NETWORKS

NUR ATIKAH BINTI SALAHUDIN

A thesis submitted in fulfilment of the
requirements for the award of the degree of
Doctor of Philosophy (Mathematics)

Faculty of Science
Universiti Teknologi Malaysia

OCTOBER 2018

To my beloved husband and sons

♣

Mohamad Amirul Hakim bin Abu Bakar

Mohamad Adam Uwais bin Mohamad Amirul Hakim

Muhamad Aqeef Imran bin Mohamad Amirul Hakim

My parents

♣

Salahudin bin Mahmud

Kamariah binti Che Mat

Family-in-laws

♣

Abu Bakar bin Ahmad

Suliah binti Abu

and all family members

ACKNOWLEDGEMENTS

BismillahirRahmaanirRahiim. Alhamdulillaahi rabbil ‘aalamiin.

In the name of Allah the Most Gracious and the Most Merciful, I thank Thee with all my heart for granting Thy Servant immeasurable help during the course of this study.

I wish to deeply express my gratitude to my supervisor, Prof. Dr. Shaharuddin Salleh for the great opportunity to join in this research. His confidence, understanding, supervision, motivation and support have been essential factors for me to work on this study. I really appreciate what he doing to help me finish the research.

Next, I would like to thank MyPhD MyBrain15, Kementerian Pendidikan Malaysia for financial support. My sincere appreciation also extends to all lecturers and postgraduate staff at the Department of Mathematics, Faculty of Science, UTM Johor Bahru.

I wish to express my heartfelt thanks for my family during my study: my husband, sons, parents, family-in-laws and family members. Their support, understanding, patience, love, prayer and sacrifice are unbounded.

Finally, I would like to extend my sincere appreciation to all who has helped me in one way or another, but whose names are not mentioned.

ABSTRACT

Channel assignment is an important step in communication networks. The objectives of minimizing networks interference and the channels used are the problems in the channel assignments of the networks. In real environments, some difference will be expected in the performance of the networks when the channel allocation algorithms under more accurate interference models are deployed. In this research, the wireless mesh networks represent dynamic networks while static networks are represented by the cellular networks. In the wireless mesh networks, communication between a pair of nodes happens when both nodes are assigned with channels. The cellular networks are the radio network distributed over land areas called cells, each served by at least one fixed-location transceiver. Channel assignments in the networks is an application of the vertex coloring in graph theory. Previously, the Greedy Algorithm was used for link scheduling but only the adjacent channel constraint was considered. Here, an algorithm called Improved Greedy Algorithm was proposed to solve the channel assignments by considering the adjacent channel and co-channel constraints which is an improvement to the algorithm. Besides, Simulated Annealing and *T*-coloring problem are combined to minimize the channels used. The algorithms are applied for single and multiple channels communications in the wireless mesh networks and cellular networks to show the different results of the channel assignments. Further improvement is made on the multiple channels case where the Improved Greedy Algorithm is applied by considering the cosite constraint in addition to the co-channel and adjacent channel constraints. The Improved Greedy Algorithm has been tested in a series of simulations. Results for the simulations prove that the Improved Greedy Algorithm perform significantly well for the channel assignment problem.

ABSTRAK

Tugasan saluran adalah satu langkah yang penting dalam rangkaian komunikasi. Objektif meminimumkan gangguan rangkaian dan saluran yang digunakan adalah masalah dalam rangkaian tugasan saluran. Dalam persekitaran sebenar, beberapa perbezaan akan dijangka dalam prestasi rangkaian apabila algoritma peruntukan saluran di bawah model gangguan yang lebih tepat digunakan. Dalam kajian ini, rangkaian *mesh* tanpa wayar mewakili rangkaian dinamik manakala rangkaian statik diwakili oleh rangkaian selular. Dalam rangkaian *mesh* tanpa wayar, komunikasi antara sepasang nod berlaku apabila setiap nod diperuntukkan dengan satu saluran. Rangkaian selular adalah rangkaian radio bagi satu kawasan dipanggil sel-sel, yang mewakili satu stesen pangkalan yang tetap. Tugasan saluran dalam rangkaian adalah satu aplikasi pewarna bucu dalam teori graf. Sebelum ini, Algoritma *Greedy* digunakan untuk penjadualan pautan tetapi hanya mempertimbangkan gangguan saluran bersebelahan. Di sini, satu algoritma dicadangkan iaitu Algoritma *Improved Greedy* untuk menyelesaikan tugasan saluran dengan mempertimbangkan gangguan saluran bersebelahan dan gangguan saluran bersama di mana ianya merupakan pembaharuan bagi algoritma tersebut. Selain itu, Algoritma *Simulated Annealing* dan *T-coloring* digabungkan untuk mengurangkan penggunaan saluran. Algoritma ini diaplikasikan dalam komunikasi saluran tunggal dan saluran berganda dalam rangkaian *mesh* tanpa wayar dan rangkaian selular untuk menunjukkan keputusan tugasan saluran yang berbeza. Penambahbaikan selanjutnya dibuat pada kes saluran berganda di mana Algoritma *Improved Greedy* digunakan dengan mempertimbangkan gangguan *cosite* sebagai tambahan kepada gangguan saluran bersama dan saluran bersebelahan. Algoritma *Improved Greedy* telah diuji dalam satu siri simulasi. Keputusan simulasi itu membuktikan bahawa Algoritma *Improved Greedy* dapat melaksanakan dengan baik untuk masalah tugasan saluran.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

LIST OF ABBREVIATIONS

WMN	-	Wireless mesh network
WLAN	-	Wireless local area networks
ADCA	-	Adaptive dynamic channel allocation protocol
NICs	-	Network interface cards
TWIN	-	Time domain wavelength interleaved network
TWSN	-	Time wavelength switched network
LCA	-	Level channel assignment
MCM	-	Multi-channel multicast
MAC	-	Medium access control
ICAR	-	Interference and congestion aware routing

LIST OF SYMBOLS

adj	-	The adjacent channel constraint
coc	-	The cochannel constraint
cos	-	The cosite constraint
C	-	A set of channels
c_a	-	Channel for node/cell a
c_{ip}	-	Channel number i for node/cell p
$d(a,b,k)$	-	Distance between nodes/cells a and b with value k
E	-	Edge of graph
$G(V,E)$	-	Graph with vertex V and edge E
V	-	Vertex of a graph
$\bar{V}$	-	A set of rearrangement vertex/cell
$\bar{v}$	-	The rearrangement vertex/cell
$\{v_i\}$	-	A set of vertex
$\{e_{ij}\}$	-	A set of edge
$sp_T(c)$	-	c -span
$sp_T(G)$	-	T -span
$\chi(G)$	-	Chromatic number of G
$\chi_T(G)$	-	T-chromatic number

LIST OF APPENDICES

CHAPTER 1

INTRODUCTION

1.1 Introduction

Channel assignment is an important thing in a communication network. Channel allocation schemes in the communication network can be divided into three types which are dynamic channel allocation, static channel allocation, and hybrid channel allocation. The types of the channel assignments depend on the communication network.

Dynamic channel allocation is applied in wireless network. Any type of computer network that uses wireless data connections for connecting network nodes is a wireless network (Kirti, 2014). Wireless networking is a method to avoid the costly process of introducing cables into a building, or as a connection between various equipment locations. There are several types of wireless networks such as wireless mesh networks (WMN), wireless sensor networks, and wireless local area networks (WLAN).

Static or fixed channel allocation usually use in cellular network where geographical regions were divided into cells, represented in hexagonal and each cell had a number of antennas with an associated set of frequency bands (Claudia *et al*., 2013). A channel assignment problem in a cellular network is defined as minimize the number of channels for the network depends on the interference.

Hybrid channel allocation is a combination from static channel allocation and dynamic channel allocation. In the network, each mesh node has both static and dynamic interfaces as proposed by Ding *et al.* (2013). They present an Adaptive Dynamic Channel Allocation protocol (ADCA), which considers optimization for both throughput and delay in the channel assignment. The channel assignment problem is usually solved by graph coloring theory (Sivarajan *et al.,* 1989).

The next section in this chapter includes the background and problem statement of the research. Research questions, objectives, the scope of the study and significant of the study are also explained. Finally, the brief explanation for each chapter is outlined in thesis organization.

1.2 Background of the Study

Wireless networks are being used widely around the world nowadays. A wireless mesh network (WMN) is a communication network that enables to apply in many applications such as broadband home networking, community networks, last-mile internet access, etc. The networks can automatically re-routing around a node that has lost power.

WMN consists of mesh clients which represent laptop, cell phones and other wireless devices while mesh routers represent the traffic or connection between the nodes (channels). The WMN routers effectively form a multi-hop wireless access backbone. Some of the special nodes are connected with gateways which directly connected to the Internet. Figure 1.1 shows an example of a possible configuration for a wireless mesh network.

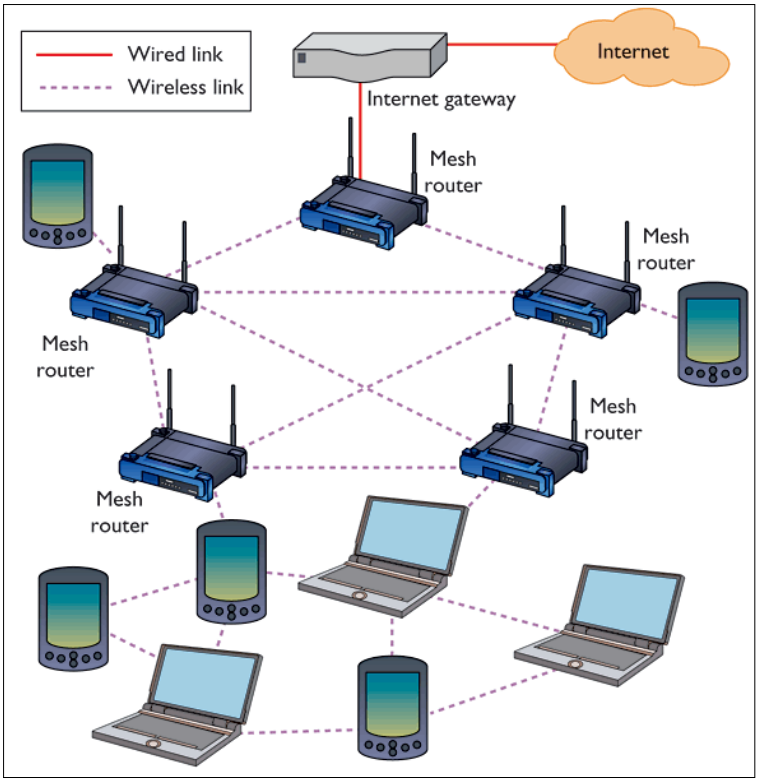

Figure 1.1 Example of a possible configuration for a wireless mesh network (Portmann and Pirzada, 2008)

Cellular network is represented in hexagon network consist of cells. The cells served by at least one transceiver from fixed-location known as a cell site or base station. These cells provide radio coverage over a wide geographic area when joined together. This enables the communications to happen between the cells with fixed transceivers and telephones anywhere in the network, via base stations, even if some of the transceivers are moving through more than one cell during transmission.

Ding, Y (2014) analyzed that channel assignments in the networks become a promising technology that enables many useful applications. In their study, they survey that interference give different performance of the channel assignments. The expected performance will give accurate results when deployed in real environments. Therefore, it is necessary to design channel allocation algorithms based on more realistic interference.

1.3 Problem Statement

In the wireless mesh network, channel assignment problem can be modeled as a connected graph $G(V, E)$ representing a wireless network with n nodes and m edges, where $V = \{v_i\}$ for $i = 1, 2, \dots, n$ and $E = \{e_{ij}\}$ for $i, j = 1, 2, \dots, m$. Similar with wireless mesh network, the cellular network also can be modeled as a connected graph $G(V, E)$ representing a wireless network with n nodes and m edges which represent in hexagonal network. The cell for the hexagon network represents the node for the graph where each cell is assigned with one transmitter. We shall assume that, to avoid interference, two constraints are considered for single channel communication which are adjacent constraint and cochannel constraint while for multi-channel assignment, there is an addition constraint which is cosite constraint.

The channels are assigned in such a way that they are constantly reused once a particular assignment is completed. In what way can the channels be assigned to the nodes with minimum use of channels in order to transfer data communication by considering the electromagnetic constraints?

1.4 Research Questions

The research questions of the study are:

a. How is the graph coloring changing when interference happen?
b. How can the graph model adapt to different settings in the cases of static and dynamic networks?
c. How to minimize number of channel used in the network?
d. How to optimize the performance of the network?
e. What simulation software is used to prove the algorithm?

1.5 Objectives of the Study

The objectives of the study are:

a. Propose an improvement to the channel assignments for static and dynamic graph models using single channel on nodes in the network.
b. Propose an improvement to the channel assignments for static and dynamic graph models using multi-channel on nodes in the network.
c. Develop new metaheuristic methods based on simulated annealing for single and multiple channels.
d. Applications to a, b, and c above on the problem of channel assignments for mesh and cellular networks.

1.6 Scope of the Study

This study is about channel allocation in cellular and wireless mesh networks where represents the static and dynamic networks respectively. In communication

networks, channel assignment is an important thing to optimize the performance of the network. The channel allocation is a graph coloring problem where we are focusing on the vertex coloring. As explained above, two constraints are considered in single channel communication namely adjacent constraint and co-channel constraint. For the multi-channel communication, cosite constraint is considered in the channel assignment. The network is optimized if the channel used is minimized by considering the constraints. Most of the previous research in cellular and wireless mesh networks are in computer and mobile engineering. Our study is considering and focusing on graph coloring to allocate channels by considering the constraints and not involved in the engineering and computing field. Our algorithms are applied in wireless mesh networks and cellular networks for single and multi-channels assignments.

1.7 Significance of the Study

Channel assignment in communication networks is a graph coloring problem. The optimize performance of the networks can be achieved by minimizing the channel used while reducing the interference of the nodes. In the research, we proposed an algorithm of channel assignment for single channel and multi-channel communication by considering three constraints; adjacent, co-channel and cosite constraints using simulated annealing and T-coloring problem. We improve the Greedy method by adding the constraints. The arrangement of the nodes in mesh networks is important in our algorithm that inspired us to develop metaheuristic method using simulated annealing. This model focused on single channel communication and multi-channel communication. The results from the study are useful for optimizing the performance of the cellular network and wireless mesh network in real environments..

1.8 Thesis Organization

The thesis is organized into six chapters. Chapter 1 is the introduction which discusses the research plan of the study and introduction of the networks. Chapter 2 is reviewing of the related works from previous authors as references. Some of the previous models are explained briefly in this chapter. The graph coloring is describing deeply as the main problem that related with our study.

In Chapter 3, a new algorithm namely Improved Greedy algorithm with adjacent channel and cochannel constraints is proposed to assign a single channel for the networks. In Chapter 4, the multi-channel assignment is proposed using Improved Greedy algorithm by considering the three constraints; adjacent, co-channel and cosite constraints. Both algorithms are applied in mesh and cellular networks.

The algorithm is improved in Chapter 5 by using Improved Greedy algorithm combining with simulated annealing and T-coloring problem. The two constraints; adjacent and co-channel constraints are considered in single channel communication while in multi-channel communication, three constraints; adjacent channel, co-channel, and cosite constraints are being considered. Conclusion and open issues are discussing in Chapter 6 for further study in the future.

REFERENCES

Akella, M. R., Batta, R., Sudit, M., Rogerson, P., and Blatt, A. (2007). Cellular network configuration with co-channel and adjacent-channel interference constraints. *Computers & Operations Research*. 35(2008): 3738 – 3757.

Akyildiz, F., Wang, X., and Wand, W. (2005). Wireless mesh networks: a survey. *Computer Networks.* 47(4): 445-487.

Alon, N. (2003). A simple algorithm for edge-coloring bipartite multigraphs. *Information Processing Letters*. 85(6): 301-302.

Alon, N., Sudakov, B., and Zaks, A. (2001). Acyclic edge colorings of graphs. *Journal of Graph Theory*. 37(3): 157-167.

Appel, K., and Haken, W. (1976). Research announcements every planar map is four colorable. *Bulletin of the American Mathematical Society*. 82(5): 711-712.

Beljadid, A., Hafid, A. S., and Gendreau, M. (2007). Optimal design of broadband wireless mesh networks. *Proc. of the 50th International Conference on GLOBECOM 07.*

Brar , G., Blough, D. M., and Santi, P. (2006). Computationally efficient scheduling with the physical interference model for throughput improvement in wireless mesh networks. *Proceedings of the 12th annual international conference on Mobile computing and networking*. September 23-29. Los Angeles, CA, USA.

Bu, Y., Finbow, S., Liu, D.D.-F., and Zhu, X. (2014). List backbone colouring of graphs. *Discrete Applied Mathematics*. 167: 45-51.

Claudia, V., Mirna, M., and Jezreel, M. (2013). Characterization of software processes improvement needs in SME's. *International Conference on Mechatronics, Electronics and Automotive Engineering*. 223-228.

Das, S. M., Koutsonikolas, D., Hu, Y. C., and Peroulis, D. (2006). Characterizing multi-way interference in wireless mesh networks. *Wintech, Los Angeles, California, USA.*

Das, A. K., Alazemi, H. M. K., Vijayakumar, R., and Roy, S. (2005). Optimization models for fixed channel assignment in wireless mesh networks with multiple radios. *IEEE SECON.* Santa Clara. 26-29.

Ding, Y., Pongaliur, K., and Xiao, L. (2013). Channel allocation and routing in hybrid multichannel multiradio wireless mesh networks. *IEEE Transactions on Mobile Computing.* 12(2): 206-218.

Ding, Y., and Xiao, L. (2010). Channel allocation in multichannel wireless mesh networks. *Journal of Computer Communications (Article in Press).*

Ding, Y., Pongaliur, K., and Xiao, L. (2009). Hybrid multi-channel multi-radio wireless mesh networks. *Quality of Service. IWQoS. 17th International Workshop on IEEE.* doi: 10.1109/IWQoS.2009.5201403.

Gadkar, A., and Subramaniam, S. (2010). Wavelength-reuse in optical time-slotted networks. *Optical Switching and Networking.* 7(4): 153-164.

Geltman, K. E. (2014, February 20). The simulated annealing algorithm. Retrieved From http://katrinaeg.com/simulated-annealing.html.

Girgis, M. R., Mahmoud, T. M., Abdullatif, B. A., and Rabie, A. M. (2014). Solving the wireless mesh network design problem using genetic algorithm and simulated annealing optimization methods. *International Journal of Computer Applications.* 96(11): 0975-8887.

Gore, A. D., and Karandikar, A. (2011). Link Scheduling algorithms for wireless mesh networks. *IEEE Communications Surveys and Tutorials*. 13(2): 258-273.

Hale, W. K. (1980). Frequency assignment: Theory and applications. *Proc. IEEE.* 68: 1497-1514.

Heawood, P. J. (1890). Map-colour theorems. *Quarterly Journal of Mathematics*. Oxford. 24: 332-338.

Holyer, I. (1981). The NP-completeness of edge-colouring. *SIAM J. COMPUT Society for Industrial and Applied Mathematics.* 10(4): 718-720.

Kaabi, F., Ghannay, S., and Filali, F. (2010). Channel allocation and routing in wireless mesh networks: a survey and qualitative comparison between schemes. *International Journal of Wireless & Mobile Networks*. 2(1).

Kirti. (2014). Basic concepts of wireless network. *International Journal of Science and Research (IJSR)*. 3(7): 2319-7064.

Kubicka, E., and Schwenk, A. J. (1989). An introduction to chromatic sums. *Proc. ACM Computer Science Conference.* Louisville, New York. 39–45.

Liu, W., Han, Y., and Yu, H. (2000). Channel Assignment Strategies for Cellular Phone Systems. *Mathematical Contest in Modeling (MCM).*

Matsui, T., Sukegawa, N., and Miyauchi, A. (2014). Fractional programming formulation for the vertex coloring problem. *Information Processing Letters, Article in Press.*

Mor, V., and Kumar, Harish. (2017). Energy Efficient Greedy Algorithm for Wireless Mesh Networks. *International Journal of Current Research.* 9(10): 53-57.

Pan, D., and Xing, B. (2008). An ant routing algorithm for wireless mesh network. *Intelligent Control and Automation.* Chongqing. 4595-4599.

Portmann, M., and Pirzada, A. A. (2008). Wireless Mesh Networks for Public Safety and Crisis Management Applications. *IEEE Internet Computing*. 12(1): 18-25.

Raman, B. (2006). Channel allocation in 802.11-based mesh networks. *Proceedings IEEE INFOCOM*. doi: 10.1109/INFOCOM.2006.317.

Raniwala, A., Gopalan, K., and Chiueh, T. (2005). Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks. *Mobile Computing and Communications Review*. 8(2).

Rasheed, T., and Slongo, M. (2008). Channel assignment in wireless mesh networks: a state-of-art. *Create-Net Technical Report CN-TR- 200800022.*

Roberts, F.S. (1991). T-colorings of graphs: recent results and open problems. *Discrete Mathematics*. 93(2-3): 229-245.

Roos, D. (2007, June 20). *How wireless mesh networks work.* Retrieved From http://computer.howstuffworks.com/how-wireless-mesh-networks-work.htm.

Rouse, M. (2015, February). *Greedy algorithm*. Retrieved From http://whatis.techtarget.com/definition/greedy-algorithm.

Sahni, S., and Gonzales, T.(1976). P-Complete approximation problem. *Proc. 32nd Ann. ACM Symp. on the Theory of Computing.*

Salleh, S., Zomaya, A., Olariu, S., and Sanugi, B. (2005). Numerical simulation and case studies using Visual C++.Net. *Wiley-Interscience, USA.*

Si, W., Selvakennedy, S., and Zomaya, A.Y. (2010). An overview of channel assignment methods for multi-radio multi-channel wireless mesh networks. (70)505-524.

Sivarajan, K. N., McEliece, R. J., and Ketchum, J.W. (1989). Channel assignment in cellular radio. *Proc. 39th IEEE Veh. Technol. Soc. Conf*., 846-850.

Skulrattanakulchai, S. (2006). Δ-List vertex coloring in linear time. *Information Processing Letters*. 98(3): 101-106.

Subramanian, A. P., Gupta, H., Das, S. R., and Cao, J. (2008). Minimum interference channel assignment in multiradio wireless mesh networks. *IEEE Transactions on Mobile Computing*. 7(12): 1459-1473.

Weisstein, E. W. (2016, Aug 18). *Vertex coloring*. Retrieved From http://mathworld.wolfram.com/VertexColoring.html.

Weisstein, E. W. (2016, Aug 18). *Edge coloring*. Retrieved From http://mathworld.wolfram.com/EdgeColoring.html.

Weisstein, E. W. (2016, Aug 18). *Four-color theorem*. Retrieved From http://mathworld.wolfram.com/Four-ColorTheorem.html.

Yang, D., Fang, X., Li, N., and Xue, G. (2009). A simple greedy algorithm for link scheduling with the physical interference model. *GLOBECOM - IEEE Global Telecommunications Conference.*

Zeng, G., Wang, B., Ding, Xiao, Y. L., and Mutka, M. (2007). Multicast algorithms for multi-channel wireless mesh networks. *IEEE International Conference on Network Protocols.* Beijing. 1-10.