Channel Assignment and Routing in Cooperative and Competitive Wireless Mesh Networks

A Thesis submitted for the Degree of
Doctor of Philosophy

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Abstract

In this thesis, the channel assignment and routing problems have been investigated for both cooperative and competitive Wireless Mesh networks (WMNs). A dynamic and distributed channel assignment scheme has been proposed which generates the network topologies ensuring less interference and better connectivity. The proposed channel assignment scheme is capable of detecting the node failures and mobility in an efficient manner. The channel monitoring module precisely records the quality of bi-directional links in terms of link delays. In addition, a Quality of Service based Multi-Radio Ad-hoc On Demand Distance Vector (QMR-AODV) routing protocol has been devised. QMR-AODV is multi-radio compatible and provides delay guarantees on end-to-end paths. The inherited problem of AODV's network wide flooding has been addressed by selectively forwarding the routing queries on specified interfaces. The QoS based delay routing metric, combined with the selective route request forwarding, reduces the routing overhead from 24% up to 36% and produces 40.4% to 55.89% less network delays for traffic profiles of 10 to 60 flows, respectively.

A distributed channel assignment scheme has been proposed for competitive WMNs, where the problem has been investigated by applying the concepts from non-cooperative bargaining Game Theory in two stages. In the first stage of the game, individual nodes of the non-cooperative setup are considered as the unit of analysis, where sufficient and necessary conditions for the existence of Nash Equilibrium (NE) and Negotiation-Proof Nash Equilibrium (N-PNE) have been derived. A distributed algorithm, based on non-cooperative bargaining, has been presented with perfect information available to the nodes of the network. In the presence of perfect information, each node has the knowledge of interference experience by the channels in its collision domain. The game converges to N-PNE in finite time and the average fairness achieved by all the nodes is greater than 0.79 (79%) as measured through Jain Fairness Index. Since N-PNE and NE are not always a system optimal solutions when considered from the end-nodes prospective, the model is further extended to incorporate non-cooperative end-users bargaining between two end user's Mesh Access Points (MAPs), where an increase of 10% to 27% in end-to-end throughput is achieved.

Furthermore, a non-cooperative game theoretical model is proposed for end-users flow routing in a multi-radio multi-channel WMNs. The end user nodes are selfish and compete for the channel resources across the WMNs backbone, aiming to maximize their own benefit without taking care for the overall system optimization. The end-to-end throughputs achieved by the flows of an end node and interference experienced across the WMNs backbone are considered as the performance parameters in the utility function. Theoretical foundation has been drawn based on the concepts from the Game Theory and necessary conditions for the existence of NE have been extensively derived. A distributed algorithm running on each end node with imperfect information has been implemented to assess the usefulness of the proposed mechanism. The analytical results have proven that a pure strategy Nash Equilibrium exists with the proposed necessary conditions in a game of imperfect information. Based on a distributed algorithm, the game converges to a stable state in finite time. The proposed game theoretical model provides a more reasonable solution with a standard deviation of 2.19Mbps as compared to 3.74Mbps of the random flow routing. Finally, the Price of Anarchy (*PoA*) of the system is close to one which shows the efficiency of the proposed scheme.

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AODV	Ad-hoc On-demand Distance Vector
APs	Access Points
BSS	Basic Service Set
CBR	Constant Bit Rate
CG	Conflict Graphs
DCA	Dynamic Channel Assignment
DCF	Distributed Coordination Function
DSDV	Destination-Sequenced Distance Vector
FCA	Fixed Channel Assignment
FTP	File Transfer Protocol
GLTM	Global Link Topology Matrix
HCA	Hybrid Channel Assignment
HTTP	Hyper Text Transfer Protocol
IEEE	Institute of Electrical and Electronics Engineers
ISM	Industrial, Scientific and Medical
MAC	Medium Access Control
MANETs	Mobile Ad-hoc Networks
MAPs	Mesh Access Points
MCs	Mesh Clients
MPs	Mesh Points
AODV-MR	Ad-hoc On-demand Distance Vector- Multi Radio
MR-CG	Multi Radios-Conflict Graph
MRMC	Multi Radios Multi Channels
NCU	Neighbour’s Channel List
NE	Nash Equilibrium
NS2	Network Simulator-2
PDR	Packet Delivery Ratio
OLSR	Optimized Link State Routing
PoA	Price of Anarchy

QMR-AODV	Quality of service based Multi Radio- Ad-hoc On-demand Distance Vector
QoS	Quality of Service
SRMC	Single Radio Multiple Channels
SRSC	Single Radio Single Channel
TCL	Tool Command Language
TCP/IP	Transmission Control Protocol/Internet Protocol
VoIP	Voice over IP
WLANs	Wireless Local Area Networks
WMNs	Wireless Mesh Networks
WPANs	Wireless Personal Area Networks
WSN	Wireless Sensor Networks

Author’s Declaration

The work described in this thesis has not been previously submitted for a degree in this or any other university and unless otherwise referenced it is the author’s own work.

Statement of Copyright

CHAPTER 1

Introduction and Motivation

This chapter presents brief background of the problems investigated, motivation of work, aim and objectives for undertaking this research. Further, the major contributions and the research methodology to achieve them have been described. Finally, this chapter briefly outlines the next chapters in this thesis.

1.1 Background

Channel assignment and routing in multi radio multi-hop environment is a challenging issue in recent years because of the possibility to deploy multiple radios on the relaying nodes in the recent emerging wireless access networks [1]. The multiple non-overlapping channels in the free ISM (Industrial, Scientific and Medical) band provides an opportunity to the research community to exploit the spectrum for multi radio access networks [2], resulting in increased overall network throughput and connectivity through communication parallelism. The channel assignment and routing problems have been addressed in several studies ranging from the last mile of traditional cellular mobile networks [3] to the specialized Mobile Ad-hoc Networks (MANETs) [4-5] and Wireless Sensor Networks (WSNs) [6]. In all these cases, a single radio per node has been considered in the problem formulation. Equipping the wireless relay nodes with multiple radios along with assigning multiple non-overlapping channels poses a fundamental question of efficient spectrum utilization. Another challenge, which all the emerging access technologies are facing, is the gap between the end users demands and the capability of network to ensure such Quality of Service (QoS) by filling this gap. Routing, in multi-hop networks, plays an important role in providing the efficient end-to-end paths in the end user's prospective.

Channel assignment and routing are fundamentally interdependent on each other. The aim of channel assignment in a multi radio network is to control the interference as much as possible. However, the interference phenomenon cannot be eliminated from the networks due to the limited range of frequencies available in the ISM band. Combined with routing, the channel assignment can be re-arranged based on the routing loads on links. Routing, on the other hand, determines the end-to-end paths across the network between any source-destination pair. The path provided by the routing protocol transverses multiple links and hence the channel assignment algorithms applied play an important role. To address this combined problem of routing and channel assignment, several research studies have been carried out [7-9] in the past decade with an implicit focus on the QoS provisioning in these networks. However, no such real effort has been made explicitly to provide these QoS guarantees to the end users as for as the joint problem of routing and channel assignment is concerned in Wireless Mesh Networks (WMNs).

WMNs protocols are extremely distributed due to the self-configuring and self-healing nature of these networks [10], therefore, each entity in the network can behave selfishly by deviating from the standard defined protocol to increase its own benefit from the network resources. Since channel assignment plays and important role in the performance of WMNs, the selfishness of network entities can exploit it exclusively for their own benefit. Therefore, some mechanisms are needed to address the behaviour of these selfish nodes inside the network for smooth functioning. In such a competitive network, the traditional standard protocols need to be revisited in order to meet these challenges [11].

1.2 Motivation

In recent years, the field of wireless networks has witnessed a tremendous growth in terms of their deployment and have attracted more users. Such networks have improved the people’s life style by keeping them more connected, entertained and have impacted their productivity [12]. However, ranging from the traditional cellular access for voice traffic to the wireless data access networks for broadband connectivity, each wireless access technology faces the same fundamental problems of interference, capacity limitations and scalability [13]. The available finite spectrum is the main issue, which limits the capacity and growth of wireless networks. On the other hand, the user’s expectations are increasing with the passage of time, *i.e.,* the emerging applications like video conferencing, voice communication and online games nowadays require real time data transfer. In a multi user network, the main objective is to satisfy the demands put by the end users applications. To cope up with the varying demands of end users from the underlying network, each wireless technology providers aim at to improve the QoS provisioning mechanisms for smooth functioning of the network and to meet with the customer's expectations. The emergence of IEEE 802.11 based WMNs as the last mile wireless Internet broadband connectivity anywhere, anytime and to anyone has provided new avenues in terms of research and the user's satisfaction [14 -15]. Being capable to be equipped with multiple interfaces, the WMNs backbone effective capacity can scale up to provide the broadband connectivity to the end users by exploiting the free ISM spectrum in the 2.4GHz and 5 GHZ range. However, the existence of limited non-overlapping channels in the free ISM band, the multiple number of radios per node in the network and the link quality of the end-to-end paths pose a limitations as for as the end user's demands are concerned. This needs that the existing protocols should be revisited to accommodate the users' QoS demands in the current WMNs architecture.

The competitive and selfish nature of nodes poses threat to the network performance because of the extremely distributed and self-organizing nature of WMNs. The selfishness of network entities can degrade the overall performance during the channel assignment and routing leaving it at standstill. To tackle such problems in a competitive environment, Game Theory [16] and its employment for balancing the use of network resources among the competing users is of tremendous importance.

The work presented in this thesis is motivated by the following issues in cooperative and competitive WMNs:

1. WMNs are gaining popularity to be deployed as the future broadband access networks in the user's premises due to their static, self-configuring and self-organizing nature. The existence of multiple non-overlapping channels, assigned to the multi-radios of devices in these networks, results in communication parallelism and improves the overall connectivity and capacity of the network. Multi-radio Multi-channels (MRMC) Medium Access Control (MAC) has gained popularity recently because of their capability to increase the wireless networks capacity, connectivity and scale. These wireless networks, however, suffer from interference, congestions, packet losses and capacity problems due to the wireless nature of the medium. Keeping the above limitations in mind, it is necessary to design a channel

assignment scheme, which is dynamic, distributive and works with simple operations.

2. The QoS requirements of the end users increase with time and the network should be able to meet them. The most important requirement for the emerging voice and video applications is the delay guarantees on the end-to-end paths. For this reason, the routing protocols, which are designed over MRMC capable wireless networks, should be re-investigated to provide paths matching for these QoS demands of the delay sensitive video and audio applications.
3. The channel assignment and routing are two separate problems but are highly interdependent. Being located at the two different layers of the protocol stack, an efficient solution should be provided to interlink the two.
4. Channel assignment in competitive WMNs is a challenging issue because the network routers are located in multiple collision domains and a mechanism is needed to cope with the selfish behaviour of these nodes during channel assignment. Game Theory provides an efficient solution for tackling the selfish behaviour because of its ability to model individual decision makers whose decisions can potentially affect other's decisions.
5. The WMNs provide the wireless backbone for the Internet access where the routers are spread over multiple collision domains. Being equipped with multiple radios assigned to multiple non-overlapping channels, there can be multiple paths across the backbone from the end users to the Gateways destinations. The selfishness of end users during the path selection on end-to-end basis in the interference-constrained topology of WMNs can potentially degrade their individual fairness and the network performance as a result. This selfish behaviour should be tackled in order to provide the smooth functioning of the network.

1.3 Aim and Objectives

The aim of the research presented in this thesis is to design and implement channel assignment and routing for 802.11 based Multi-Radios Multi-Channels cooperative and competitive (*i.e.* non-cooperative) WMNs. The main objectives are to provide QoS to the end users and ensure the fairness among the competing nodes. The research aims and objectives are summarized as follows:

1. To utilize the non-overlapping multiple channels effectively and efficiently by providing a distributive and dynamic channel assignment scheme.
2. The research aims to design a distributed and dynamic joint channel assignment and routing protocol capable of providing the required QoS as demanded by the end users.
3. To ensure the link quality, design an efficient mechanism at MAC layer to provide input to the routing protocol during the decision making process.
4. The research also aims at to design Game Theoretical models for channel assignment in non-cooperative MRMC WMNs. The objective is to look at the channel assignment, taking the nodes of the network as the unit of analysis, by providing solutions from the non-cooperative alternating offer braining game theory. Further, it also aimed at to look at the channel assignment from the end user's prospective and to provide QoS and throughput enhancements using concepts from non-cooperative bargaining games.
5. To solve the selfish routing problem in a non-cooperative MRMC WMNs by using the concept of Game Theory. The research aims at to use the non-cooperative game theory to provide maximum fairness during the flow routing of the end user nodes across the network backbone.

1.4 Contribution to Knowledge

This thesis contributes to knowledge in the research area of channel assignment and routing considering the IEEE 802.11 based WMNs. These two research issues have been addressed jointly considering the QoS requirements of the end nodes in cooperative WMNs. Further, a channel assignment and routing scheme has been developed for non-cooperative WMNs. The issues of QoS for the end users and fairness among them have been thoroughly investigated. The key contributions are summarized as follows:

1. A minimum interference channel assignment scheme has been developed for assigning multiple non-overlapping channels, as present in the IEEE 802.11a and IEEE 802.11b/g standards, to the multiple radios of the mesh backbone routers. The channel assignment scheme has the following capabilities.

a. The channel assignment scheme ensures the minimum interference among the nodes of the network and provides maximum connectivity.
b. It can be initiated from any point in the WMNs backbone and therefore gives the freedom to the network planners to initiate the process based on the network load in a specific region of the WMNs backbone.
c. It is capable to record accurately and maintain the bi-directional link quality by measuring the delays on specific associated links between any two nodes. This delay metric is further utilized by the routing protocol for determining the end- to-end paths across the WMNs backbone on source-destination basis.
d. The channel assignment scheme quickly responds to the routing load, mobility and nodes failures by re-assigning the channels when and where necessary.

2. A QoS based routing scheme has been proposed to provide end-to-end guarantees to the applications in terms of path delays. The proposed scheme has the following properties.

a. It is based on the Ad-hoc On Demand Distance Vector (AODV) routing protocol and paths are established whenever it is necessary.
b. The network wide flooding phenomenon associated with the on-demand routing protocols has been controlled based on selective forwarding on specific interfaces. The routing module only forwards the routing requests on those interfaces which qualify the end user's QoS bounds.
c. The routing protocol, combined with the channel assignment module, ensures end-to-end paths according to the end users delay

requirements. This scheme enhances the packet delivery ratio by eliminating the flood of unnecessary route request packets and the overall latency of the network is minimized. This further provides a mechanism of load balancing across the WMNs backbone by avoiding the already congested links to establish routes between end users and the gateway destinations.

3. A game theoretic model has been developed for assigning channels to the multiple radios of the WMNs backbone routers by considering the non-cooperative environment. The WMNs routers are assumed to be in multiple collision domains and the interference phenomena is captured by using the concept from the graph theory. The channel assignment scheme has been formulated by considering a two stage static non-cooperative game.

a. The WMNs backbone is partitioned into multiple collision domains by using the concepts from Conflict Graphs (CG). Channels are assigned to the interfaces in a distributed manner, where each node is considered a self maximizer entity. Solution is provided using the concepts of non-cooperative bargaining game theory.
b. An end user non-cooperative bargaining scheme has been proposed. In the second stage of the game, the end users Mesh Access Points (MAPs) come into contact with each others and bargain on the channels in their end-to- end paths. Two Mesh Access Points bargain with each other when the channels exchange, in their end-to-end paths, has an advantage for one in terms of throughput and for other in terms of money. This channel exchange has been modelled with a non-cooperative bargaining game, where information is considered as imperfect.

4. A selfish flow routing scheme in non-cooperative multiple radio multiple channels WMNs has been developed. End users of the network are selfish and non-cooperative aiming to route their flows across the end-to-end paths of the WMNs backbone with high utility. The Game Theoretic model provides a solution to balance the traffic on the individual links.

a. The selfish flow routing over MRMC WMNs was modelled using the non-cooperative games. The necessary conditions for the existence of NE were derived.
b. A distributed algorithm running on each end node was developed which aims to establish links across the end-to-end paths from source to destination. The fairness issues were addressed in the model.

1.5 Research Methodology

The research methodology used for conducting the research presented in this thesis is summarized as follows:

1. In the beginning phase, an extensive literature review was conducted of the present and past research work done in the area of channel assignment and routing in both cooperative and non-cooperative WMNs. During this stage, the IEEE standards, routing protocols RFCs, sate of the art related to the issues addressed and Game Theory concepts were studied and investigated.
2. Literature review was followed by the implementation phase which included the development of channel assignment scheme for multi radio WMNs and a multi radio extension for the AODV routing protocol. Conventional AODV works only with a single radio by disseminating the routing packets over a single interface. This was followed by implementing the delay metric for the proposed routing protocol. The performance of the proposed scheme was measured by carrying out extensive simulations with adequate confidence interval (averaging 20 independent runs) and the results in terms of delay, packet loss, packet delivery ratio and response time were compared taking Multi-Radio AODV (AODV-MR) [17,18] as a comparison benchmark. For channel assignment to the multiple radios, the protocol has been implemented on the guidelines as in [26]. The link monitoring and cross layer functionalities have been added by modifying the various files at MAC and

routing layers. Network Simulator2 (NS-2) version 2.34 [19] was used as implementation and testing platform. The code was compiled and tested under the Linux Kernel version 2.6.34 in the openSUSE [20] version 11.3 platform. NS2 is an open source discrete event simulator which provides interfaces to develop new protocols at various layers of the Transmission Control Protocol/Internet Protocol (TCP/IP) [21] protocol stack. Necessary modifications were made to various libraries, header functions and C++ files at MAC as well as Network Layers for the implementation of the proposed schemes. Scripts were written in the Tool Command Language (TCL) for network topology generation and traffic profile definitions in the testing phase.

3. In the Chapter 3, for the designing of QoS based routing and channel assignment, the protocol model was followed as compared to the physical model [13]. The protocol model enables the nodes to know about the degree of interference on the various channels/links, available in their vicinity, through the exchange of messages. The physical model, on the other hand, provides more accurate information about the interference on the channels by deploying some specialized hardware on each node. Although, the physical model for measuring the interference is more accurate and precise due to its capability to take measurements through the signal strength; however, protocol model was considered in this work due to its cost effectiveness.

4. For physical propagation, the TwoRayGround reflection model was used in the NS-2 simulations. The two-ray ground reflection model considers both the direct path and a ground reflection path. It has been proved in studies that this model gives more accurate prediction at a long distance than the free space model [22].

5. For channel assignment and flow routing schemes in competitive WMNs, a thorough understanding of the Game Theory concepts was obtained and the utility functions were designed for each issue. The proposed algorithms for the schemes were implemented in MATLAB [23] version R2007a under the Linux Kernel version 2.6.34 in the openSUSE version 11.3 platform. MATLAB

provides an easy and interactive programming environment for mathematical and numerical algorithm implementation. It allows matrix manipulation which best suits the Game Theoretic models proposed.

6. The Stanford GraphBase version 3.4e [24] program was used for generating the graphs for the topologies of the networks under the Linux Kernel version 2.6.34 in the openSUSE version 11.3 platform. For channel assignment and flow routing in the competitive WMNs, the results were validated by taking the average of 40 independent runs to get the appropriate confidence. For channel assignment in the competitive WMNs, the work of [25] was taken as a base and benchmark model and the results obtained for the proposed algorithms were compared in terms of achieved throughput and fairness. The results were analyzed with an in depth discussion of their fairness capabilities. Further, the results of the proposed end-users bargaining were compared with the N-PNE outcome of the first stage of the game. For flow routing in the competitive WMNs, the obtained results from the proposed game theoretic models were compared with the random selection scheme, where flows of the end users select the end-to-end paths across multiple collision domain WMNs through the standard protocol's deviation in the absence of game theoretical model.

1.6 Thesis Structure

This thesis consists of six chapters, beginning with this introductory chapter which provides a brief synopsis of the whole thesis. Chapter-2 presents the history and fundamental concepts of Game Theory and its applications in various telecommunication systems. This chapter provides a base later for chapter 4 and 5, where the non-cooperative game theory has been applied to solve the channel assignment and routing problems in competitive WMNs.

Chapter-3 provides a brief introduction to WMNs, channel assignment and routing in these networks. A comprehensive literature review has been outlined and discussed with the merits and demerits of each. Further, the proposed channel assignment and routing schemes in cooperative WMNs are presented in the same chapter. The chapter ends with the comprehensive performance evaluation of the proposed schemes.

In chapter-4, a channel assignment scheme has been presented in competitive WMNs. The problem is addressed by using the concepts from non-cooperative game theory by proposing a two non-cooperative game theoretical models, with perfect information in the first one and imperfect information in the second stage of the game. The network is represented by a standard as well as Conflict Graph to capture the interference among links and the nodes. Various conditions for the existence of the N-PNE have been proved. This chapter also outlines two algorithms for channel assignment and re-assignment in the competitive WMNs. The chapter ends with the performance evaluation of the presented scheme and conclusion.

Chapter-5 addresses the issue of flow routing in non-cooperative WMNs. Similar to chapter-4, a graph theoretic model has been presented for the representation of network topology. Selfish end users routing over WMNs has been modeled as a non-cooperative game, where the proposed scheme has been proved with extensive analytical analysis and the conditions for the distributed algorithm have been outlined. The chapter ends with the performance evaluation of the proposed scheme and the summary of the chapter.

Finally, chapter-6 concludes the research findings of the thesis and suggests future work that may be carried out in connection with the research presented in this thesis.

1.7 References

[1] Y. Zhang and H. Hu, Wireless Mesh Networking: Architectures, Protocols and Standards. Auerbach Pub, 2006.

[2] Akyildiz, I. F., Wang, X., & Wang, W, Wireless mesh networks: A survey. Computer Networks, 47(4), 445-487, 2005.

[3] I. Katzela and M. Naghshineh, "Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive survey," Personal Communications, IEEE, vol. 3, pp. 10-31, 1996.

[4] S. L. Wu, C. Y. Lin, Y. C. Tseng and J. L. Sheu, "A new multi-channel MAC protocol with on-demand channel assignment for multi-hop mobile ad hoc networks," in Parallel Architectures, Algorithms and Networks, 2000. I-SPAN 2000. Proceedings. International Symposium on, pp. 232-237, 2000.

[5] S. L. Wu, Y. C. Tseng, C. Y. Lin and J. P. Sheu, "A multi-channel MAC protocol with power control for multi-hop mobile ad hoc networks," The Computer Journal, vol. 45, pp. 101-110, 2002.

[6] Y. Wu, J. A. Stankovic, T. He and S. Lin, "Realistic and efficient multi-channel communications in wireless sensor networks," in INFOCOM 2008. the 27th Conference on Computer Communications. IEEE, pp. 1193-1201, 2008.

[7] P. Kyasanur and N. H. Vaidya, "Routing and interface assignment in multi-channel multi-interface wireless networks," in Wireless Communications and Networking Conference, 2005 IEEE, pp. 2051-2056 Vol. 4. , 2005.

[8] C. Cicconetti, V. Gardellin, L. Lenzini and E. Mingozzi, "PaMeLA: A joint channel assignment and routing algorithm for multi-radio multi-channel wireless mesh networks with grid topology," in Mobile Adhoc and Sensor Systems, 2009. MASS'09. IEEE 6th International Conference on, pp. 199-207. , 2009.

[9] L. Bononi, M. Di Felice, A. Molinaro and S. Pizzi, "A cross-layer architecture for effective channel assignment with load-balancing in multi-radio multi-path wireless

mesh networks," International Journal of Communication Systems, vol. 22, pp. 1267-1296, 2009.

[10] J. H. Huang, L. C. Wang and C. J. Chang, "Architectures and Deployment Strategies for Wireless Mesh Networks," Wireless Mesh Networks, pp. 29-56, 2007.

[11] K. Akkarajitsakul, E. Hossain, D. Niyato and D. I. Kim, "Game theoretic approaches for multiple access in wireless networks: A survey," Communications Surveys & Tutorials, IEEE, vol. 13, pp. 372-395, 2011.

[12] P. Nicopolitidis, M. S. Obaidat, G. I. Papadimitriou and A. S. Pomportsis, Wireless Networks. Wiley Online Library, 2003.

[13] P. Gupta and P. R. Kumar, "The capacity of wireless networks," Information Theory, IEEE Transactions on, vol. 46, pp. 388-404, 2000.

[14] Bruno, R., Conti, M., & Gregori, E., Mesh networks: Commodity multihop ad hoc networks. Communications Magazine, IEEE, 43(3), 123-131., 2005.

[15] T. Fowler, "Mesh networks for broadband access," IEE Rev, vol. 47, pp. 17-22, 2001.

[16] M. J. Osborne and A. Rubinstein, A Course in Game Theory. The MIT press, 1994.

[17] A. A. Pirzada, M. Portmann and J. Indulska, "Evaluation of multi-radio extensions to AODV for wireless mesh networks," in Proceedings of the 4th ACM International Workshop on Mobility Management and Wireless Access, pp. 45-51, 2006.

[18] A. A. Pirzada, M. Portmann and J. Indulska, "Performance analysis of multi-radio AODV in hybrid wireless mesh networks," Comput. Commun., vol. 31, pp. 885-895, 2008.

[19] The Network Simulator, NS-2: www.isi.edu/nsnam/ns/ [Accessed May 2011].

[20] http://software.opensuse.org/121/en [Accessed May 2011].

[21] W. R. Stevens, TCP/IP Illustrated: The Protocols. Addison-Wesley Professional, 1994.

[22] http://www.isi.edu/nsnam/ns/doc/node216.html [Accessed June 2012].

[23] http://www.mathworks.co.uk/products/matlab/ [Accessed August 2010].

[24] http://www-cs-faculty.stanford.edu/~uno/sgb.html [Accessed June 2012].

[25] R. D. Vallam, A. A. Kanagasabapathy and C. S. R. Murthy, "A non-cooperative game-theoretic approach to channel assignment in multi-channel multi-radio wireless networks," Wireless Networks, vol. 17, pp. 411-435, 2011.

[26] K. Xing, X. Cheng, L. Ma and Q. Liang, "Superimposed code based channel assignment in multi-radio multi-channel wireless mesh networks," in Proceedings of the 13th Annual ACM International Conference on Mobile Computing and Networking, pp. 15-26, 2007.

CHAPTER 2

Game Theory – An Overview

2.1 Fundamental Concepts of Game Theory

Game Theory [1-3] is the study of mathematical models, which are used in a situation when multiple entities interact with each other in a strategic setup. The theory in its true sense deals with the ability of an entity or individual (called *player* in Game Theory) to take a certain decision keeping in view the effect of other entities decisions on him, in a situation of confrontation. A wage negotiation between a firm and its employees can be considered as a game between two parties, where each party makes a decision or move in the negotiation process based on other party's move. Similarly, a business run by a group of people can be considered as a game played against its competitors or customers.

The concept of modern Game Theory was introduced by John Von Neumann and Oskar Morgenstern [4] in 1944, who described the word 'game' for the first time by systematically specifying the rules of the game, the move of players, the information they possess during their moves and the outcome for each player at the end of the game [5]. They are considered the pioneers of modern Game Theory who modelled the economic situations as decision mathematics models for the first time and presented it as a static game, where individuals come into contact only once. Their models were successfully used in economics in later years. In 1950, John McDonalds [6] published his famous book "Strategy in Poker, Business and War", where he demonstrated the use of strategic interaction in the real world environments. Game Theory took a revolutionary leap when John Nash presented the models for non-cooperative games in 1951 [7]. His proposed solution for non-cooperative games, later on called Nash Equilibrium, is still considered as a standard for any conflicting situation's outcome. R. Luce and H. Raiffa [8, 9] introduced the concept of incomplete information in games in 1957, where they argued that it is not necessary that the participants of a game are fully aware about the rules under which they play and about the utility functions of other players. The co-operative games were introduced by Harsanyi [10] in 1960, where he argued that the commitments (*i.e.* threats, punishments, agreements) in a game are enforceable. The progress of Game Theory continued since its inception and later on and was used in many other fields other than economics. Game Theory has now become an important mathematical tool, which is used in situations that involves several entities whose decisions are influenced by the decisions of other entities playing with them.

Any game, when played, consists of the participants called *players* or *agents* of the game, each having his own preference or goal. Each player of the game has an associated amount of benefit or gain, which he receives at the end of the game, called *payoff* or *utility*, which measure the degree of satisfaction an individual player derives from the conflicting situation. For each player of the game, the choices available to them are called *strategies*. The solution of a game is referred to as *Nash Equilibrium* or *Strategic Equilibrium*, where each player cannot get a better *payoff* than the existing one by individually changing to another new *strategy*. The *utility function* is a mapping of a player's choices into a real number [1]. To understand the concepts presented so for, refer to the Table 2-1, where two players P_1 and P_2 come in a strategic interaction to play this game. For ease, the game is represented by a matrix, called *payoff matrix*, which shows the choices available to players and the outcome for each choice he makes against the others. As shown in the *payoff matrix* of the game between P_1 and P_2, each one has to decide either to choose *X* or *Y*. The setup is strategic, so the choice of individual player's *payoff* depends on the choice made by other player as a response to his strategy. If player P_1 chooses *X*, then his payoff depends upon which choice the player P_2 makes. If P_1 choose *X* and P_2 also chooses *X*, P_1 payoff will be 2, otherwise 10. Similarly, if P_1 chooses the *Y*, then depending upon the choice of P_2 he will either receive 10 or 3. The same choices are available to the player P_2 and the corresponding outcome/payoff received by him. Here in this game, the players are P_1 and P_2, the strategies for each are *X* and *Y* and the *benefits or outcome* of the game are represented in the form of matrix where each entry shows the *payoffs* in the form (*payoff* of P_1, *payoff* of P_2) duple. The numerical outcome for each player depends on the *utility function* used by each in the situation in which this game is played.

Table 2-1: An Example Game in Strategic form

		P_2 X	P_2 Y
P_1	X	***(2, 8)***	***(10, 5)***
P_1	Y	***(5, 10)***	***(3, 3)***

Formally, a game can be defined [1] as consisting of a non-empty finite set of N= {N_1, $N2$, … .., $N_{|N|}$} players, a complete set of actions/strategies A_i={a_1,a_2,…$a_{|Ai|}$} for each $N_i \in$ N. A set of all strategies space of all players, represented by the matrix **A**=$A_1 x A_2 x \ldots x A_{|N|}$. $A(a_i, a_{-i})$ is a strategy profile when a player $N_i \in$N selects an action a_i from its action set A_i against the actions of all other players N_{-i}. The subscripted notation *–i* is a convenient way to represent a set of entities or set of events excluding a specific entity or event in a strategic setup. For example N_{-i} means set of all players excluding N_i and a_{-i} means set of actions of all players excluding the action of the player N_i during a strategic interaction. At the end of the game, each player $N_i \in$N gets benefit in the form of a real number (*R*) called *payoff* of the player which is determined by the utility function U_i as: U_i=$A_i \rightarrow R$.

2.2 Examples of Games

In this section, some famous games are presented along with the associated important definitions, concepts and their classifications according to some parameters.

2.2.1 Prisoners' Dilemma

The well known game of Prisoner's Dilemma was presented by Professor Tucker of Princeton University in 1950 [11-12]. This game depicts an imaginary situation where two persons are arrested under the suspicion of their involvement in a crime. The police place both the suspects in separate rooms so they are not able to communicate with each other during the interrogation process. Each suspect is informed of the following *payoffs* based on their *strategies*, separately:

1. If both suspects confess the crime, each will serve in jail for ten years.

2. If both deny the crime, both will serve in jail for 3 years.

3. If one confess and the other deny, the confessor will be set free and the denier will be sent to jail for 15 years.

The choices available to the suspects and their corresponding outcomes when they play this game are given in the Table 2-2.

Table 2-2: Prisoners' Dilemma game

		Suspect 2	
		Confess	*Deny*
Suspect 1	*Confess*	***(10, 10)***	***(0,15)***
	Deny	***(15, 0)***	***(3, 3)***

Prisoner's Dilemma is an example of simultaneous move game and the solution lies in one of the concept of Game Theory called *dominant strategy*. The game is solvable and both players will be better off, if they opt for the (*Deny, Deny*) strategy giving both a maximum *payoff* of 3 years jail sentence. Since both players of the game are unaware of the decision of each other due to the lack of communication and therefore no cooperation is possible in this case. To solve this game, each player has to weight the possible outcome of his strategies as well as the opponent's decisions in this game. Considering the above game in the *Suspect 1* prospective, the possible *payoffs* for his different *strategies* are: (***Confess***, *Confess*) = 10 years, (***Confess***, *Deny*) = 0 years, (***Deny***, *Confess)* = 15 years, (***Deny***, *Deny*) =3 years. By a method call Cell-by-Cell Inspection, *Confess* seems the best *strategy* to be played by *Suspect 1*, irrespective of the *Suspect 2's strategies*. In Game Theory's terminology, such a strategy is called the *dominant strategy or best response* and is defined as the *strategy* of a player which earns him the larger *payoff* than any other strategies, irrespective of the strategies played by other players in a game. All other strategies are called *dominated strategies*. In the game above, *Suspect 1* will always go for *Confess*, irrespective of *suspect 2* decisions. Similarly, in the prospective of *Suspect 2*, *Confess* is the dominant strategy; irrespective of *Suspect 1's* adopted strategies. Assuming that both players are rational, the solution of this game is (*Confess, Confess*) *i.e.*, both players play their *dominant strategies*.

2.2.2 Battle of the Sexes

Another famous game in the field of Game Theory is called the Battle of the Sexes and was introduced by R. Duncan Luce and Howard Raiffa [9] in 1957. The game is played between a wife and husband and both have to decide between two independent and simultaneous accruing events to attend. The game assumes that there are two events, a football match and a musical concert, and both the husband and wife have different payoffs from each. The payoff matrix and the strategy set for each player is shown in the Table 2-3.

Table 2-3: Battle of the Sexes game

		Wife	
		Football	*Music*
	Football	***(3,1)***	***(0,0)***
Husband	*Music*	***(0,0)***	***(1,3)***

By looking at the strategy matrix of the Table 2-3, none of the players would like to end up attending an event alone so (***Football, Music***) and (***Music, Football***) are two unacceptable outcomes in both player's prospective. However, husband prefers Football more than Music based on his *utility function* while the wife has high preference for Music based on her *utility function*. In this particular game, there is no *dominant strategy* for both players and hence the solution space is either (***Football, Football***) or (***Music, Music***). This particular example shows that a game might have more than one solutions *i.e.,* multiple Nash Equilibriums.

2.3 Nash Equilibrium and Pareto Efficiency

2.3.1 Nash Equilibrium

Definition*:* Nash Equilibrium [7] for any game is the set of strategies of all players, called the *strategy profile*, where no player can increase its *payoff* by changing his current strategy, assuming that all other players keep their current strategies intact. Mathematically, a Nash Equilibrium of a game is the strategy profile **A** of all players such that:

$$U_i(A_i, A_{-i}) \geq U_i(A'_i, A_{-i}) \quad \forall\ i \in \text{N},\ \forall\ A'_i \in \mathbf{A} \tag{2.1}$$

Where A_i is the current strategy of player i against all other strategies of other players (A_{-i}). A'_i are all other strategies of player i. This simply means that a strategy profile **A** (combined strategies of all the players) will be a Nash Equilibrium if and only if the condition in the Equation (2.1) holds for all the players. In the examples given in the Sections 2.2.1 and 2.2.2, (***Confess, Confess***) is the Nash Equilibrium for the Prisoner's Dilemma game while (***Football, Football***) and (***Music, Music***) are the Nash Equilibriums for the Battle of the Sexes game. In the case of all other outcomes in the given games, players can deviate from their current strategies to increase their *payoffs* and hence they are not accepted as the Nash Equilibriums.

2.3.2 Pareto Efficiency

Definition*:* *Pareto Efficiency* or *Pareto Optimality*, named after Vilfredo Pareto, is defined as "A situation is said to be Pareto efficient if there is no way to rearrange things to make at least one person better off without making anyone worse off" [13]. *Pareto Efficiency* is the measures the performance a game outcome. If such a strategy exists in a game, where any single player can increase his payoff by changing his current strategy without hurting the payoffs of other players, then the outcome is not *Pareto Efficient*. In other words, in a *Pareto Efficient* outcome of a game, every player stick to the current strategy and if a single deviation of a player can increase his payoff, it will definitely harm the payoff of other players in the game.

It is not always necessary that a Nash Equilibrium outcome of a game be the *Pareto Efficient* one.

Mathematically, a strategy profile **A** will be *Pareto Efficient* if and only if there is no such other profiles A_i' and A'_j, such that for any players i, j:

$$U(A'_i) \geq U(A_i) \qquad \forall\ i \in \text{N},\ \forall\ A'_i \in \mathbf{A} \tag{2.2}$$

and:

$$U(A'_j) \leq U(A_j) \qquad \textit{for any } j \in \text{N}, \textit{for any } A'_j \in \mathbf{A} \tag{2.3}$$

2.3.3 Pure and Mixed Strategy Nash Equilibrium

When players are playing a game, the *strategies* can be pure or mixed. In a pure strategy game, all the players are taking moves in discrete values. This means that all the players are playing with a probability of one on all of their set of strategies. Refer to the example game in the Section 2.1 again with different payoff values as given in the Table 2-4, with two players P_1 and P_2. The set of strategies for both are {*X* ,*Y*}. If both players pick *X* or *Y* discretely during the play of a game, then their strategies are called pure and the equilibrium in such a case is called pure strategy Nash Equilibrium. However, in some situations players don't always play with pure strategies. For example if the game shown in the Table 2-4 is repeated for multiple times, it is possible that in some stages of the game, the players might decide to randomize their strategies by picking multiple strategies from their strategies set with some probabilities. By definition, a game is called of mixed strategy when the players randomize their moves over the set of pure strategies and the outcome of the game is called mixed strategy Nash Equilibrium [15]. Let us assume that player P_1 picks *X* with a probability of 0.7 times and *Y* with a probability of 0.3 times. It is assumed that player P_2 play with pure strategies, either *X* or *Y*. For this game, the player P_1 will have an expected *payoff* for playing *X* or *Y* in terms of player P_1 's randomization. *i.e*:

Expected payoff of P_2 *f*or playing *X*= $[(2 \text{ x } 0.7) + (2 \text{ x } 0.3) = 2]$and for playing *Y*= $[(3 \text{ x } 0.7) + (1 \text{ x } 0.3) = 2]$.

Table 2-4: Mixed Strategy Equilibrium Example

		P_2: *X*	P_2: *Y*
P_1	*X(probability=0.7)*	***(2, 2)***	***(1, 3)***
P_1	*Y(probability=0.3)*	***(4, 2)***	***(0, 1)***

The mixed strategies are normally used in the repeated games where players know the history of each other's preference over the strategy set. There might be situation that a player play with mixed strategy when he is indifferent towards his all pure strategies or when the game is of a pure guess or when the players can guess the next move of each other [1]. There might be a situation for a player to play with mixed strategies, when the strategies available to it are not dominated by each other in his own set of choices. There might be the situations where a pure strategy game does not converge to the Nash Equilibrium. The mixed strategy games always have a Nash Equilibrium solution.

In order to calculate the expected utilities in mixed strategies applied by the players of the Battle of the Sexes game, lets assume that the women want to go to music and football events equally likely as shown in the Table 2-5. For this assumption, let the husband want to randomize his move over his pure strategies by 1/3 and 2/3 *i.e.,* he will want 1/3 of the time to go to music event and 2/3 of the time to go to the football event. The expected utilities of wife in terms of the mixed strategies of her husband can be calculated as follows:

$$E(U)_F^W = (Football, \varphi) = [(\varphi * payoff_F^W) + (1 - \varphi) * payoff_F^W] \quad (2.4)$$

$$E(U)_M^W = (Music, \varphi) = [(\varphi * payoff_M^W) + (1 - \varphi) * payoff_M^W] \quad (2.5)$$

Where $E(U)_M^W$ is the expected value of wife's payoff when the husband is going to the music event 1/3(φ) times in the game. Similarly $E(U)_F^W$ is the expected payoff of wife when the husband is going (1- φ) times to the football match. $payoff_M^W$ is the wife payoff in pure strategies when her husband is opting for music event. Similarly, the wife can also randomize her moves over her pure strategies and husband can derive his expected value of utility from the game of mixed strategies.

Table 2-5: Battle of the Sexes game

		Wife	
		Football(1/3)	*Music(2/3)*
Husband	*Football(2/3)*	***(3,1)***	***(0,0)***
	Music (1/3)	***(0,0)***	***(1,3)***

2.4 Classification of Games

Depending on the player's knowledge about each other's strategies, payoffs, and past histories; games can be subdivided into different categories. Depending upon the number of players, a game can be classified as 2-player game or n-players where n>2. Depending upon the cooperation level, information available and the occurring of moves of the individual players the games can be broadly categorized as follows.

2.4.1 Non-Cooperative and Cooperative Games

In non-cooperative games, each participant player acts in his own interest and the unit of analysis is always the individual player instead of group of players. In these types of games, the players are always selfish – *i.e.,* they always try to increase their own individual payoffs without taking care of other player's payoffs in the game. So, non-cooperative game theory studies the competitive nature of individual players where players come into contact with the sole aim to increase their own benefits from the strategic situation [16].

In cooperative games, the groups of players are the unit of analysis and the players tend to increase their group payoffs as well as their own. A cooperative game can be considered as a competition among the groups in a game rather than individual players. The applications of cooperative game theoretical models are in the situations where players form groups, called coalitions, and the individual or group of player's contribution towards the game depends on the actions of other agents in the game [17].

Most of the problems in Telecommunication Systems have been modelled as non-cooperative games, where each node is considered to be a selfish self maximizer without taking care of the benefit of other nodes in a conflicting situation. However, there are some studies where the coalitions games have been modelled to study the individual nodes behaviour in a network each contributing to a coalition [17].

2.4.2 Sequential and Simultaneous Move Games

Those games where the players take their decisions sequentially are called sequential move or extensive games. The basic characteristic of these games is that the players are aware about the strategies of other players and the moves are observable. The sequential move games involve strategic interaction where there is a very strict order of play and the players take turns during making their decisions. Each player has the knowledge about the decision of a player who moves ahead of him. Such games require strategic interaction in terms of a player's current move effects on the future move and this adds to help every player to calculate his current strategy. The game of chess is an example of sequential move games. These games are solved with decision tree or game tree. The sequential games can be one shot or repeated [18].

In the simultaneous or strategic move games, players are unaware of the other player's strategies ahead of time and the moves are simultaneous in that sense. The information about other players selection of a strategy over his strategy profile is not known to other players but it is assumed that the list of the strategies might be known. In these type of games each player thinks strategically not only about their own best response but also the best responses of other players in the game. Normally, the simultaneous move games are represented by the *game matrix* or *payoff matrix*. Prisoner's Dilemma and the Battle of the Sexes are the example of simultaneous move games.

2.4.3 Zero-Sum and Non-Zero Sum Games

A game is called Zero-Sum where the total payoffs of all the players are equal to zero at the end of the game. These are the games which present the total win-total loss of players in a game. These are strictly competitive games where the player's interaction is in complete conflict. Many games are Zero-Sum *e.g.,* in all sport games; one team or individual's win (+1) is the loss (-1) of the other team or individual. In the Non-Zero sum game, every player gets some share of the total benefit or some loss at the end of the game. There is no total loss and the competition is not that much strict as that of the Zero-Sum games. The basic difference between these two games is that in Zero-Sum games, the players have no common interests and in Non-Zero-Sum games, players have conflicting and sometimes common interests. These types of games are very common in most economic activities and trading.

2.4.4 Games with Perfect and Imperfect Information

When each player knows exactly about all the decision of other players during his turn, the type of game is called a game with complete information. For example, all the sequential games are games of complete information. In other cases, when there is no information about other players past strategies then the game is called of imperfect information. All simultaneous move games are games of imperfect information. For example the games presented in the Sections 2.2.1 and 2.2.2 (The Prisoner's Dilemma and the Battle of the Sexes) are the games of imperfect information.

2.4.5 Games with Complete and Incomplete Information

When all the factors of the game are the common knowledge to all the participant players, such games are called games with complete information. The information in the game is symmetric and each player equally knows about other player's strategies and payoffs associated with those strategies in these players prospective. The complete information games are perfectly competitive and the moves of the players are extremely strategic and calculated. The games where the knowledge of players regarding each other strategies and payoffs is limited are called games of incomplete information. These games can further be categorized as games of symmetric incomplete information or games of asymmetric incomplete information [19]. In the symmetric incomplete information, the absence of knowledge is equal for all the players. For example, in a sealed bid auction all players are equally unaware about the strategies of other players and the outcome associated with each. In the case of asymmetric incomplete information, some players know more than the other players. This knowledge or asymmetric information can be used by the possessive player as a threat or ultimatum to the other players of the game for his own advantage. For example, in the game of poker each player has only partial knowledge about the cards held by the other players.

2.4.6 Rationality in Games

One of the important factors in the games is the assumption of rationality of the players. A player is called rational if he tries to maximize his payoff from the game as high as possible. The idea of expected value maximization was first justified by Von Neumann and Morgenstern [4] in their work in 1944. In terms of human behaviour, rationality does not mean that a player is selfish and always self maximizer. For example humans can rate highly the well being of others and incorporating this high rating in his own payoffs [17]. For reasoning purposes, human seldom use the propositional calculus, which concerns truth functions of propositions *i.e.,* the logical truths [18]. The assumption of rational behaviour in the prospective of selfishness is perfectly justified in the computing and communication systems where the devices can be programmed to act in a certain way.

2.5 Evolutionary Games

The pioneering work of Von Neumann and Morgenstern in classical game theory is based on the rationality of all individual players. This assumption, however, when made in presence of novice players who have no prior necessary experience to choose their best strategies, can lead to unpredictable equilibrium. The concept of evolutionary game theory was first introduced by John Maynard Smith and George R. Price in 1973 [20-21], whose argument was based on the pure biological evolution. Their work accommodates the novice players, where they can improve their strategies in non-cooperative evolutionary games with learning and observing others in multiple stages. In evolutionary games, the non-cooperative games concepts are re-defined in the light of biological evolution. The players are not assumed to be rational maximizers but each come with a strategy which is pre-programmed [18]. Just like genetic evolution, those strategies with whom players get better payoffs multiply faster and those who earn less payoffs decline. This mechanism of growth and decay in biology is controlled by genes through reproduction process, while in other systems; the players get the same mechanism in social or cultural context. These types of games have attracted scientists from different backgrounds including economists, biologists, and sociologists. The reason behind the popularity of this very idea is that the rationality assumptions as made in evolutionary game models are more appropriate in the social and cultural context [20].

2.6 Applications of Game Theory in Communication Systems

Almost all the communication systems follow some standards, *e.g.*, the Internet architecture follows the popular TCP/IP (Transmission Control Protocol/Internet Protocol) [22] protocol suits where all the involved network entities are assumed to follow the rules of the protocol in exact order. However, the cooperation to follow a certain protocol cannot be taken as for granted. Since devices are built by different vendors and it is quite possible that some manufacturers design their network devices such that they behave selfishly by deviating from the standard protocol, while other devices adhere to the same set of rules in the same network. This selfish behaviour enables the individual devices to maximize their own performance in the shared network resource pool at the cost of others [23]. There is also the possibility that the end users of these devices program them in a selfish way. This maximization of one’s own benefit in a communication system at the cost of other users is called selfishness in the game theory. There are two approaches to cope with this selfish behaviour in otherwise cooperative communication system. First, there are studies which provide some incentives and punishment mechanisms to force these selfish entities for cooperation. The misbehaviour can also be modelled as a trust mechanism where only those entities in the network are served who cooperate [24, 25]. The other approach to tackle this behaviour is found in the non-cooperative game theory. This theory gives a perfect match and aims to solve the selfish behaviour of the individual entities in a network by outlining rules of the game, which are same for all the participant agents. By not following these rules of the game, saying generally, no network entity can do better while others are following the same set of rules. This gives a huge advantage to address the non-cooperative behaviour as for as telecommunication systems are concerned. The use of non-cooperative game theoretic models is not new and a huge amount of literature can be found at different protocol layers and for different telecommunication systems. There is a huge amount of work on the access mechanisms, which tries to solve the non-cooperative behaviour of nodes during accessing the shared medium with the game theoretic approaches [26]. The routing layer problems have been solved in many contexts, initially taking the concept of the application of non-cooperative game theory in transportation system and then extending the same findings to the network routing [27]. Thus, the aim of applying the game theoretic models for routing solves the path finding problem, where routing and resource allocation problems have been solved as a joint game formulation. The non-cooperative routing games aim to solve the ‘path’ problem where a path is the route established inside a network from a source to destination, both aim to maximize the route benefit for themselves and compete with other source, destination pairs in the network. The flow routing games across Multi-Radio Multi-Channel WMNs have been modelled by

[42, 43]. The problems at transport layer have been addressed in many research findings [28], where the behaviour of TCP protocol has been fully analyzed and solutions from the non-cooperative game theory have been provided to solve the congestion problem in the selfish environment. There is a huge interest in studying the cognitive radio networks with the help of non-cooperative game theory [29-32]. Since cognitive networks consist of primary and secondary users, the spectrum access mechanism is designed with a game outlining the rules to maximize the spectrum utilization as well as the user's personal *payoffs*.

Several telecommunication problems have been addressed in studies where the mechanisms are being developed based on the models from cooperative game theory. The studies of [24-25], address the issues concerning the physical layer of the protocol stack using cooperative game theory. The network layer issues have been addressed in the work of [25], while congestion control cooperative games have been studied by [33-34]. Comparatively, designing cooperative games in a large system like Internet and other scalable networks faces many challenges ranging from efficiency, complexity and fairness among the individual users. The fundamental role of the cooperation among the entities of a network and their effect on the overall system performance has been reported in most recent studies. This basis of cooperative communication can be traced back to the work of [35], who have introduced the relay channel cooperation games. Recently the work of [36, 37] have used the idea of cooperative communications and proposed models based on the cooperative strategies by the network entities. Similarly, in [38, 39] the authors have proven that the use of cooperation can increase the energy efficiency in wireless ad-hoc networks. However, these studies assume that the network users cooperate and forward the packets for others in the network at the expense of their own energy consumption. In the emerging networks, which are distributed in nature and not being in the authority of single organization; this assumption cannot hold. For example, Mobile Ad-hoc Networks (MANETs) [40] and Wireless Mesh Networks (WMNs) [41] are extremely decentralized, auto-configured and the nature of resource is very distributed. In such environment, the assumption of cooperation may not be valid. The increased capability of re-programmability of wireless devices offers another threat to this assumption. It is, therefore, important that the issues in networks like WMNs and MANETs should be addressed by using the concepts from non-cooperative game theory. Chapters 4 and 5 of this thesis are the application of non-cooperative game theory in a strategic wireless network setup. These chapters present the game theoretic models to assess the selfishness posed by the individual nodes during their flow routing and channel assignment to their nodes.

2.7 Summary

This chapter presents a detailed study of game theory and the associated concepts. The classification of games based on the information, rules, moves and rationality has been discussed. The two famous games in the literature of game theory, Prisoner's Dilemma and the Battle of the Sexes have been investigated in detail with the associated concepts of pure and mixed strategies. Nash Equilibrium along with *Pareto Efficiency* has been covered in detail along with their properties. Finally, the chapter gives an insight to the use of game theory in the problems of telecommunication both from cooperative and non-cooperative perspectives.

2.8 References:

[1] M. J. Osborne, An Introduction to Game Theory. Oxford University Press New York, NY, 2004.

[2] G. Owen, “Game Theory”, London, UK: Academic Press, 3rd edition, October 1995.

[3] D. Fudenberg and J. Tirole, “Game Theory”, MIT Press, 1983.

[4] J. von Neumann and O. Morgenstern, “Theory of Games and Economic Behavior”, Princeton University Press, 1944.

[5] J. Von Neumann, O. Morgenstern, A. Rubinstein and H. W. Kuhn, Theory of Games and Economic Behavior. Princeton Univ Pr, 2007.

[6] J. McDonald, Strategy in Poker, Business and War. WW Norton & Company, 1996.

[7] J. Nash, “Non-Cooperative Games”, Second series, vol. 54, No. 2, pp. 286-295, 1951.

[8] R. D. Luce and H. Raiffa, Games and Decisions: Introduction and Critical Survey. Dover Pubns, 1989.

[9] R. D. Luce and H. Raiffa, "Game and decisions," 1957.

[10] J. C. Harsanyi, "Games with incomplete information played by" bayesian" players, i-iii. part i. the basic model," Management Science, pp. 159-182, 1967.

[11] Prisoner's Dilemma, Stanford encyclopaedia of Philosophy, Available online at; http://plato.stanford.edu/entries/prisoner-dilemma/ [Accessed January, 2012].

[12] A. Rapoport and M. Chammah, “Prisoner’s dilemma: a study in conflict and cooperation”, The University of Michigan Press, Second edition, 1970.

[13] D. Fudenberg and J. Tirole, “Game Theory”, MIT Press, 1983.

[14] W. David, K. Yeung, and L. A. Petrosyan, “Cooperative Stochastic Differential Games”, Springer Series in Operations Research and Financial Engineering, 2004.

[15] I. K. Geçkil and P. L. Anderson, Applied Game Theory and Strategic Behavior. Chapman & Hall/CRC, 2010.

[16] E. E. C. Damme, "Non-cooperative games," Discussion Paper, 2000.

[17] R. J. Aumann and J. H. Dreze, "Cooperative games with coalition structures," International Journal of Game Theory, vol. 3, pp. 217-237, 1974.

[18] J. Friedman (Ed.), “The Rational Choice Controversy”, Yale University Press, 1996.

[19] A. K. Dixit, S. Skeath and D. H. Reiley, Games of Strategy. Norton New York, 1999.

[20] J.M. Smith, “Evolution and the Theory of Games”, Cambridge University Press, 1982.

[21] Hofbauer, "From Nash and Brown to Maynard Smith: equilibria, dynamics and ESS," Selection, vol. 1, pp. 81-88, 2001.

[22] W. R. Stevens, TCP/IP Illustrated: The Protocols. Addison-Wesley Professional, 1994.

[23] A. Urpi, M. Bonuccelli and S. Giordano, "Modelling cooperation in mobile ad hoc networks: a formal description of selfishness," 2003.

[24] Z. Han and K.J. Liu, “Resource Allocation for Wireless Networks: Basics, Techniques, and Applications”, New York, USA: Cambridge University Press, 2008.

[25] T. Alpcan and T. Basar, “A Globally Stable Adaptive Congestion Control Scheme for Internet-Style Networks with Delay”, IEEE/ACM Trans. On Networking, vol. 13, pp. 1261–1274, Dec. 2005.

[26] L. Chen, S. H. Low and J. C. Doyle, "Random access game and medium access control design," IEEE/ACM Transactions on Networking (TON), vol. 18, pp. 1303-1316, 2010.

[27] E. Altman, T. Boulogne, R. El-Azouzi, T. Jimenez and L. Wynter, "A survey on networking games in telecommunications," Comput. Oper. Res., vol. 33, pp. 286-311, 2006.

[28] T. Alpcan and T. Basar, "A game-theoretic framework for congestion control in general topology networks (I)," in IEEE Conference On Decision and Control, Maui, USA, pp. 1218-1224, 2002.

[29] D. Niyato and E. Hossain, "Competitive pricing for spectrum sharing in cognitive radio networks: Dynamic game, inefficiency of nash equilibrium, and collusion," Selected Areas in Communications, IEEE Journal on, vol. 26, pp. 192-202, 2008.

[30] N. Nie and C. Comaniciu, "Adaptive channel allocation spectrum etiquette for cognitive radio networks," Mobile Networks and Applications, vol. 11, pp. 779-797, 2006.

[31] D. Niyato and E. Hossain, "Competitive spectrum sharing in cognitive radio networks: a dynamic game approach," Wireless Communications, IEEE Transactions on, vol. 7, pp. 2651-2660, 2008.

[32] B. Wang, Y. Wu and K. Liu, "Game theory for cognitive radio networks: An overview," Computer Networks, vol. 54, pp. 2537-2561, 2010.

[33] S. Floyd and K. Fall, "Promoting the use of end-to-end congestion control in the Internet," IEEE/ACM Transactions on Networking (TON), vol. 7, pp. 458-472, 1999.

[34] F. Kelly, "Fairness and stability of end-to-end congestion control," European Journal of Control, vol. 9, pp. 159-176, 2003.

[35] T. Basar and G. J. Olsder, "Dynamic Noncooperative Game Theory", Philadelphia, PA, USA: SIAM Series in Classics in Applied Mathematics, Jan. 1999.

[36] T. Alpcan, T. Basar, R. Srikant, and E. Altman, "CDMA Uplink Power Control as A Noncooperative Game", Wireless Networks, vol. 8, pp. 659–670, 2002.

[37] A. MacKenzie, L. DaSilva, and W. Tranter, "Game Theory for Wireless Engineers", Morgan&Claypool Publishers, March 2006.

[38] R. Thrall, and W. Lucas, "N-person Games in Partition Function Form", Naval Research Logistics Quarterly, vol. 10, pp. 281–298, 1963.

[39] T. Basar and G. J. Olsder, "Dynamic Noncooperative Game Theory", Philadelphia, PA, USA: SIAM Series in Classics in Applied Mathematics, Jan. 1999.

[40] S. Giordano, "Mobile ad hoc networks," Handbook of Wireless Networks and Mobile Computing, pp. 325-346, 2002.

[41] I. F. Akyildiz and X. Wang, "Wireless Mesh Networks." John Wiley & Sons Inc, 2009.

[42] I. Shah, Sadaqat Jan, Kok-Keong Loo, "Selfish Flow Games in Non-Cooperative Multi-Radio Multi-Channel Wireless Mesh Networks in Interference constrained topology ", International Journal of Advances in Telecommunications. Volume 4, Number 2. issn: 1942-2601 , 2011

[43] I. Shah, S Jan, K-K Loo, "Selfish Flow Games in Non-Cooperative Multi-Radio Multi-Channel Wireless Mesh Networks With Imperfect Information", The Sixth

International Conference on Wireless and Mobile Communications (ICWMC), Valencia, Spain, Pages: 219 – 225, Print ISBN: 978-1-4244-8021-0, , Year of Publication:2010

CHAPTER 3

Channel Assignment and QoS Routing in Co-operative Wireless Mesh Networks

3.1 Introduction

The Multiple-Radio capability, and their assignment to the multiple non-overlapping channels, makes Wireless Mesh Networks (WMNs) as one of the prime candidate to be deployed as the future wireless broadband access technology. The WMNs are characterized by the self-organizing, self-healing, dynamic and distributed architecture, where the backbone routers are relatively static. On the other hand, WMNs are facing the same inherited problems of capacity limitations and interference being in the category of multi-hop wireless networks. First, the multi-hop nature of its routers put an upper bound on the end-to-end data rate achievements. Secondly, the interference phenomenon needs to be seriously considered while developing any protocol for such types of networks. Support for providing the Quality of Service (QoS) to the recent broadband applications like Voice over IP (VoIP), Video Conferencing and Online Games is one of the essential requirements from the access technologies. These QoS in the form of delays and bandwidth must not be compromised and should be guaranteed for the smooth functioning of the network. If channel assignment is one of the deterministic parameter in improving the capacity of the network by minimizing the interference and providing communication parallelism among the multiple radios of the neighbouring nodes, routing plays an equally important role by providing the guaranteed end-to-end path selection based on some required metric. Both these issues are interdependent and hence affect each other.

In this chapter, a joint routing and channel assignment scheme for the WMNs has been developed, where the channel assignment scheme tries to minimize the interference of the network while ensuring the connectivity. Routing, on the other hand, provides an end-to -end guaranteed path based on the end users' delay requirements. A MANET routing protocol, called Ad-hoc On Demand Distance Vector (AODV) [25], has been extended to make it Multi-Radio Multi-Channel (MRMC) compatible and to provide an end-to-end path to the end users ensuring the maximum tolerable delays guarantees. The decision of end-to-end route selection between a pair of source-destination nodes is taken based on the end users requirements and the capabilities match of each individual link with those requirements. Experimental results show that the proposed scheme achieves low network latency, high throughput and low routing overheads in the network.

3.2 Wireless Mesh Networks-An overview

Wireless networks have been evolved with time to cope with the ever increasing end users demands in terms of data rate, scalability, reach-ability, mobility and ease of use. The recent advancements in wireless network access technologies have provided a platform of ubiquitous communication for multiple types of data including voice, multimedia and other web-based applications. However, the scale-ability and data rate of wireless networks are constrained due to the wireless nature of medium and the availability of finite spectrum [1].

Wireless Mesh Networks (WMNs) [2-5], a key technology in the wireless access, have emerged recently to provide on the go connectivity to the end users. WMNs are dynamic multi-hope networks having the capabilities of self organization and self configuration. Conceptually, WMNs have been evolved from Mobile Ad-hoc Networks (MANETs) [3] and thus inherit the forwarding and self configuration capabilities from them. WMNs consist of two main components *i.e.*, Mesh Points (MPs) and Mesh Clients (MCs). While MPs are the wireless routers interconnected to one another in a multi-hop fashion to form what is called the mesh backbone, end users MCs typically consist of the client machines accessing Internet through the mesh backbone with wired or wireless medium. Depending upon the location and functionalities of MPs in WMNs, they are further divided into three categories [3]. Those mesh routers which give connectivity to the end users are called Mesh Access Points (MAPs) and are usually located at the user premises. Those mesh routers inside the WMNs backbone which are responsible for forwarding the MCs data to/from the Internet are called Mesh Points (MPs). There are some backbone routers, called Gateways, which provide connectivity between WMNs backhaul and the Internet through wired medium. In the Figure 3-1, a WMN is shown, where some MCs are connected to the MAPs and the traffic is forwarded by the MPs to the Gateways. Gateways in turn play the role of an exit/entrance door for the data traffic from and to the Internet to/from the WMNs.

WMNs are a promising technology to provide broadband wireless connectivity in the user premises [6] due to their rich resources and fixed wireless routers, having stable power supplies. The multi-hop capability results in a scalable solution for otherwise limited ranged networks. These networks are highly resilient as failure of some nodes has no effect on the connectivity of end users and overall network at large. The always connected and robust

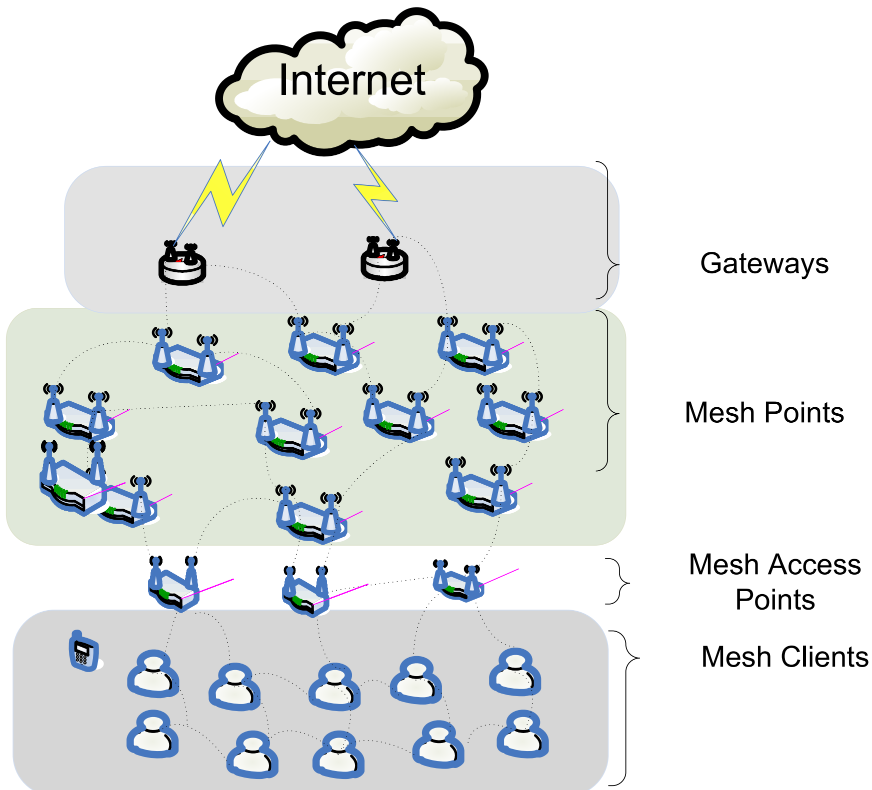


Figure 3-1: A Wireless Mesh Network

nature of WMNs qualifies it to be deployed as future broadband wireless solution in the user premises. Due to the advantages of WMNs, IEEE has established subgroups to include mesh capability in their existing standards like IEEE 802.11s for Wireless Local Area Networks (WLANs), IEEE 802.15.5 for Wireless Personnel Area Networks (WPANs) and IEEE

802.16e for Wireless Metropolitan Area Networks (WMANs) [7, 52]. Many commercial products are also available in market for the deployment [8, 9] and vendors like Motorola, Nokia and Mesh Dynamics have implemented practical WMNs topologies [10, 11, 12]. The work presented in this thesis is related to the IEEE 802.11 based WMNs. WMNs can be divided into three broad categories based on their architecture [13].

1. **Flat Mesh:** In Flat WMNs, all the nodes connect to each other in a peer-to-peer fashion. Just like MANETs, all nodes function as forwarding relays as well as clients as shown in the Figure 3-2. This type of meshing can be achieved inside homes and offices and is constrained by the scalability issue.

2. **Hierarchical Mesh:** In these types of WMNs, components of the network are divided into different tiers. The Mesh Clients, forming tier1 of the networks, are connected to the Mesh Access Points to get Internet access. In tier2, Mesh Points form the backbone of the network to facilitate the forwarding of data from/to the Mesh Clients as shown in the Figure 3-1. Besides forwarding facility, they can also provide the bridging facility to give connectivity to clients having different access technologies. In tier3, the Gateway routers are located and their only functionality is to give a wired connectivity between wireless mesh backbone and the Internet.

3. **Hybrid Mesh:** These types of WMNs are the combination of both Flat and Hierarchical Mesh. The MCs can also connect with each other in an Ad-hoc manner.

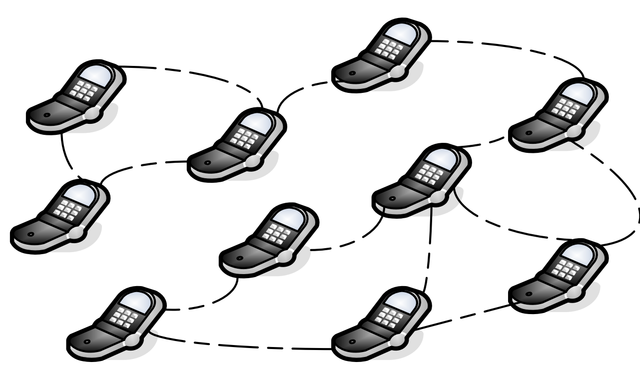


Figure 3-2: A Flat Wireless Mesh Network

Since the 802.11 based WMNs historically evolved from the traditional Wireless Local Area Networks (WLANs) [7] and inherited the advantages of MANETs, therefore it is necessary to clarify the difference between WMNs, MANETs and WLANs. WLANs are the type of wireless networks where clients, called Stations (STAs), are connected through a single router called Access Point (AP). AP is further connected to the Internet through a wired connection. The surrounding area served by an AP including STAs is called a Basic Service Set (BSS). These types of networks are used inside homes and offices for wireless connectivity and give roaming facility to the users within the limited coverage area. MANETs are special type of networks where nodes, having moderate to high mobility, serve as data generation point as well as relays to forward other node's data. These types of networks are deployed on ad-hoc basis in emergency situations like earthquake and military operations. In the Table 3-1, these three types of networks are compared in terms of their capabilities [13].

Table 3-1: WLAN, MANETs and WMNs comparison

	WLAN	MANETs	WMNs
Topology	Static	Dynamic	Relatively static
Mobility of routers	Static	Medium to high mobility	Relatively static
Scale	Office or Home	medium area	Large area/Towns
Infrastructure requirements	Yes	No	Yes
Stable power Supply	Yes	No	Yes
Multi-Radio Multi-Channel capability	Normally no	No	Yes
Relaying capability	No	Yes	Yes

3.2.1 Channel Assignment in Wireless Mesh Networks

In typical WLANs [14] and MANETs [15], based on the IEEE 802.11 a/b/g/n standards [16, 17, 18], all nodes are equipped with a single radio where nodes compete for a single channel across the whole network or collision domain. Keeping in view the higher user demand in a wireless broadband setup and the multi-hop nature of WMNs, a single radio solution is not feasible for implementation. A channel is a band of frequency which can be used by a transmitter and receiver when both simultaneously tune their radios to it. The

IEEE 802.11a and [16] IEEE 802.11 b/g [17] standards define 12 and 3 non-overlapping channels in the Industrial Scientific and Medical (ISM) band, respectively. These non-overlapping channels can be used inside a single collision domain without causing any interference. As shown in the Figure 3-3, a total of 23 channels are available in the 4GHz spectrum for IEEE 802.11b/g out of which only 3 are non-overlapping.

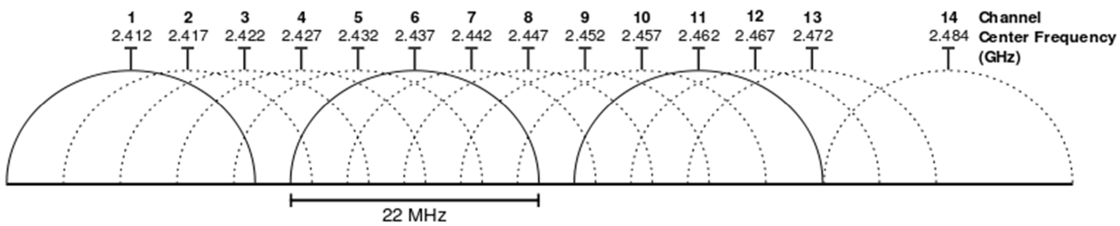


Figure 3-3: Non-overlapping channels in IEEE 802.11b/g

Wireless mesh routers can be equipped with multiple radios due to their static nature and the existence of permanent power supplies. Since multiple channels are available in the free ISM 2.4 and 5 GHz bands, multiple radios can be tuned simultaneously to exploit the free non-overlapping channels and hence increase the overall capacity, connectivity and resilience of the wireless mesh backhaul. Due to these characteristics, WMNs is a prime candidate to be implemented as a broadband wireless access network in the user premises.

Multi-Radio Multi-Channel (MRMC) capabilities in Wireless Mesh Networks can enormously increase backhaul connectivity, network throughput and fault tolerance as simultaneous transmissions can be achieved through multiple radios tuned to non-overlapping channels with minimum degree of interference. To illustrate the effectiveness of MRMC phenomenon in WMNS, consider the example given in the Figure 3-4. Figure 3-4(a) shows six nodes residing in the same collision (interference) domain and communicating with each other in a set of three sessions. Each node is equipped with a single radio and it is assumed that a single channel is available to all pair of nodes for communication. Two nodes can communicate only if they are in each other's transmission ranges and their radios have been assigned the same channel. As can be seen, communication between nodes (A – B, C – D, E

– F) is established by tuning their respective radios to channel C_1 in times t_1, t_2, t_3 respectively. This is an example of Single-Radio, Single-Channel (SRSC) and is widely applied to 802.11 based MANETs and WLANs. In the Figure 3-4(b), each node is equipped with a single radio, parallel communication session is achieved by tuning each set of radios to multiple orthogonal channels (C_1, C_2, C_3) at time t_1. In this example of Single-Radio, Multiple-Channel (SRMC) [19], theoretical throughput increases by 3 times effectively as compared to SRSC. If each node is equipped with multiple radios, the system throughput and connectivity can be further increased by intelligently tuning their radios to the multiple available channels as shown in the Figure 3-4(c), where nodes D and F are equipped with two interfaces. Given the set of non-overlapping channels C= {C_1, C_2,….., $C_{|C|}$}, tuning the multiple radios of mesh routers to these non-overlapping channels across multiple collision domain is called Multi-Radio, Multi-Channel(MRMC) [20] assignment.

There are two approaches for channel assignment, static and dynamic. In static channel assignment schemes, channels are assigned once and forever to the interfaces/radios of the nodes. This type of assignment is simple but it has the cost of non-conforming with the dynamics of the network. In a dynamic channel assignment, the channel assignment changes with the change in network dynamics or the user's requirements. This channel assignment has the cost in the form of overhead it generates for managing the channel assignment/re-assignment based on the traffic demands or network conditions.

The third type of channel assignment problem studied in the literature is hybrid channel assignment, where some of the interfaces are assigned permanent channels based on their traffic characteristics while other nodes channel assignment is done in a dynamic fashion [21]. This approach reaps the advantages of both static channel assignment and dynamic channel assignment schemes.

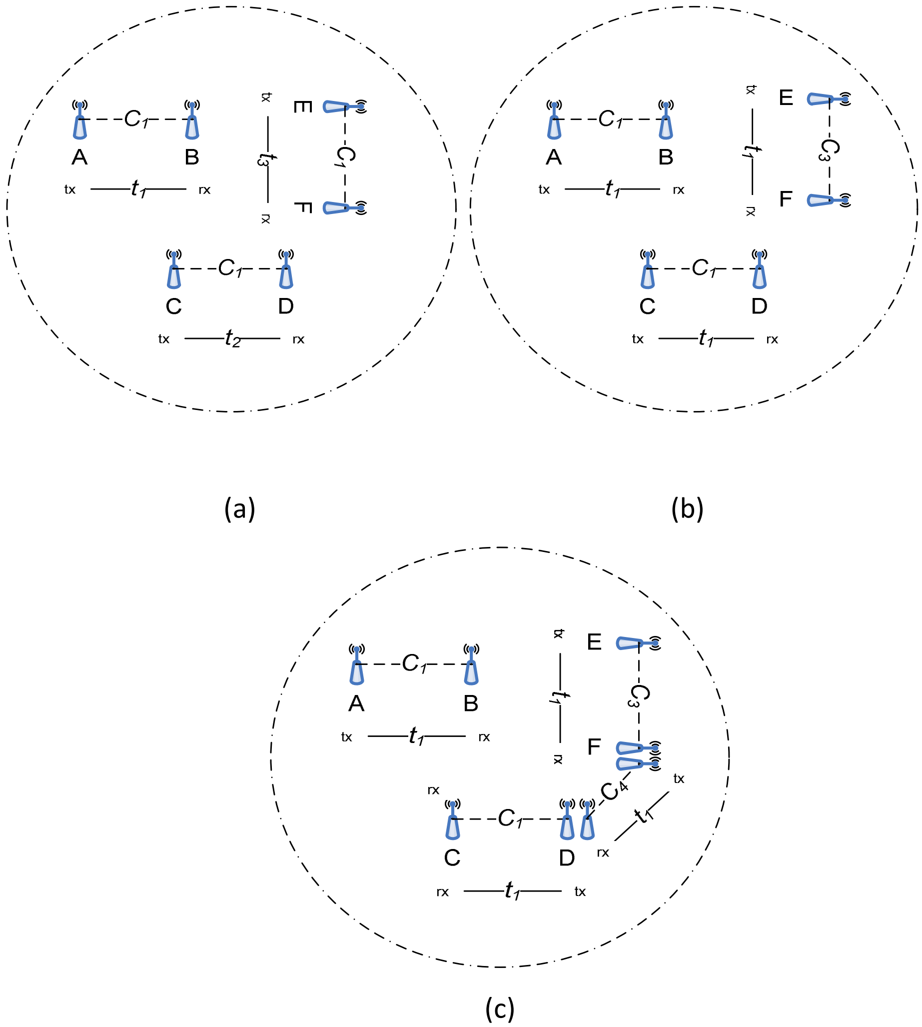


Figure 3-4: (a) SRSC (b) SRMC (c) MRMC

Channel assignment can also be categorized as centralized and distributed. In centralized approaches [20], a central node runs the channel assignment algorithm and other nodes are only informed of the resultant channel assignment matrix as to which channel should be used between which pair of nodes in the entire network. While in distributed channel assignment schemes, the channel assignment is performed by all the nodes independently with coordination with other nodes. Centralized channel assignment schemes have the advantages of being simple at the cost of single point of failure. Further, full knowledge of the entire network topology is needed. Distributed channel assignment has the advantages of being efficient but costs more control traffic to the network.

3.2.2 Routing in Wireless Mesh Networks

While channel assignment is one of the fundamental issues of MRMC-WMNs [3], routing, too, has its impact on the network performance. On one hand, channel assignment scheme in WMNs assigns channels to the node's radios/links, while on the other hand; routing determines the end-to-end path from source to destination and transverses these individual channels assigned to the end-to-end path links. Although routing is fundamentally the Network layer functionality while channel assignment is performed at the Medium Access Control (MAC) layer, both these issues are interdependent. A channel assignment can be affected by the routing due to the ups and downs in the load on specific channels assigned to links, similarly two different channel assignments in the same network can result in different end-to-end paths for the same routing protocol [22]. This interdependency between the two has motivated the research community to solve this problem jointly. Combining routing and channel assignment needs more cross layer information exchange between the two mentioned layers in the case of MRMC WMNs.

Broadly, routing protocols can be categorized into two classes, *i.e.,* proactive or table driven and reactive or on-demand. The main difference between these two classes of protocols is how the routing information is maintained by the individual nodes. Routing determines the end-to-end path from a source node to a destination node. In the case of proactive routing protocols, each node maintains routing tables and periodically updates them. These routing tables on each node contain fresh routes to all other nodes in the network. Thus each node knows the path to all other nodes in the network. The advantage is fast response time at the expense of high routing overhead. In MANETs, Optimized Link State Routing (OLSR) [23] and Destination Sequenced Distance Vector (DSDV) [24] belong to this class of routing protocols. In the case of reactive routing protocols, each node need not to maintain the routing information. These protocols are called on-demand as the routing path is determined from source to the destination prior to data session, whenever they are needed. AODV [25] and Dynamic Source Routing (DSR) [26] belong to this class of routing protocols.

3.3 Related Work

Channel assignment has been studied widely for cellular communication systems [21], where various schemes have been proposed. With the emergence of WMNs and its capability of supporting multiple radios at its routers, MRMC has been a hot research topic since 2004. Since a MRMC scheme affects the network interference level, connectivity, scalability, throughput, routing, latency and fairness, therefore considerable research has been conducted in this area for the last few years. Similarly, routing and MRMC assignment are studied as a combined problem in various studies.

The centralized channel assignment problem based on graph theory has been studied by [27, 28, 29, 30], where network topology has been considered as a graph G (V, E) [31] where V and E, the set of vertices and edges in graph, show the set of nodes and links of the wireless network interconnecting these nodes respectively. Marina *et al.* [27] proposed an algorithm which assigns channels to nodes according to priority by applying the depth-first searching technique over the network graph. The proposed algorithm has the disadvantage of being greedy in some aspects and fairness in channel assignment is compromised. Tang *et al.* [28] further extended this work by including weights in the link matrix of the network topology, thus capturing the interference in some way. The main requirement of this scheme is an equal number of radios on each node and it provides strong connectivity than [28]. In [29], the authors have formulated channel assignment as coloring the conflict graph with the aim of minimizing the total interference in the whole network. In [30], the authors modeled MRMC problem as Multi-Radio Conflict Graph (MR-CG) for the first time, to truly capture the multi-radio concept in graph theoretical analysis. Their formulation has two main objectives*, i.e.*, calculation of interference inside the backbone (internal interference) and external interference from the sources outside the network.

A set of other centralized schemes formulate the channel assignment problem based on the network flows [32, 33, 34]. In all these approaches, the network flow, in the form of end-to-end or on each link, is assumed to be known to the channel assignment algorithm in advance. This global link load information is further fed to the centralized scheme for channel assignment. Raniwala *et al.* [32] considered a centralized load aware channel assignment with routing in MRMC WMNs. They have solved the channel assignment problem first followed by routing with a greedy heuristic. Their centralized algorithm first measures the flow on each link by using heuristics and then assign channels accordingly, taking gateways of the WMNs as the starting reference point. Kodialam *et al*. [33] have solved channel assignment in WMNs by considering it as a joint problem with routing and scheduling. The authors in [34] solved flow based channel assignment along with routing as a joint problem by using the concept from linear programming. All the flow based centralized channel assignment schemes assume a constant traffic flow which is not always the case in bursty or un-predictable networks. Further, the basic flaw associated with the centralized schemes is the failure of the central operation point responsible for channel assignment, which could lead to the whole system's standstill.

In distributed algorithms, the pioneering work of Raniwala *et al.* [22] solves channel assignment and routing as a combined problem. They have proposed a WMNs architecture called "Hyacinth", which assumes the presence of gateway/gateways in the WMNs backbone. The solution provided is gateway centric and the merit of this scheme is it's adaptation to the varying load inside the network. This scheme performs routing in the first stage followed by the channel assignment. The channel assignment is guided by the routing, where load on each link is measured and channels are assigned appropriately. The architecture presents a parent-child relationship among the nodes of WMNs. Gateways are considered as the initial root/parent of all the other nodes in the network and this relationship goes down till the MAPs. Only the parents can assign channels to the downward children nodes. The disadvantage of this scheme is the long time it takes to assign channels to the new nodes which join the network. The second drawback in this work is the parent-child relationship in the nodes of the network. If a parent node in the network fails, all the children are isolated from the mesh topology. Das *et al.* [35] proposed DMesh, where the authors have proposed the use of directional antennas. Their solution is identical to that of [22], inheriting the same parent-child relationship during the channel assignment. The limitation of this scheme is the manual setup of directional antennas in a specific focus during deployment and this setup is unchangeable. The work of Xing *et al.* [36] is based on the superimposed codes theory, where the channels are assigned to nodes in distributed manner. Each node computes the superimposed code and assigns channels to the interfaces according to its own interference constraint. The limitation of this scheme is its scalability, which is constrained by the number of nodes in the network. To further improve their mechanism, the authors have proposed partition of the whole network into different cells. In [37], the authors have proposed a joint channel allocation and congestion control mechanisms. In [38], the authors have addressed topology control and channel assignment. At the network start up, the network nodes are grouped together in clusters and the channel assignment is run in the next phase. The intra-cluster connectivity is provided by a default common channel.

Kyasanur *et al*. [39] have proposed channel assignment based on the probabilistic usage of each channel by each radio. They divide the whole set of radios into two groups *i.e.,* static/non-switchable and dynamic/switchable. Their channel assignment algorithm switches the static radios only at periodic manner while the dynamic radios are switched from one channel to another with the variation of traffic demand.

Joint routing and channel assignment algorithms have been studied in [22, 32, 33, 34, 40, 41, 42], where both problems have been solved together. Although, QoS has not been considered explicitly as a source- destination performance measure in their design, all these studies try to provide a solution having minimum interference in the network or high throughput and high connectivity. In [22, 32], the authors have addressed the problem by considering routing first and in second phase assign channels iteratively to the links based on the network load information. The authors in [41] have solved the routing and channel assignment problem by splitting the large optimization problem into small manageable sub-problems. The feasible solution is obtained after independently solving the sub-problems. The work of Bononi *et al.* [26] presents a multipath routing solution by splitting the flow at different paths while minimizing the interference. Their solution obtains the load balancing across the mesh backhaul routes. Rad *et* al. [42] have solved the joint routing and channel assignment problem by considering it as a linear mixed integer problem and cross layer information is used to compute the routes and assign channels to the paths accordingly. All the above cited research has tackled the QoS indirectly by considering the flow information.

However, no bounds for the QoS parameter have been considered in their work as for as the end-to-end applications demands are concerned.

The problem of QoS based routing for MANETs has been considered by [43, 44, 45], where routing is performed without channel assignment. Each approach has devised specific route metric for the selection of best end-to-end path. For designing the routing metrics for WMNs, Campista *et al.* [46] have discussed the key performance parameters.

A QoS based routing and channel assignment scheme is proposed by Bakhshi *et al.* [47], where the authors perform routing in the network according to their pre-defined routing metric and then assign channels according to the end users demands. Their provided solution is dynamic but centralized.

In this chapter, we propose a dynamic and distributed QoS based routing and channel assignment scheme in MRMC WMNs keeping in view the end users demands. To the best of our knowledge, all the studies till now have ignored the mobility of the backbone WMNs routers by considering them as always static. Further, the channel assignment scheme presented in this chapter captures the mobility of the WMNs backbone routers and efficiently re-assigns channels to them at their new locations.

3.4 System Model

An infrastructure based hierarchical WMN is considered where the Mesh Clients, consisting of end users, access the Internet via Mesh Backbone as shown in the Figure 3-1, Section 3.2. There is always some data at the Mesh Clients or at the server connected to the gateways, which have some QoS demands in terms of end-to-end network delays. The application scenarios of WMNs are always in the form of data travelling to or from the Mesh Clients towards the gateways. This means that the QoS provided on an end-to-end path must be bi-directional. For instance, consider the example given in the Figure 3-5, where node A wants to send some data to node B on path $P_{a\text{-}b}$. Let $\alpha_{a\text{-}b}$ be the maximum delay node A's data can tolerate, on-end-to end path $P_{a\text{-}b}$, where the total path delay is the cumulative delays of individual links. If $\alpha_{a\text{-}b}>=9$ units, the path is feasible for the said application. However, delays on bi-directional links are not the same from both sides. For example, it is possible that node A data experience one type of delay while sending it to node c; on the opposite c might experience different delay when sending some data to node A on the same link.

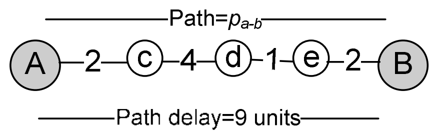


Figure 3-5: End-to-end delay example

Generally, for a path $P_{a\text{-}b}$ in the multi-hop network, the end-to-end delay is given by:

$$Path\_Delay = \sum_{i=1}^{|l|} l^{i}_{delay} \tag{3.1}$$

Where l^{i}_{delay} is the delay associated with the i^{th} link across the path.

Let S={S_1,S_2,S_3,….., $S_{|S|}$} be the set of source nodes requesting for some delay sensitive data like a request from the network to find a route to a video conferencing application or a VoIP server. Let D= {D_1, D_2, D_3, …., $D_{|D|}$} be the set of destination nodes in the network. In the case of WMNs the (S_i, D_i) is always the (end user nodes, gateways) or (gateways, end user nodes). Lets each (S_i, D_i) have some data to send across the WMNs backbone through a path $P_{S\text{-}D}$ with the some delay constraint. Since WMNs consist of multi-hop routers spreading across multiple collision domains and each router is equipped with multiple radios deployed to multiple channels; therefore, there are multiple routes possible for this data to transport from the source to the destination. The routing function is to select such a route across these multiple collision domains so that the delay constraint imposed by the (source, destination) is satisfied.

A channel assignment scheme based on minimum interference is proposed to achieve the above objective. Secondly, a reactive routing protocol is extended for MRMC WMNs which achieves the minimum requirements set by the end users applications. Both routing and channel assignment are inter-dependent as channel assignment scheme affects the routing decisions on each node; and the load due to the already established connections by the routing decisions triggers the channel re-assignment.

3.5 QoS based Channel Assignment and Routing

We consider an 802.11 based WMNs, where each mesh router is equipped with *K* multiple radios/IEEE 802.11 compatible network interfaces. The topology of the network is considered relatively static and only a few routers are able to move in the whole network. Multiple orthogonal channels, *C*, (12 or 3) are available to each node as according to the IEEE 8021.11 a/b/g standards. All the routers, afterwards called nodes, have equal transmission capabilities. This means that all the radios of the nodes belong to the same technology *i.e.,* either IEEE 802.11a or IEEE 802.11 b/g. Similarly all the radios have the same transmission and interference ranges as defined in these standards. A node can assign only one radio to a specific channel. This is necessary because assigning the same channel to two different radios of a specific node causes co-channel interference [48]. The aim of the channel assignment scheme is to assign channels from the channel set *C* to each link connecting two radios of a pair of nodes in the mesh backbone such that the interference is minimized.

3.5.1 Channel Assignment

We follow the protocol model [1] for developing the proposed channel assignment and routing scheme. The channel assignment model consists of the following sub-modules, where the interference is minimized using a similar concept as in [36].

1. Initialization and channel assignment
2. Channel/link Assessment and Neighbors Monitoring
3. Channel Re-Assignment

3.5.2 Initialization and Channel Assignment

This module assigns multiple non-overlapping channels from the set C to the multiple radios set K of the nodes. The aim of channel assignment is to produce a network topology inside the WMNs backbone so that each link gets a channel causing minimum interference and the backbone is highly connected. In this work, it is assumed for simulation purposes that the channel assignment process is initiated at the gateways. Our assumption is based on one of the basic characteristic of WMNs data traffic which travels from MAPs all the way towards the gateways. This assumption is made in all gateways oriented channel assignment protocols [22, 32, 35]. However, the algorithm is flexible enough that the starting point can be any mesh router in the mesh backbone. It is assumed that there is no prior channel assignment inside the backbone and all the radios of all nodes listen to arbitrary channels for broadcast messages. Broadcast messages are special type of messages as defined in IEEE 802.11 standard, where the destination address is set to all 1's. Any node *N* in the WMNs backbone can initiate the channel assignment process by sending a special channel assignment request in the form of CH_{Req} frame. The first field of this frame is set to broadcast address so that all the neighboring nodes listen to it. The second field is the MAC address of source node which initiated the CH_{Req} frame. The third field is the Request Type which shows the type of the frame used in the proposed channel assignment protocol. Six types of frames are used in the proposed model. CH_{Req}, CH_{Reply}, CH_{Usage}, $CH_{UsageReply}$, CH_{Ack} and *Hello*, each having its own code in the Channel Type field, as shown in the Figure 3-6. The fourth field of CH_{Req} is 4 bits long showing the number of channels available to the system. Four bits are sufficient to cover all the non-overlapping channels in the IEEE 802.11 standards. However, the fourth field of the $CH_{UsageReply}$ packet consists of 26 bits, where each two bits are used to show the usage of a channel by the replying node. Upon listening the CH_{Req} broadcast, all the neighboring nodes reply with a CH_{Reply} frame in a unicast manner, setting those channel fields where this node has assigned its radios before, with the value of 1, if no prior channel is assigned by the replying node, this field is set to zero accordingly. CH_{Reply} frame has exactly the same fields as that of CH_{Req} but with the last field having 26 bits as shown in the Figure 3-6. Each 2 consecutive bits in the last filed of CH_{Req} represents the number of channels the replying node maintains in it's Neighboring Channel Usage (NCU) table. Upon receiving the CH_{Reply} frame, the initiating node *N* assigns channels to its radios according to the following rules.

1. Assign among those channels which are not already been assigned to one of the initiating node own radios. This is necessary to avoid the co-channel interference on the initiating node.
2. Assign a channel to each interface while applying rule 1 in neighbors prospective. This will ensure to avoid the co-channel interference on the

neighboring nodes. For this, initiating node looks at the channels already been assigned by the sending nodes to their interfaces.

3. Initiating node *N* assigns those channels to the interfaces which cause least interference to it by looking at the Neighbor's Channel Usage (NCU) list.
4. If all channels under consideration cause same level of interference to initiating node *N*, send a unicast message to each neighboring node requesting for their NCU lists. Assign channels to each specific interface, causing least interference to the specific neighboring node.
5. If neighboring nodes NCUs have a tie, assign channels to each interface arbitrarily keeping rules 1 and 2 in view.

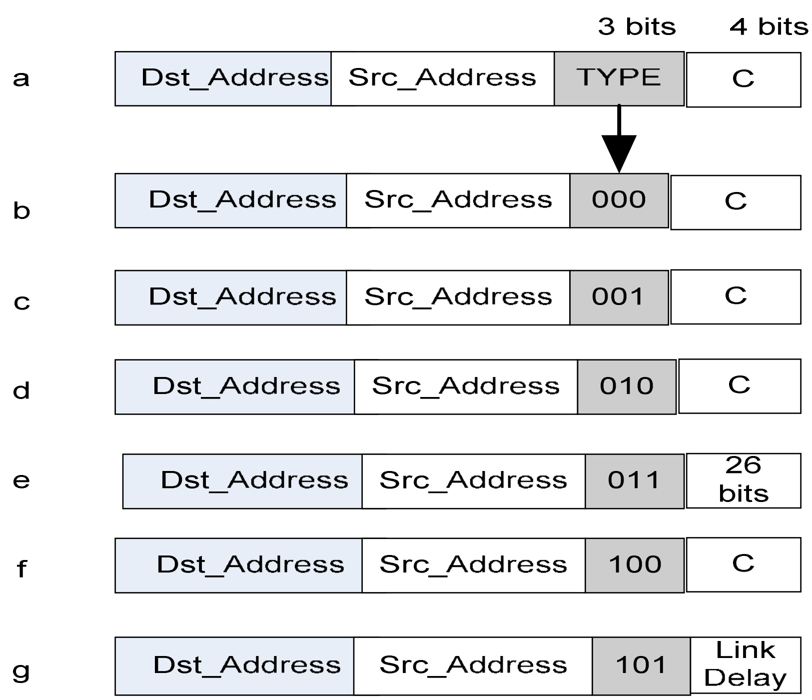


Figure 3-6: (a) Generic MRMC frame type (b) CH_{Req} (c) CH_{Reply} (d) CH_{Usage} (e) $CH_{UsageReply}$ (f) CH_{Ack} (g) Hello

An example channel assignment is shown in the Figure 3-7. Five non-overlapping channels are available to the system and node 'a' initiates the channel assignment process by broadcasting the CH_{Req} frame to all of it neighbors nodes 1, 2, 3 and 4, as shown in the Figure 3-7(a). When these nodes receive the CH_{Req} frame, each unicasts the CH_{Reply} frame to the initiating node, on the channel on which it has received the CH_{Req} broadcast. In the Figure 3-7(c), node 'a' assigns channels to its neighbors according to rules 1-5. Those nodes upon channel assignment to at least one of their interfaces, repeat the process for their neighbors, as shown in the Figure 3-7(d).

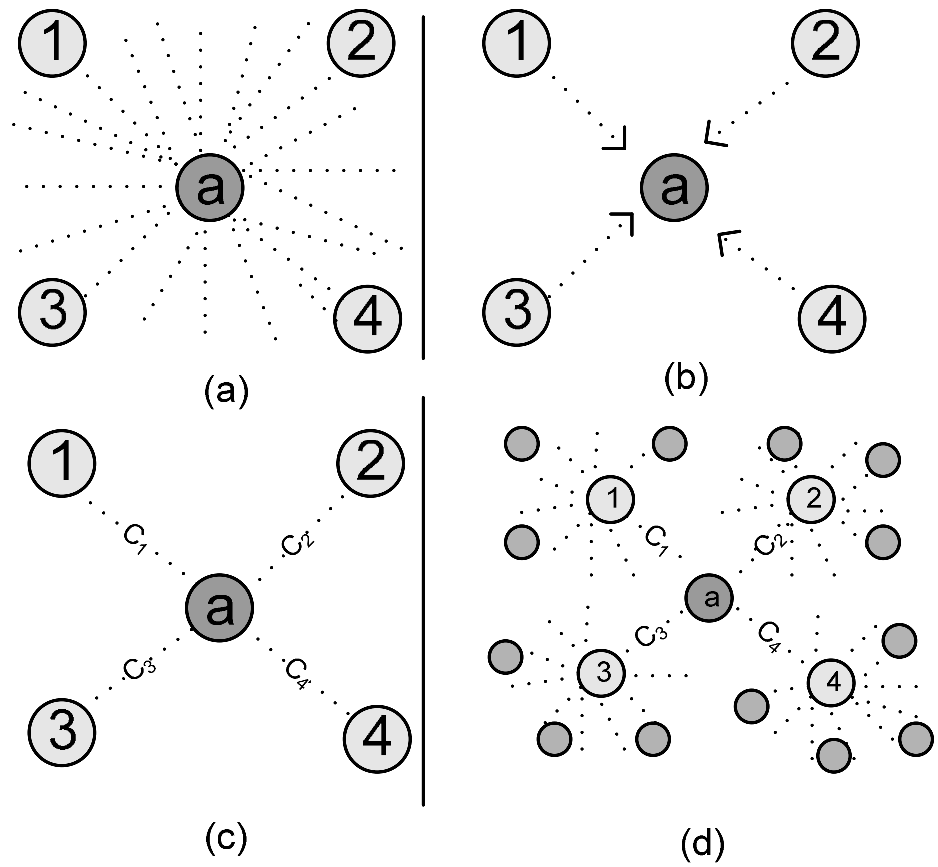


Figure 3-7: An example channel assignment

Each node keeps the record of channel usage in two separate tables. The first one is of its own interfaces and the channels assigned to each. This table, called the Channel Usage Table, contains the information of each interface of the current node *N*, channels assigned to each interface and the MAC addresses of other neighboring nodes to which this current node *N* is connected through these specific interfaces. Table 3-2 shows the Channel Usage

Table for a node *N* where the first column in the table shows the interfaces/radios {inf_1, inf_2, …, inf_n} of the node N. The second column of the Table 3-2 shows the MAC addresses of the neighboring nodes to which it is connected through its interface (inf_i) in the corresponding previous column. The next columns shows which channel is used by the node N for its connection to the corresponding neighboring node. The second table is called Neighboring Channel Usage (NCU) table. As shown in the Table 3-3, the table shows node *N*'s NCU for all its neighbors and their channels they have assigned to their interfaces. First column shows the node number/MAC address and the corresponding columns show the channel usage of each neighboring node on each channel. The rank of a channel is calculated by the node *N* as the number of interfaces assigned to *C* by all its neighbors, accordingly. Information required for rule 1 is available to node *N* from its own Channel Usage Table. For rule 2, the initiating node gets the information from the NCU to avoid the co-channel interference on the neighboring nodes. The information in NCU is also used to calculate the rank of each channel usage by node *N* in its neighborhood and it selects a channel according to rule 3 causing least interference to node *N*.

Table 3-2: An example Channel Usage Table

Node MAC	Neighbors /MAC	Ch_1	Ch_2	Ch_3	… …	Ch_n
Inf_1	1	1	0	0	…. .	0
Inf_2	2	0	1	0	…. .	0
…	…	…	….	….	…	…
inf_n	x	0	0	0	….	1

Table 3-3: An example Neighbouring Channel Usage (NCU) table at node N for all its neighbours {1, 2, 3…, x}

Node/MAC	Ch_1	Ch_2	Ch_3	……	Ch_n
1	1	1	0	…..	0
2	0	1	1	…..	0
…	…	….	….	…	…
x	1	0	0	….	1
Channel Rank	2	2	1	…	1

If all the channels are of the same rank, it means that all cause the same level of interference to the initiating node *N* and therefore it sends a CH_{Usage} frame to each neighbor and requests their NCUs. All neighboring nodes reply with a $CH_{UsageReply}$ frame containing theirs NCUs ranks for each channel. The channels are assigned to each interface according to the ranks of each channel in the neighboring node's NCUs. This last step reduces the chances of interference for the neighbor nodes.

Once the initiating node *N* assigns channels to all of its interfaces, it sends the last frame called CH_{Ack} to all its neighbors which contains the channel usage of the current node *N*. All the neighboring nodes update their NCUs for the initiating node *N*, accordingly. All the neighbors of the initiating node *N* further repeat the above procedure to assign channels to their remaining interfaces in stages. This process continues till all the nodes in the network have assigned channels to all of their interfaces. The proposed algorithm can be initiated by any node of the WMNs network and multiple nodes can start the same process simultaneously. Once a node *N* has assigned channels to all its interfaces, it does not listen to further broadcast CH_{Req} frames. The channel re-assignment is triggered in two cases. First, if a neighboring node fails and second, if the set routing threshold is not met by all the interfaces of a specific node. This will be explained further in the Section 3.5.4.

3.5.2.1 Channel Assessment and Neighbours Monitoring

When each node assigns channels to all of its radios/interfaces, they switch to the monitoring state. Monitoring state is the state in which each node frequently monitors the channel usage status of all its interfaces. Each node also monitors the status of all its neighbors, whether they are alive or not, through the exchange of *Hello* messages. The *Hello* messages, as shown in the Figure 3-6(g), are also used to update the link delay by the nodes they are connected through. This is necessary because the link delay on a bi-directional link is different from both nodes prospective. A greater delay in the *Hello* message replaces the smaller one on both nodes. Monitoring the link status is needed to calculate the metric for the QoS based routing later on, as discussed in the Section 3.5.3, where the decision of selecting an end-to-end path is made based on the individual links quality in the path.

Each node, in the monitoring state, maintains and frequently updates a table called the Channel State Table. This table, as shown in the Table 3-4, contains information about the quality of the individual bi-directional links between each pair of nodes sharing a common channel, and has four parameters *i.e.,* Average Queue Length, Average MAC layer *backoffs*, Transmission rate and Average Lost packets retransmission time. Average Queue Length is the average taken over specific period of time of the MAC layer's queue associated with the interface of a node. This parameter indicates how much a single application layer packet has to wait in the queue of the interface. Average MAC layer *backoff* is the average value taken over specific times for the number of successful transmitted packet. Transmission time/rate is the number of bits a node's interface can transmit over a medium in per unit time. This value depends on the physical layer modulation techniques and the width of frequency called bandwidth. The Lost packet retransmission is the time it takes for retransmission of lost packets in a given number of packets transmitted over a link.

Table 3-4: Links Quality State Table on each node

MAC address	$Q_{av_{length}}(bits)$	$\delta_{av}(seconds)$	$Tx_{rate}(\frac{bits}{s})$	α_{av} $(Seconds)$
Inf_0	X	Y	Z	a
Inf_1	X	Y	Z	b
--	--	--	--	c
Inf_n	X	Y	Z	e

The QoS parameter for the proposed routing protocol is defined in terms of links delays expected to be experienced by a single application packet, when it is routed over the end-to-end path consisting of individual bi-directional links. The delay sensitive applications like video or audio should have an end-to-end delay guarantees from the network. The information provided by the channel monitoring module is available to the network layer as shown in the Figure 3-8. Delay of an end-to-end path in an 802.11 based WMNs depends on many parameters. Since IEEE 802.11 is a shared wireless medium and even in MRMC there is always a chance that a given channel *C*, assigned to a link connecting two radios, is also assigned to another link in the same transmission or interference ranges. This makes each radio to follow the access mechanism for the wireless medium called Distributed

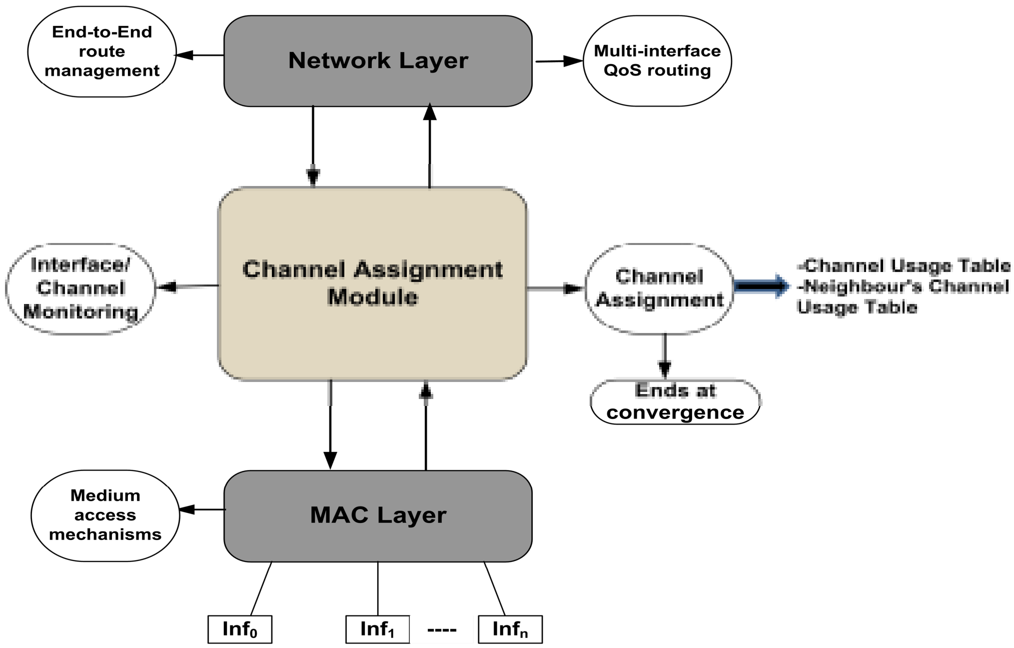


Figure 3-8: Cross layer information for link monitoring and routing decisions

Coordination Function (DCF) in IEEE 802.11 literature [16, 17, 18]. The *backoff time* in DCF system, in which a transmitting system goes into the idle state, increases exponentially with each lost frames. Even with DCF arbitration for the shared medium, there is always a chance of losing packets on the wireless medium. This parameter is captured in terms of packet loss ratio and is accurately calculated. The lost packet ratio is the number of lost packets *x* in a given number of transmitted packets *y*. In IEEE 802.11, those packets are considered lost for which the transmitting MAC does not receive an acknowledgement. Lets a node sends *y* number of packets on one of its interface, say inf_0, in which x packets are lost, the expected retransmission time for one lost packet is calculated as:

$$\alpha_{av} = \left(\frac{x/y}{Tx_{rate}}\right) \quad (3.2)$$

This delay information is captured in the parameter α_{av} and is averaged over time. Similarly, there is a limit on the medium and radio capability to transmit at some bounded rates. Each node calculates this average transmission rate (Tx_{rate}) for each of its link associated with each of its radio and shows the number of bits transmitted over a link per unit time. Transmission rate value is calculated from the link queue. This whole information is fed to the total delay which is supposed to be experienced by a single packet to be considered for forwarding through a specific interface's link.

$$T_{delay} = \left(\delta_{av} + \partial_{app} * T_{per\_bit} + \alpha_{av}\right) \quad (3.3)$$

Where T_{per_bit} is calculated as follows:

$$T_{per\_bit} = \frac{Q_{av\_length}}{Tx_{rate}} \quad (3.4)$$

∂_{app} is the MAC layer frame size in bits and the variable δ_{av} in the Equation (3.3) represents the average *backoff* on the specified interface, where the expected δ_{av} for a single packet is calculated as follows. Let the backoff incurred over a link during m successful transmitted frames be n, then the expected backoff for one packet (δ_{av}) is calculated as:

$$\delta_{av} = \frac{m}{n}\ seconds \quad (3.5)$$

The total delay calculation for a single packet is maintained in a separate table associated with each interface of a node. As shown in the Figure 3.9, node B is connected to node A through interface0 (inf_0) where channel C_2 is assigned to their shared link. Similarly, it is connected to node C through interface1 (inf_1) with C_1 assigned to their common link. The figure shows the delays calculations for each individual links. This delay information is updated in a bi-directional manner through the periodic *Hello* message exchange. If delay *x* Milliseconds maintained by node B for B-C link is less than the delay it received from node C for the same link in the periodic *Hello* message, x will be replaced with the new delay for the same link. All nodes update this delay information for the bi-directional links in a similar way.

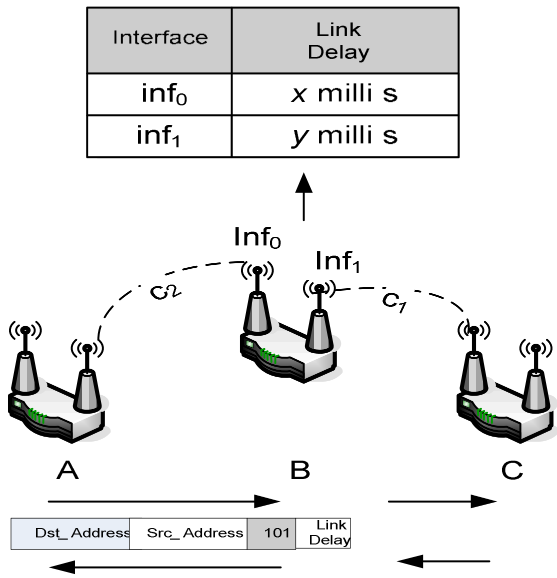


Figure 3-9: "Hello" Message exchange for delay updates and neighbour's monitoring

3.5.3 QoS Based Routing

Quality of Service (QoS) is the provisioning of some guarantees by the network to the end users in terms of a set of performance parameters like delay, jitter, bandwidth and packet loss [46]. Since routing determines the end-to-end path for each source-destination pair in a network, therefore, it is one of the important design factors to be considered in providing these QoS guarantees to the end users. In MANETs, all the standard routing protocols have explicitly ignored this important issue. Since MANETs are emergency networks and extremely mobile, QoS provision is very difficult task to be achieved on an end-to- end basis. The main factor in deciding the QoS is the routing metric, *i.e.,* the parameter or set of parameters based on which the routing decisions take place. Almost all MANETs routing protocols use minimum hop count as the only metric and the shortest path is considered as the best path. While minimum hop count is a best metric in networks where reach-ability is the only concern, the end users of WMNs put some constraints other than mere reaching to the destination.

QoS of the end users is considered as a prime parameter in the proposed joint routing and channel assignment scheme. The MANETs AODV protocol has been used as a base for developing the routing protocol in the proposed solution. However, AODV has the some shortcomings when used in its original form in the WMNs. First, it is based on network level flooding to forward a route request, thus creating a lot of extra overhead packets. For example, for a network of *N* nodes and for finding a single path between any source and destination, a total of (*N*-1) route request packets are flooded in the entire network. Second, there is no defined metric for routes selection in the AODV and thus QoS can't be supported explicitly. Although, AODV prefers the shortest paths, but shortest paths can be worst in providing the QoS as compared to the longest ones in the wireless networks. Third, AODV only supports Single-Radio Single-Channel MAC architecture, while WMNs routers are equipped with Multiple-Radios operating on multiple non-overlapping channels.

AODV works as follows. For a pair of Source-Destination (*S, D*), S broadcasts the requests to its neighbours for a route to *D* with RREQ packet. It is on demand in the sense that requests are only sent by the source node, whenever it needs to have connection with the destination for sending some data. All the neighbours of *S* rebroadcast this route request to their neighbours and the process continues until it reaches either the intended destination or an intermediate node, which have updated route to the destination *D*, Destination Sequence Number field along with Destination IP address in the RREQ packet is used in the later case. Intermediate nodes avoid duplicate RREQ reception by dropping them if the Originator IP and RREQ ID of the current message is matched with the one maintained by it for the previous RREQ packet. Upon reaching the destination, a unicast RREP packet is sent back to the neighbouring node through which it received the first RREQ packet. All next RREQs for the same requests are dropped by the destination. Routes in AODV are maintained through route error (RERR) messages. If a source node moves, it reinitiates the route to the destination. If an intermediate node along the path moves, the neighbour nodes notice this and inform sender node of this failure by sending back the RERR message.

A WMNs backbone can be exposed to two types of data as for as its end users are concerned, one which has a bound on some QoS parameters; for example video and audio applications are extremely delay sensitive and if these requirements are not met, it can severely affect users perception and the quality. The other category of applications which do not need any specific requirements can be considered as best effort as for as the network bandwidth and delay requirements are concerned. Providing of QoS in WMNs is essential as its deployment forecast in the future wireless broadband access technology.

Similarly, we divide the applications for the proposed MRMC routing scheme into two categories. One, which has some bounds on the QoS of end-to-end path and others which is best effort and do not need any services from the underlying network in terms of delays and bandwidth *e.g.,* FTP, HTTP and other delay insensitive applications.

The AODV extension in the proposed solution is called Quality of Service based Multi-Radio multi channel capable AODV (QMR-AODV). In the simple AODV and Multi-Radio AODV (AODV-MR) [49, 50], the selected end-to-end path does not ensures the QoS requirements and simply establish routes for the requesting users. In the case of AODV-MR [49, 50], multiple radios are deployed on each node and these radios are tuned to the multiple non-overlapping channels as present in the IEEE 802.11a/b/g standards. When a source, S, needs a route to a destination, D, a RREQ is broadcasted by the source node on all of it's interfaces simultaneously. If the RREQ is not a duplicate, each neighbouring node of the source 'S', upon hearing this broadcast, re-broadcasts the RREQ all of its interfaces. This process of broadcasting continues and disseminates in the whole network until the destination is found. It is important to mention that in the case of AODV-MR, those neighbouring nodes which share a common channel hears the broadcast on that channel. Before broadcasting the RREQ, each node maintains the reverse route, which points towards the source node from which this current node has received the RREQ packet. The flooding mechanism, as discussed before, even worsen in AODV-MR as each mesh router now rebroadcasts the RREQ packet on multiple interfaces creating a total of (N-1)x i overhead packets, with an N routers WMNs backbone each having *i* interfaces. Further, there is no QoS provisioning in both these protocols. Generally, the proposed QMR-AODV works as follows. As shown in the Figure 3-10, when an end user wants to establish a connection with the destination (Gateway), it sends the modified RREQ packet. The modified route request packet has four important fields to be considered by the end users as well as the rely routers. As shown in the Figure 3-11, first the D flag, it is set by the route requesting node which needs this RREQ to be replied by the destination only. Thus, a RREQ

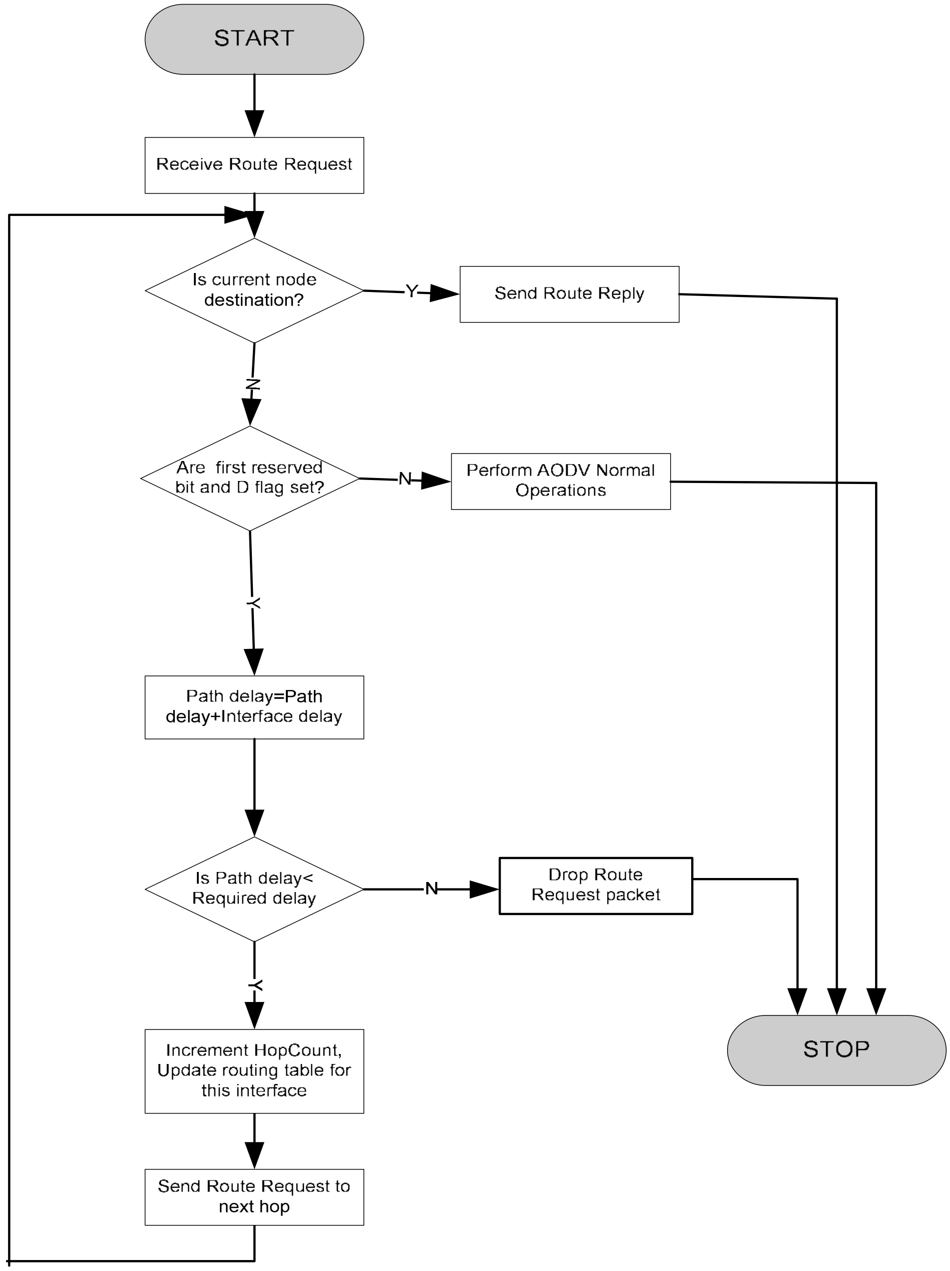


Figure 3-10: The modified RREQ flow of function

with D flag set will never return a path to destination from an intermediate node. This ensures that a path returned by QAODV-MR will always satisfy the end-to-end requirements of user's applications.

```
                              Set=1 in RREQ
 -+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|     Type      |J|R|G|D|U|                     |   Hop Count   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                            RREQ ID                            |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Destination IP Address                     |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Destination Sequence Number                  |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                    Originator IP Address                      |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
|                  Originator Sequence Number                   |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
| User's QoS Bounds                | Total Path  Delay          |
+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+-+
```

Figure 3-11: Modified RREQ packet format

The first bit in the reserved field is either set or zero. If this bit is set by the requesting end user, it is an indication for the intermediate nodes that some specific QoS is required by the source node. The last field of modified RREQ packet is divided into two halves, the first half shows the maximum delay an application can tolerate (User's QoS Bounds) for each of its individual packet on end-to-end basis. The RREQ packet initiator node, based on the application requirements, sets this field by putting the appropriate value of maximum delay, which can be tolerated by the end users application on the end-to-end path requested. The second half of this field, Total Path Delay, shows the cumulated delay of the path from the initiating node to this current node so far. Upon receiving the RREQ packet, the intermediate node (and the destination node if that is the case) first checks the Destination IP address in the REEQ packet. If a match is found between the Destination IP and the IP address of the current node, the RREQ is for a path request to this node and a RREP is unicasted to the initiating node. If the current receiving node is not the destination, then the intermediate node first checks the D flag and the first reserved bit. If both are zero, the request is considered as a normal AODV RREQ and is forwarded over multiple radios/interfaces of the node, as shown in the flowchart of Figure 3-10. If current node is

Algorithm for routing decision on each node

for each node(*n*) on receiving RREQ packet

If RREQ_DEST_IP== NODE_IP //then this node is the destination

Send RREP

else if (**D**=0 and **Reserved**=0)

Forward packet through normal AODV-MR/AODV operations

else // QMR-AODV operations

for i=inf_0 to inf_n

Total_Path_Delay=Total_Path_Delay+ inf_i_delay

If {Total_Path_Delay≤ User's required delay

Hop_Count=Hop_Count+1

Send RREQ to next hop

else

Drop RREQ for inf_i

end if

next i

end if

Figure 3-12: Algorithm for QoS (delay) based on demand routing

not the destination, then all the interfaces of this current node are evaluated for providing the required QoS (delay) as requested by the source node as follows. The intermediate node adds up the delay of bi-directional link associated with the current interface as maintained by the channel monitoring module, discussed in the Section 3.5.2.1. This updated delay associated with the link/channel assigned to the interface of the node under consideration is added up with last 16 bits field, Total Path Delay, and is compared with the User's QoS demanded delay. As shown in the Figure 3-12, if the User's QoS demanded delay bound is less than the one calculated by the current node for it's aspecific interface, the RREQ is dropped for that interface. This means that the current interface's delay added up with the path delay so far cannot guarantee the QoS requirements of the end user application. In this case the RREQ packet is dropped by the node from forwarding at the current interface as shown in the algorithm of the Figure 3-12. Otherwise, Total Path Delay is updated and the RREQ packet is sent to the next hop by this interface. Upon reaching the destination, a RREP packet is unicasted for the first RREQ packet it receive from the one hop neighbour. All other successive RREQs for the same connection are dropped. As shown in the Figure 3-13, the mesh routers B, C, D and H do not forward the RREQ on some of their interfaces simply because the QoS limit set by the end user can't be satisfied. This technique has two fold gain.

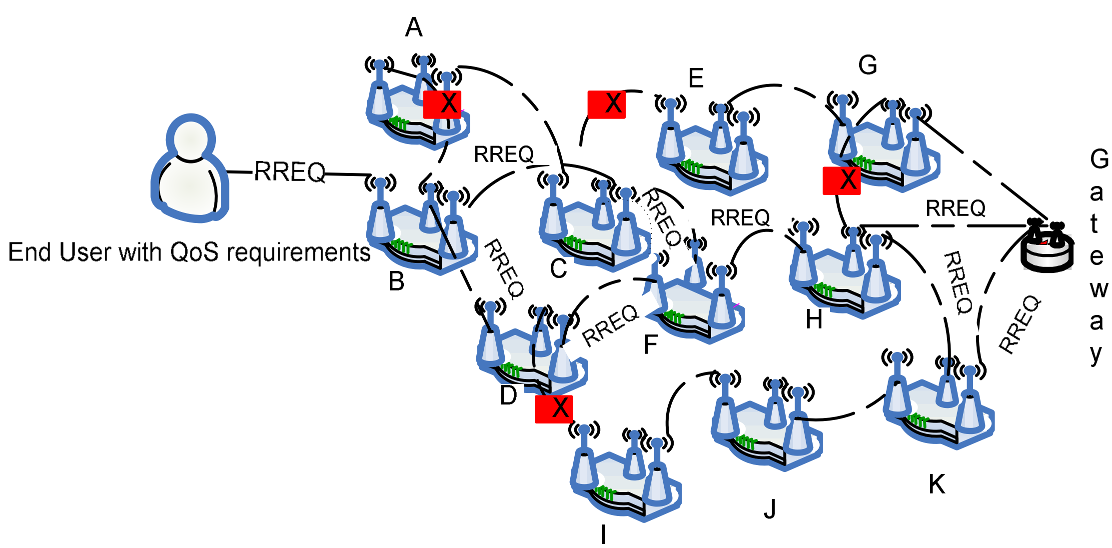


Figure 3-13: RREQ selective forwarding by the WMNs backbone routers

First, the flooding associated with the AODV-MR [49, 50] is reduced from (*N*-1)x*i* to (*N*-1) in the case if only one interface of all the routers in the path is satisfying the QoS requirements. Another advantage is that by setting the D flag in RREQ packet, only the destination is bound to reply the RREP packet. This, combined with the QoS value comparison on each node's interface ensures the requested quality of the end-to-end path.

3.5.4 Channel Re-Assignment

Nodes can fail inside the network backbone and this failure can affect the performance of network in terms of connectivity and throughput. If a channel assignment scheme is not capable to detect the node's failures, the network nodes can go into isolation. For self-configurable networks like WMNs, node failure should be tackled effectively. In the proposed channel assignment and routing scheme, the channel re-assignment is triggered with three events. First, if a node fails with some or all of its interfaces then this node failure is detected by the Channel Assignment module and channel re-assignment is performed in that locality. Although, WMNs have relatively very static topology and the routers are almost fixed, however, in some cases the routers can be mobile *e.g.,* if the routers are integrated from the Vehicular Network infrastructure inside the WMNs backbone, then mobility can be expected. In this case, a node can move from one location to another one due to mobility. This can impact the topology of the network in terms of connectivity. This information should be captured in an efficient way. Third, there might be some cases that all the interfaces of a certain node are not complying with any of the QoS based RREQ from the end users. This latter case can happen, for example, when the channel assigned to a specific node's link is interfering too much with other links in its range.

If a node fails or moves from one location in the backbone to another location, this failure or movement is detected by the neighbouring nodes through the periodic *Hello* messages. Let suppose a node 'a' fails in the example network shown in the Figure 3-15, it means that all of its neighbours will not receive the periodic unicast *Hello* messages from node 'a'. This will mean two possible events. Either the node in the vicinity has failed or it has moved to a location which is no longer in the transmission range of its previous neighbouring nodes. This event triggers the channel re-assignment module.

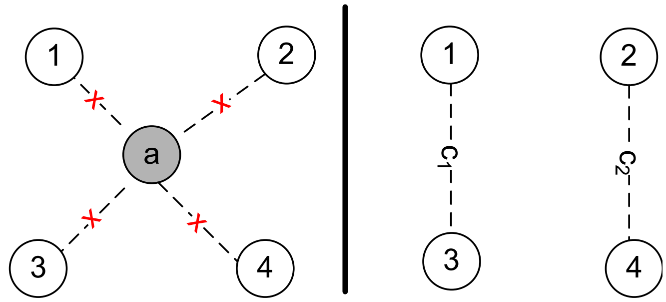


Figure 3-14: Nodes failure and channel reassignment

Each neighbouring node, which had a connection with node 'a', will remove the channel assignment information as mentioned in the Tables 3-2 and 3-3 of Section 3.5.2. In the next phase, the interface on which the neighbouring nodes were connected to node 'a' are available for channel re-assignment. Each neighbouring node of failed node 'a' broadcasts the CH_{Req} frame on all the channels. Any neighbouring node with an interface unassigned to any channel can reply with the CH_{Reply} unicast message. The channel re-assignment is performed in a similar way as mentioned in the Section 3.5.2.

Similarly, if a node 'a' moves from its current location to some other location inside the network backbone, this event is considered the same as node failure by all its neighbours and channel re-assignment is performed as mentioned for node failure. However, the re-located node, when no longer receiving the periodic *Hello* messages from its neighbouring nodes, realizes of its movement and starts broadcasting CH_{Req} messages on all of its interfaces. If there is any node in its neighbourhood (inside the transmission range) having no channel yet assigned to one of its interface, will reply with the CH_{Reply} unicast message. However, it is possible that at the new location there is no node whose interface is available for this new channel re-assignment.

The channel re-assignment can also be triggered by the routing request service threshold configured on each node. If a node rejects all the QoS based RREQ's on all of its interfaces for a certain threshold number of times, the channel re-assignment module triggers. This, however, is performed by the affected node by sending the CH_{Req} unicast messages to all of its neighbours. The requesting node, upon receiving the CH_{Reply} messages from its neighbours re-assigns channels as according to the channel assignment rules mentioned earlier in the Section 3.5.2.

3.6 Simulation Setup and Performance Evaluation

This section presents the performance evaluation of the proposed channel assignment and QMR-AODV routing protocols. Network Simulator-NS2 version 2.34 [51] was used for development and simulation of the proposed model. Four performance metrics, Routing Overhead, Packet Delivery Ratio, Average Network Latency and Response Time, were observed for a set of two different scenarios. Simulation in each scenario was run 20 times each and the average was plotted in each case to build confidence in the observed results.

Routing Overhead: Routing Overhead refers to the number of routing control packets generated inside the network.

Packet Delivery Ratio (PDR): PDR refers to the ratio of the number of packets which succeeded to reach at the destination to those packets which were generated by the end user's applications. *i.e.,*:

PDR= Total Received packets/Total generated packets (3.6)

Average Network Delay: This parameter refers to the total delay occurred inside the network for the data packets. The latency or delay is measured by calculating the time elapsed between the packet generation at the end user's nodes and when they reach at the destinations.

Average Response Time: Average Response Time is the average of time elapsed between each RREQ and when the source node gets the RREP packet.

3.6.1 Simulation Setup for Delay Sensitive Data

In this scenario, a network of 30 mesh routers was deployed in an area of 1000m x1000m in a grid topology with the following parameters as shown in the Figure 3-15. End users Mesh Clients generate Constant Bit Rate (CBR) UDP traffic with some specific delay constraint for each packet. The performance of the proposed scheme is compared with a Multi-Radio AODV (AODV-MR) [49, 50] scheme and comparative analysis is done. All the simulation parameters are given in the Table 3-5.

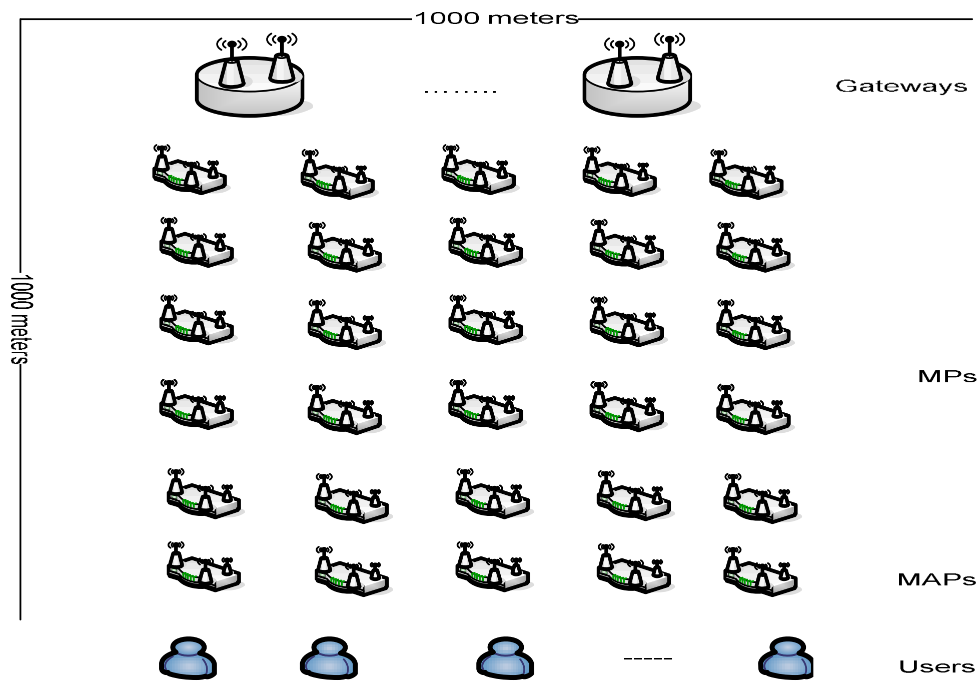


Figure 3-15: Network Deployment

Table 3-5: Simulation Setup

Simulation Parameters	Assigned Values
Topology	Grid
Number of Mesh Routers	30
Number of Interfaces(inf) on each Mesh Router	3
Number of Mesh Clients	45
Medium Access Control (MAC)	IEEE 802.11a
Number of Channels	8
Propagation	TwoRay Ground reflection
Transmission Range	250 meters
Max Interface Queue length	50
Routing Protocols	AODV-MR, QMR-AODV
Mobility Model	None(Static)
Number of flows	Varies (10 to 60)
Packet Size	1000 bytes
Packet generation rate	128 kbps per flow
Simulation time	600 Seconds
Topology covered area	1000x1000 meters
Data Rate	2MB

Routing Overhead:

As shown in the Figure 3-16, both the AODV-MR and QMR-AODV produce almost the same number of routing overhead packets at the beginning. The reason is that for less number of flows, QMR-AODV functions the same as the AODV-MR due to less load and hence less congestion in the networks. Effectively, all the interfaces of intermediate nodes are conforming to the QoS delays bounds of RREQs of the end users applications. Furthermore, when the number of flows increases from the end users, the network gets congested and QMR-AODV outperforms AODV-MR by producing less amount of routing overhead. This is because; QMR-AODV now forwards the RREQ only on those interfaces of the intermediate nodes which are capable to handle the requested delay. On contrary, with increase in the network load, AODV-MR functions the same by broadcasting each RREQ on all of its interfaces except the one on which it was received. This linear increase in the routing overhead is evident from the Figure 3-16 for number of flows 30 and onwards. The AODV-MR produces 24% more routing overhead for 30 flows going up to 36.1% for 60 flows, as compared to QMR-AODV.

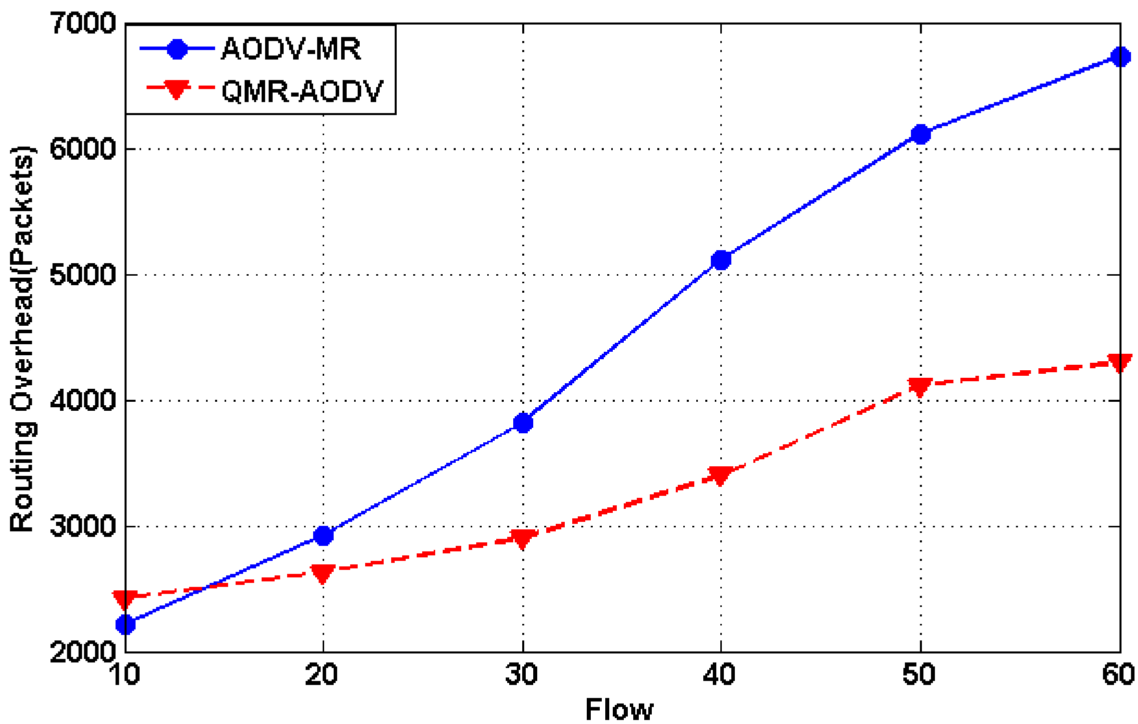


Figure 3-16: Routing Overhead for multiple number of flows

Average Network Delay:

The Average Network Delay of QMR-AODV is compared with AODV-MR for different number of end users generated flows. As shown in the Figure 3-17, QMR-AODV performs better by producing less latency in the network for all its data packets. The prime reason is the QMR-AODV's route selection mechanism based on the delay condition. While AODV-MR selects any route without QoS guarantees and thus the data is stacked on the congested links inside the network. Secondly, AODV-MR broadcasts RREQ messages on all of its interfaces which creates more congestion inside the network and hence more latency. As depicted by the Figure 3-17, the Average Network Delay increases for AODV-MR abruptly with the increase in the end user generated flows while QMR-AODV's latency increases very steadily. Overall, the average network delay for AODV-MR increases from 40.4% to 55.89% for traffic profiles 10 flows to 60 flows, comparatively.

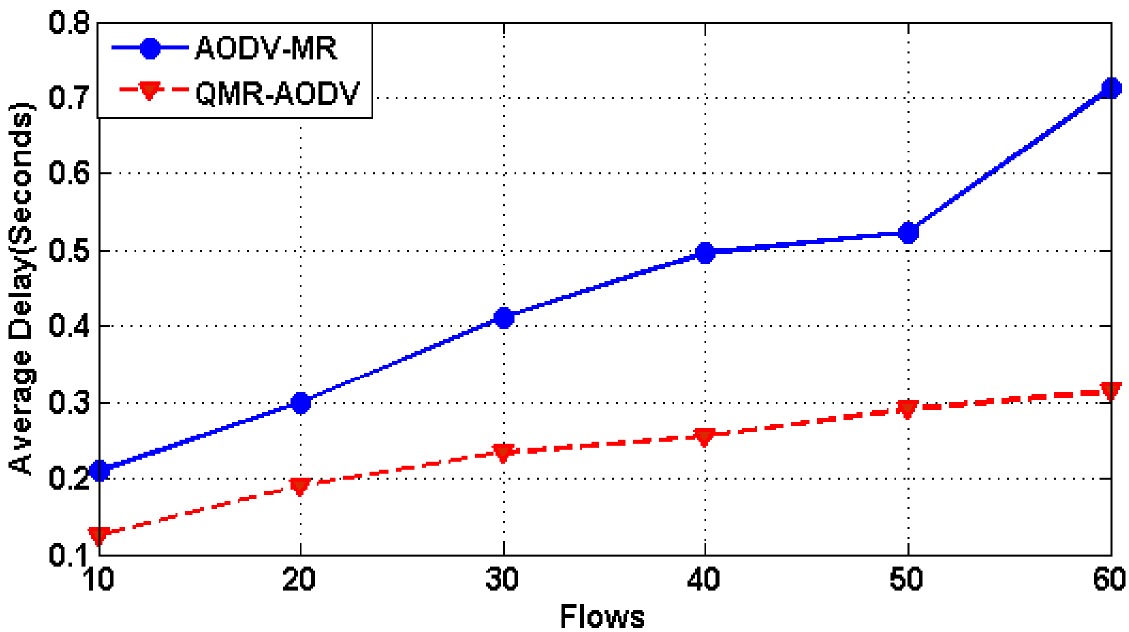


Figure 3-17: Average Network Delay for multiple number of flows

Packet Delivery Ratio (PDR):

PDR is an important performance measure of any routing protocol and indicates its significance in terms of achieved throughput on end-to-end paths. As shown in the Figure 3-18, both protocols perform equally at lower generated flows, where their PDR is almost equal to 100 percent. However, when the number of users flows increases, the PDR starts dropping for AODV-MR. AODV-MR produces more routing overhead causing more network congestions and collisions. Secondly, it selects whatever path is available and thus the end node's data is either lost due to queue overflows or due to collisions on the links. On the other hand, QMR-AODV selects paths with the delay guarantees and unicasts the RREQ packets on specific interfaces. This reduces the overhead inside the network leading to less collisions and congestions. Each end node data gets a confirmed service in terms of delays on end-to-end path and thus less data is lost during the communication. Overall, QMR-AODV performs better to carry upto 70% more data on extremely congested network as compared to AODV-MR.

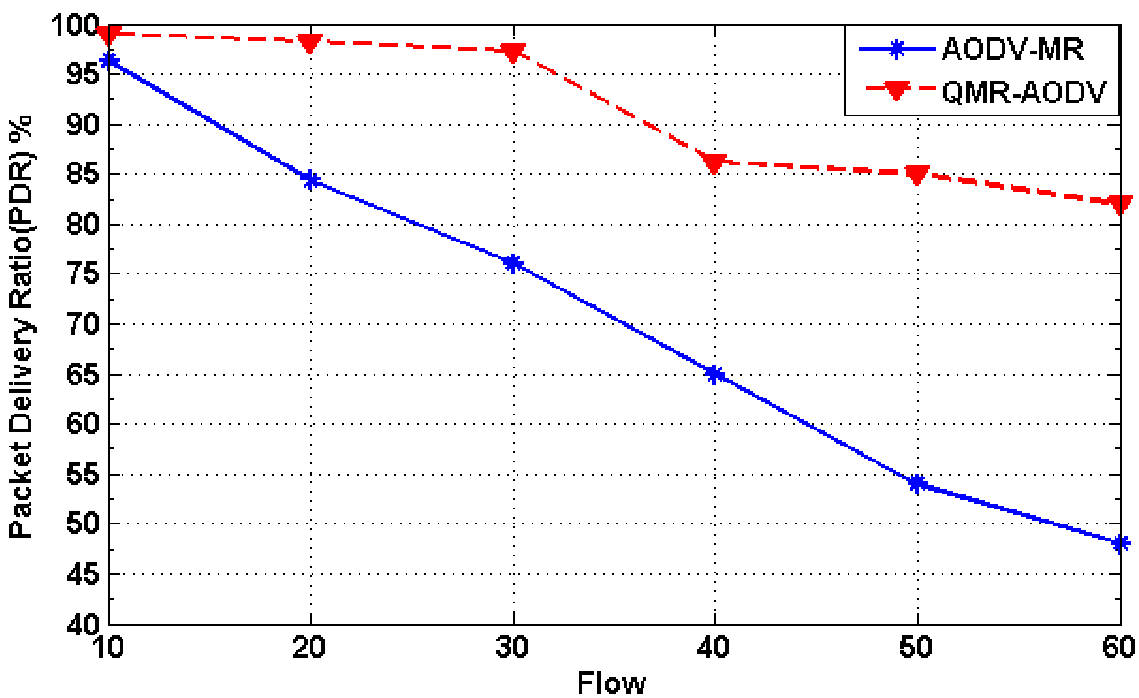


Figure 3-18: Packet Delivery Ratio (%) for multiple number of flows

Average Response Time: The Average Response Times of both protocols is measured by taking the average of the time elapsed between all RREQs and their returned RREPs at the source nodes, for different number of flows. The Average Response Time is given by:

$$R_t = P_t + N_d \tag{3.6}$$

Where R_t is the total average response time, P_t is the average processing time each RREQ and RREP packets takes for it's operation for determining the end-to-end route from source to destination and N_d is the delay associated with the network.

As shown in the Figure 3-19, AODV-MR's has a better response time for low as well as high traffic profiles. The reason is that each QMR-AODV's RREQ packet is assessed for delay requirements and the interface compatibility. This takes extra processing time for RREQ to reach at the destination. On the contrary, AODV-MR's RREQ packets are only processed at the intermediate nodes for the routing information and then broadcasted on all the interfaces. This reduces the end to end latency for the RREQ-RREP cycle between the source and destination nodes. Second, AODV-MR's RREQ might return a path for the source node's RREQ from the intermediate nodes and thus extremely decreasing the response time.

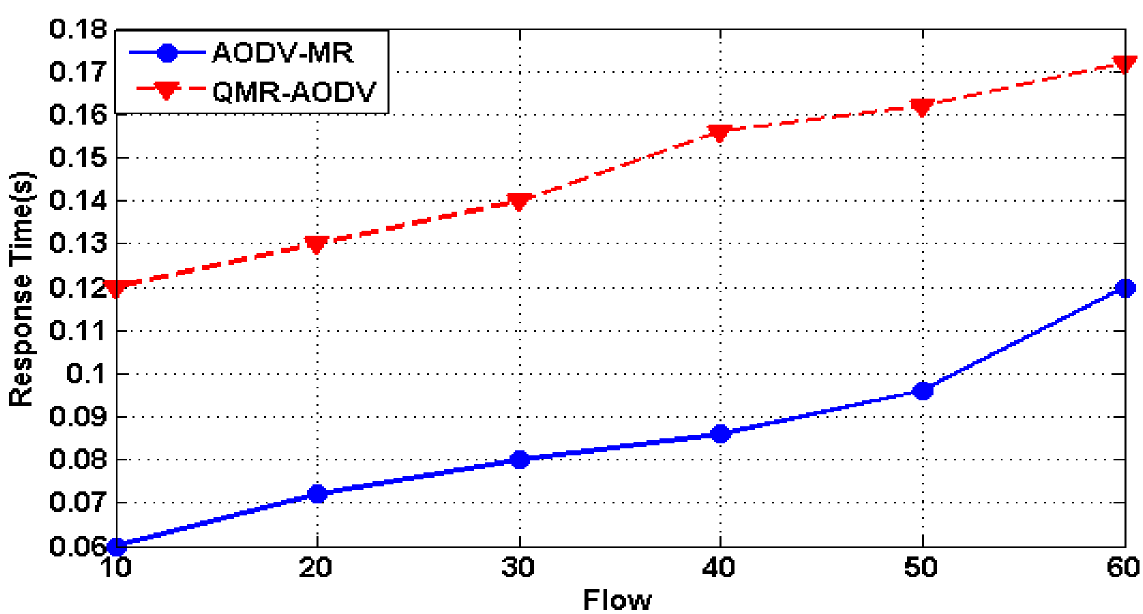


Figure 3-19: Average Response Time of the routing protocols

3.6.2 Simulation Setup for varying number of radios

In this scenario, the number of radios/interfaces per node was incremented from 2 to 8 in step 1. Each time, the average delay and routing overhead was measured based on an average of 20 simulation runs. Number of flows generated by the end nodes was kept 30. All the remaining parameters were kept as according to the Table 3-5. IEEE 802.11a was used as the underlying MAC as in the Section 5.6.1.

Figure 3-20 shows the effect of varying the number of nodes interfaces on the routing overhead. When the number of radios/interfaces on each node is 2, the Routing overhead is almost equal for both AODV-MR and QMR-AODV. This is because both are using one interface for reception and the other one for transmitting the data. In this case, QMR-AODV only unicasts the RREQ packet to its next hop neighbour when the interface is capable of meeting the delay requirements. AODV-MR broadcasts the RREQ packet as it arrives only on the second interface. Since in a two interfaced nodes, the possibly of collision is minor keeping in view the number of channels available in IEEE 802.11a, and hence both performs equal. However, when the number of radios on each node is increased to 4, an abrupt change in the routing overhead is observed for AODV-MR. This is because the RREQ is now broadcasted on all the interfaces causing more routing overhead. On the opposite, a very small increase in the QMR-AODV's routing overhead is observed with varying the number of radios per node. The reason is that QMR-AODV's selective forwarding of the RREQ messages to its next hop neighbours which effectively reduces the number of RREQ diffusion in the network. The Figure 3-20 also shows a linear increase in the routing overhead for AODV-MR from 6 to 8 radios case. This means that AODV-MR fails to work efficiently with large number of interfaces per node.

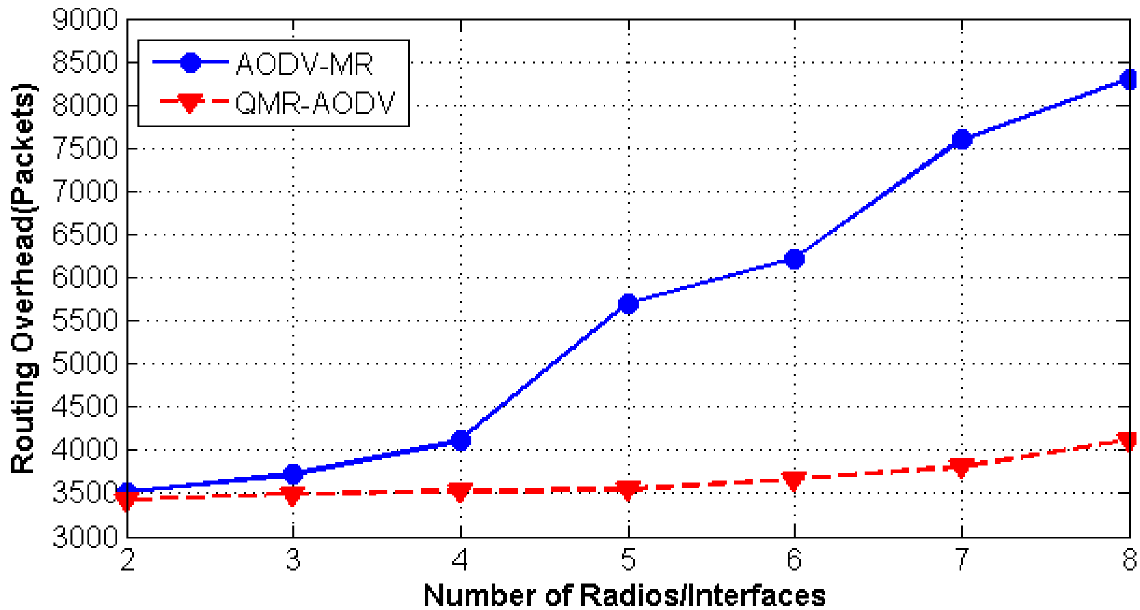


Figure 3-20: Routing Overhead with varying number of network interfaces/radios

Figure 3-21, shows the Average Delay experienced by all the packets inside the network comparatively with varying the number of radios per node. The average delay is high for both protocols when the number of interfaces is 2, where AODV-MR does better with less average delay as compared to QMR-AODV. The reason for high delay with less number of radios for both the protocols is that the network is less connected with fewer radios per node. More interfaces per node means more connectivity and more routes to the destination. It also means that with more radios per node, more parallel communication links and load distribution is achieved. With fewer interfaces per node, each link is congested with the high amount of data from the end users, which leads to congestion and network latency. For 2 interfaces per node, AODV-MR performs better than QMR-AODV because of the possibility of the latter to drop a RREQ from transmitting to the next node based on the non-compliance with the QoS requirements. Thus, those RREQs packets, which never get RREPs, are re-sent by the end source nodes and thus increase the total delay.

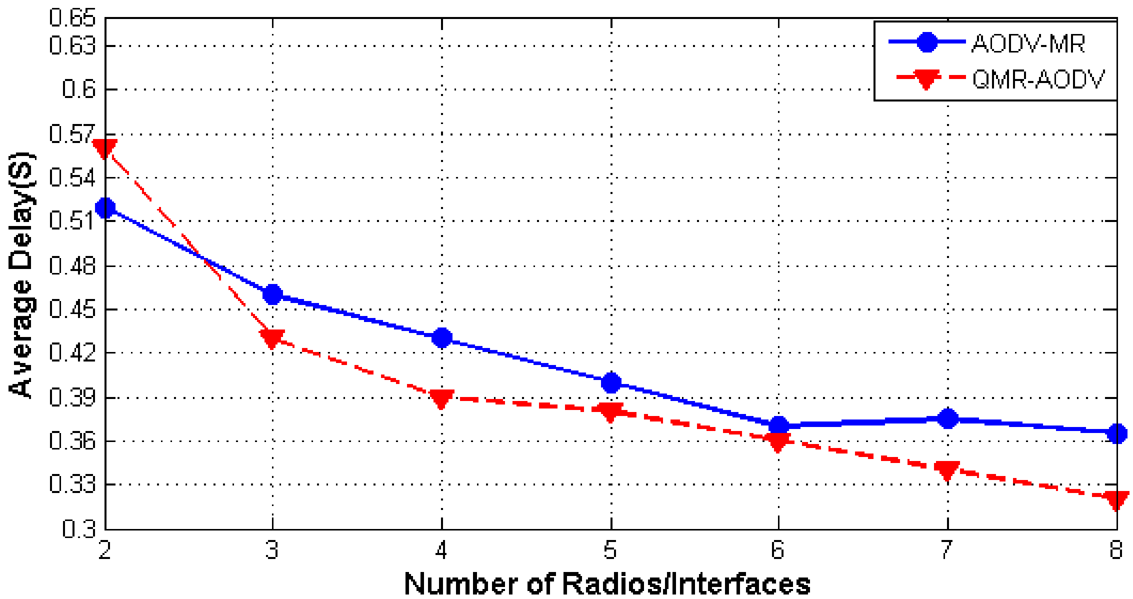


Figure 3-21: Average Delay with varying number of network interfaces/radios

However, QMR-AODV outperforms AODV-MR when the number of radios per node increases as can be seen in the Figure 3.21. This is because, increasing the interfaces per node for the same number of users' flows, connectivity increases and hence there are more chances for the RREQ to be sent on those interfaces which can meet the end users required QoS delay requirements. This ensures the data is always routed through best possible paths leading to fewer delays. Second, QMR-AODV comparatively produces less RREQ as mentioned earlier and thus decreasing the chances of congestion in the network.

3.7 Summary

This chapter presents joint channel assignment and routing scheme for Multi-Radio Multi-Channel WMNs. The proposed channel assignment scheme ensures low interference by assigning the non-overlapping channels to the multiple radios with a dynamic and distributed scheme based on channel usage exchange messages. The channel assignment scheme is capable of detecting nodes failures and mobility within the WMNs backbone. The delays associated with the bi-directional links are accurately captured by the channel monitoring module in terms of average queuing delays, backoffs, transmission rate and retransmission for the lost packets. This delay information is further used by the QoS based routing scheme as a metric for determining the end-to-end path. The proposed QMR-AODV routing protocol controls the network wide flooding of conventional AODV by selective forwarding the RREQ packets. This helps to decrease the network routing overhead. QMR-AODV returns a guaranteed end-to-end path according to the applications requirements as each node assesses each of its interface during the RREQ packet forwarding, for complying with the applications required minimum delay bounds. Further, the proposed scheme improves the packet delivery ratio, network latency and effectively reduces the routing overhead.

3.8 References

[1] P. Gupta and P. R. Kumar, "The capacity of wireless networks," Information Theory, IEEE Transactions on, vol. 46, pp. 388-404, 2000.

[2] Pabst, R., Walke, B. H., Schultz, D. C., Herhold, P., Yanikomeroglu, H., Mukherjee, S., et al. , Relay-based deployment concepts for wireless and mobile broadband radio. Communications Magazine, IEEE, 42(9), pp. 80-89, 2004.

[3] Akyildiz, I. F., Wang, X., & Wang, W, Wireless mesh networks: A survey. Computer Networks, 47(4), 445-487, 2005.

[4] Bruno, R., Conti, M., & Gregori, Mesh networks: Commodity multihop ad hoc networks. Communications Magazine, IEEE, 43(3), pp. 123-131, 2005.

[5] Lee, M. J., Zheng, J., Ko, Y. B., & Shrestha, D, Emerging standards for wireless mesh technology. Wireless Communications, IEEE, 13(2), 56-63, 2006.

[6] T. Fowler, "Mesh networks for broadband access," IEE Rev, vol. 47, pp. 17-22, 2001.

[7] M. J. Lee, J. Zheng, Y. B. Ko and D. M. Shrestha, "Emerging standards for wireless mesh technology," Wireless Communications, IEEE, vol. 13, pp. 56-63, 2006.

[8] http://www.arubanetworks.com/products/mesh-routers/ [Last accessed: June, 2011]

[9] http://www.cisco.com/en/US/prod/collateral/wireless/ps7183/ps469/product_data_sheet09186a008008883b.html [Last accessed: June, 2011]

[10] http://www.motorola.com/Business/US-EN/Business+Product+and+Services/Wireless+Broadband+Networks/Mesh+Networks/ [Last accessed: June, 2011]

[11] B. A. Chambers, The Grid Roofnet: A Rooftop Ad Hoc Wireless Network, 2002.

[12] http://www.meshdynamics.com [Last accessed: June, 2011]

[13] Y. Zhang and H. Hu, Wireless Mesh Networking: Architectures, Protocols and Standards. Auerbach Pub, 2006.

[14] B. P. Crow, I. Widjaja, L. Kim and P. T. Sakai, "IEEE 802.11 wireless local area networks," Communications Magazine, IEEE, vol. 35, pp. 116-126, 1997.

[15] Z. J. Haas, J. Deng, B. Liang, P. Papadimitratos and S. Sajama, "Wireless ad hoc networks," Encyclopedia of Telecommunications, 2002.

[16] http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=6606,last accessed: 21/06/2010

[17] IEEE 802.11b/g: www.ieee.org/, last accessed: 22/12/2010

[18] IEEE 802.11n; www.ieee.org/, last accessed: 22/12/2010

[19] R. Vedantham, S. Kakumanu, S. Lakshmanan and R. Sivakumar, "Component based channel assignment in single radio, multi-channel ad hoc networks," in Proceedings of the 12th Annual International Conference on Mobile Computing and Networking, pp. 378-389, 2006.

[20] W. Si, S. Selvakennedy and A. Y. Zomaya, "An overview of channel assignment methods for multi-radio multi-channel wireless mesh networks," Journal of Parallel and Distributed Computing, vol. 70, pp. 505-524, 2010.

[21] I. Katzela and M. Naghshineh, "Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive survey," Personal Communications, IEEE, vol. 3, pp. 10-31, 1996.

[22] A. Raniwala and T. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE, pp. 2223-2234 vol. 3., 2005.

[23] T. Clausen, P. Jacquet, C. Adjih, A. Laouiti, P. Minet, P. Muhlethaler, A. Qayyum and L. Viennot, "Optimized link state routing protocol (OLSR)," 2003.

[24] C. E. Perkins and P. Bhagwat, "Highly dynamic destination-sequenced distance-vector routing (DSDV) for mobile computers," ACM SIGCOMM Computer Communication Review, vol. 24, pp. 234-244, 1994.

[25] S. Das, C. Perkins and E. Royer, "Ad hoc on demand distance vector (AODV) routing," Mobile Ad-Hoc Network (MANET) Working Group, IETF, 2002.

[26] D. B. Johnson, D. A. Maltz and J. Broch, "DSR: The dynamic source routing protocol for multi-hop wireless ad hoc networks," Ad Hoc Networking, vol. 5, pp. 139-172, 2001.

[27] M. K. Marina, S. R. Das and A. P. Subramanian, "A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks," Computer Networks, vol. 54, pp. 241-256, 2010.

[28] J. Tang, G. Xue and W. Zhang, "Interference-aware topology control and QoS routing in multi-channel wireless mesh networks," in Proceedings of the 6th ACM International Symposium on Mobile Ad Hoc Networking and Computing, pp. 68-77, 2005.

[29] A. P. Subramanian, H. Gupta, S. R. Das and J. Cao, "Minimum interference channel assignment in multiradio wireless mesh networks," Mobile Computing, IEEE Transactions on, vol. 7, pp. 1459-1473, 2008.

[30] K. N. Ramachandran, E. M. Belding, K. C. Almeroth and M. M. Buddhikot, "Interference-aware channel assignment in multi-radio wireless mesh networks," in INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings, pp. 1-12, 2006.

[31] K. Jain, J. Padhye, V. N. Padmanabhan and L. Qiu, "Impact of interference on multi-hop wireless network performance," Wireless Networks, vol. 11, pp. 471-487, 2005.

[32] A. Raniwala, K. Gopalan and T. Chiueh, "Centralized channel assignment and routing algorithms for multi-channel wireless mesh networks," ACM SIGMOBILE Mobile Computing and Communications Review, vol. 8, pp. 50-65, 2004.

[33] M. Kodialam and T. Nandagopal, "Characterizing the capacity region in multi-radio multi-channel wireless mesh networks," in Proceedings of the 11th Annual International Conference on Mobile Computing and Networking, pp. 73-87, 2005.

[34] M. Alicherry, R. Bhatia and L. E. Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks," in Proceedings of the 11th Annual International Conference on Mobile Computing and Networking, pp. 58-72, 2005.

[35] S. M. Das, H. Pucha, D. Koutsonikolas, Y. C. Hu and D. Peroulis, "DMesh: Incorporating practical directional antennas in multichannel wireless mesh networks," Selected Areas in Communications, IEEE Journal on, vol. 24, pp. 2028-2039, 2006.

[36] K. Xing, X. Cheng, L. Ma and Q. Liang, "Superimposed code based channel assignment in multi-radio multi-channel wireless mesh networks," in Proceedings of the 13th Annual ACM International Conference on Mobile Computing and Networking, pp. 15-26, 2007.

[37] A. Mohsenian Rad and V. W. S. Wong, "Joint optimal channel assignment and congestion control for multi-channel wireless mesh networks," in Communications, 2006. ICC'06. IEEE International Conference on, pp. 1984-1989, 2006.

[38] A. Naveed, S. S. Kanhere and S. K. Jha, "Topology control and channel assignment in multi-radio multi-channel wireless mesh networks," in Mobile Adhoc and Sensor Systems, 2007. MASS 2007. IEEE Internatonal Conference on, pp. 1-9, 2007.

[39] P. Kyasanur and N. H. Vaidya, "Routing and interface assignment in multi-channel multi-interface wireless networks," in Wireless Communications and Networking Conference, IEEE, pp. 2051-2056 Vol. 4, 2005.

[40] C. Cicconetti, V. Gardellin, L. Lenzini and E. Mingozzi, "PaMeLA: A joint channel assignment and routing algorithm for multi-radio multi-channel wireless mesh networks with grid topology," in Mobile Adhoc and Sensor Systems, 2009. MASS'09. IEEE 6th International Conference on, pp. 199-207, 2009.

[41] L. Bononi, M. Di Felice, A. Molinaro and S. Pizzi, "A cross-layer architecture for effective channel assignment with load-balancing in multi-radio multi-path wireless mesh networks," International Journal of Communication Systems, vol. 22, pp. 1267-1296, 2009.

[42] A. H. M. Rad and V. W. S. Wong, "Cross-layer fair bandwidth sharing for multi-channel wireless mesh networks," Wireless Communications, IEEE Transactions on, vol. 7, pp. 3436-3445, 2008.

[43] C. R. Lin and J. S. Liu, "QoS routing in ad hoc wireless networks," Selected Areas in Communications, IEEE Journal on, vol. 17, pp. 1426-1438, 1999.

[44] R. de Renesse, M. Ghassemian, V. Friderikos and A. H. Aghvami, "QoS enabled routing in mobile ad hoc networks," in 3G Mobile Communication Technologies, Fifth IEE International Conference on, pp. 678-682, 2004.

[45] L. Chen and W. B. Heinzelman, "QoS-aware routing based on bandwidth estimation for mobile ad hoc networks," Selected Areas in Communications, IEEE Journal on, vol. 23, pp. 561-572, 2005.

[46] M. E. M. Campista, P. M. Esposito, I. M. Moraes, L. Costa, O. Duarte, D. G. Passos, C. V. N. de Albuquerque, D. C. M. Saade and M. G. Rubinstein, "Routing metrics and protocols for wireless mesh networks," Network, IEEE, vol. 22, pp. 6-12, 2008.

[47] B. Bakhshi, S. Khorsandi and A. Capone, "On-line joint QoS routing and channel assignment in multi-channel multi-radio wireless mesh networks," Comput. Commun., 2011.

[48] N. Nandiraju, D. Nandiraju, L. Santhanam, B. He, J. Wang and D. P. Agrawal, "Wireless mesh networks: Current challenges and future directions of web-in-the-sky," Wireless Communications, IEEE, vol. 14, pp. 79-89, 2007.

[49] A. A. Pirzada, M. Portmann and J. Indulska, "Evaluation of multi-radio extensions to AODV for wireless mesh networks," in Proceedings of the 4th ACM International Workshop on Mobility Management and Wireless Access, pp. 45-51, 2006.

[50] A. A. Pirzada, M. Portmann and J. Indulska, "Performance analysis of multi-radio AODV in hybrid wireless mesh networks," Comput. Commun., vol. 31, pp. 885-895, 2008.

[51] The Network Simulator-NS-2: *www.isi.edu/nsnam/ns/* [Last accessed: June, 2011]

[52] I. Shah, S. Jan, S. Mahmud and H. Al-Raweshidy, "Optimal path discovery with mobility management in heterogeneous mesh networks," in Future Computer and Communication. ICFCC 2009. International Conference on, 2009, pp. 57-61, , 2009.

CHAPTER 4

Channel Assignment in Competitive Wireless Mesh Networks with Non-Cooperative Bargaining Games

4.1 Introduction

Wireless Mesh Networks (WMNs) [1] have multi-hop topology spanning multiple collision domains. The inherited advantages of self-configuration, self-healing and self-organization along with static nature of its backhaul routers make WMNs a prime candidate for wireless broadband provisioning in users premises WMNs routers can be equipped with multiple radios due to their static nature and the existence of permanent power supplies. Since multiple channels are available in the free Industrial, Scientific and Medical (ISM) band, multiple radios can be tuned simultaneously to exploit the free non-overlapping channels and hence to increase the overall capacity, connectivity and resilience of the wireless mesh backhaul [2].

Channel assignment is a critical design factor in competitive (non-cooperative) WMNs because it affects the network interference, delays, throughput and connectivity. In a distributed environment, each node of the network runs a copy of the channel assignment algorithm independently. In such a de-centralized and independent environment, cooperation from nodes to follow the standard protocol during channel assignment cannot be taken for granted. Nodes selfishness can lead to system wide performance degradation during channel assignment, as it is highly likely that each individual node deviates from the standard protocol with the sole objective to maximize its own benefit from the channel resource.

In this chapter, a distributed channel assignment scheme has been proposed for competitive multi-hope WMNs deployed in a large area. The channel assignment problem has been investigated by applying the concepts from non-cooperative bargaining game theory. A two stage game has been modeled for WMNs by considering a multiple-collision domain topology spanning multiple hops. In the first stage of the game, sufficient and necessary conditions for the existence of Negotiation Proof Nash Equilibrium (NP-NE) [3] have been derived and a pricing mechanism is designed for the system based on the alternating offer bargaining [4,5]. A distributed algorithm has been presented based on the nature of information available and the position of the node with perfect information. It is proved analytically, that Nash Equilibrium (NE) and NP-NE are both not the system optimal solutions considering the source-gateway communication over end-to-end paths in the WMNs. Since WMNs can be deployed over a large area, it is possible for multiple organizations to get access to the Internet through these networks. In the second stage of the game, the model is further extended to incorporate the end users non-cooperative bargaining [4, 5]. The simulation results show that a moderate to good amount of fairness has been achieved while the end-users non-cooperative bargaining further increases the end-to-end throughput of the system.

4.2 Non-Cooperative Behaviour in Wireless Networks

In Non-Cooperative Networks, nodes behave selfishly to maximize their own benefit by deviating from the defined standard protocol [4], which leads to system-wide performance degradation, instability and individual unfairness. In Mobile Ad-hoc Networks (MANETs) [5], for example, each node acts as data generating user of the network as well as relays data for others. A non-cooperative node can misbehave by dropping others packets to save its battery life while sending its own packets to be forwarded by other nodes. This selfish behavior of free riders leads to limited connectivity of the network and affects individual as well as network-wide performance. If all the nodes behave selfishly in the same manner, the network will end up with each entity in isolation, as shown in the Figure 4-1, nodes ‘c’ and ‘g’ drop the incoming packets from other nodes while send their own packets to be forwarded by others in the network. To cope up with these similar behaviors, multiple techniques have been used to enforce cooperation among the nodes for the stability of overall system [2, 6]. Viewing this behavior from game theoretic prospective, a conflicting situation where each entity is self interested in the network resources or service leads to a non-cooperative game. Similarly, competition among the nodes during channel assignment, while assuming them as selfish self-maximizing individual entities, can degrade the system.

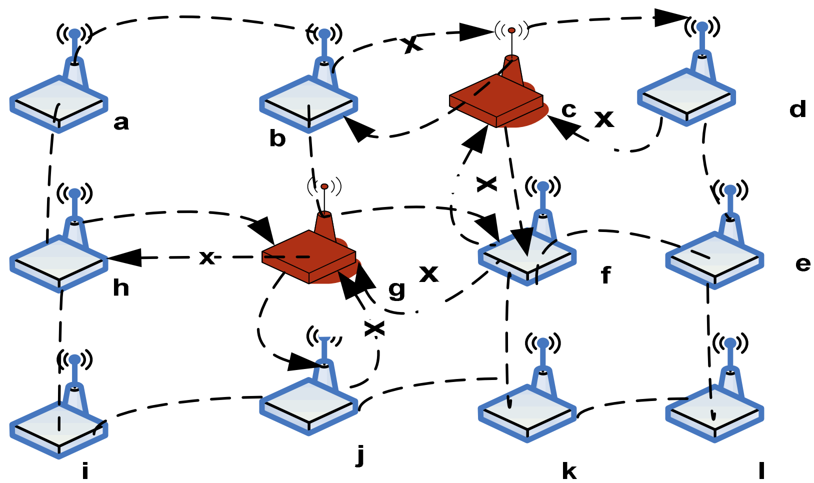


Figure 4-1: Non-Cooperative Behaviour in MANETs

In the Chapter 3, for example, a channel assignment protocol has been proposed. Refer to the Section 3.5.4 of Chapter 3, a selfish node can exploit the situation by sending $CH_{Request}$ without any necessity and with the aim to increase its own benefit from the channel resource. If all the nodes deviate from the defined protocol as suggested, sending $CH_{Request}$ can affect the performance and stability of the system when each node will make request for a channel re-allocation in its collision domain, unnecessarily and selfishly.

4.3 Related Work

The problem of Channel Assignment has extensively been studied by the research community during the last decade mainly focusing on cellular networks to provide different solutions. In a Fixed Channel Allocation (FCA) scheme, channels are permanently assigned to different cells across a cellular network while in Dynamic Channel Allocation (DCA), channels are assigned based on the traffic demand. FCA is a simple technique and performs better than DCA during high and constant traffic, the flexibility to traffic adaptation of the later makes it more practical solution. To overcome the inefficiencies of both approaches, Hybrid Channel Allocation (HCA) schemes have been developed, where some of the channels are assigned using FCA while others are dynamically assigned to all users in the network [8].

The emergence of WMNs has opened new avenues for researchers by re-considering the channel assignment problem to multiple radios of the routers in a multi-hop network. Due to WMN's routers multi-hop and multi-radio nature, co-channel interference across the backbone as well among the multiple radios of the same router must be considered during the mechanism design. The assignment of multiple non-orthogonal channels to multiple radios of routers, across WMNs backbone, is called Multi-Radio Multi-Channel (MRMC) assignment problem. MRMC problem has been addressed by many researchers keeping in view different system parameters. A graph theoretic approach has been proposed in [9], where channel assignment is guided by the topology control prospective with minimum interference. A. Raniwala *et al.* [10] have presented MRMC models based on user's traffic demands. The work of M. Alicherry *et al.* [11] has addressed routing and channel assignment in WMNs as a joint optimization problem. Although the research work so for cited has addressed MRMC from different aspects as discussed in the Chapter 3 in detail, selfish behavior of nodes during channel assignment has been explicitly ignored by assuming that all nodes co-operate with each other for the system wide throughput optimization and follow the standard defined protocols.

The assumption of cooperation in networks cannot be assured always due to the self-programmable nature of the now a day's network devices. Each self interested node can deviate from the standard defined protocol to achieve its own objectives during channel assignment/accessing at the cost of sacrificing the system-wide goal. The spectrum allocation problem in cognitive networks has been studied in [12, 13, 14, 15], where the authors have provided solutions from non-cooperative game theory. Their main focus is the conflict resolution in a strategic setup between Primary and Secondary Users, each using a single radio. In one of the pioneering work [16], the authors have solved MRMC assignment as a non-cooperative game and have proven the existence of NE. Their results show that the system converges to a stable NE, where each player gets fair share of the channel resources. The limitation of their work is that they consider all nodes reside in a single collision domain, while multi-hop networks like WMNs span multiple collision domains. The authors in [17, 18] have studied channel assignment to radios in a single collision non-cooperative network with the aim of achieving the globally optimal throughput. The work of Chen *et al*. [19] is an extension of [16] where perfect fairness has been proven to be achieved by all players with an incentive mechanism. All of the above studies have focused on solving the non-cooperative MRMC restricted to a single collision domain only, where all nodes reside one hop from each other. The work of Gao *et al*. [20] has addressed MRMC problem in multi-hop networks from a game theoretic prospective. They have proved the existence of Coalition-Proof Nash Equilibrium (CPNE), where coalitions among nodes within the same sessions lead to improvements in the achieved data rate across end-to-end paths. Although their study is related to ours as the single hop assumption has been removed, however, they assume that all nodes reside in a single collision domain. Their proposed solution is also based on the assumption that some nodes cooperate by making coalition to improve the end-to-end throughput. In practical deployment, WMNs routers are placed in multiple collision domains where a specific link interferes with a sub-set of links in the entire network. Thus, this work is not applicable to a fully non-cooperative setup in multi-collision domain. Selfish routing and channel assignment in WMNs have been formulated by Jun Xiao *et al*. [21] as a Strong Transmission Game, where it is assumed that end users assign channels to their end-to-end paths in a strategic interaction. The limitation of their Game Theoretic solution is the strong assumption of non-interference among the non-overlapping channels across the core of the network. In practice, there are limited channels in the free ISM band and channel assignment is always constrained by the interference phenomena due to the existence of multiple radios in a large scale WMNs. In the research work of Rohith *et al.* [22] and Chen *et al.* [23], the authors have studied the channel assignment in non-cooperative MRMC networks spanning multiple collision domains. In [22], the authors have solved the channel assignment problems to the multiple radios of the multi-hop nodes residing in multiple collision domains. They have provided the conditions for the existence of NE and fairness properties of the system have been thoroughly analyzed. However, their model is based on the assumption of the consideration of links, being shared by a set of nodes, as the players of the game; whereas, in a competitive networks the wireless link and hence the channel assigned to it is always shared by two or more nodes and the agreement cannot be forced upon them, *i.e.,* binding players to self enforcing agreements in non-cooperative games is not possible outside the rules of the game. The authors in [23] have extensively proved the existence of NE by designing an incentive compatible game theoretic model to achieve high throughput. Their incentive mechanism ensures that the system always converges to a Pareto-optimal outcome. Our model differs from both them in two ways. First, their solution is of significance in a MRMC network where peer-to-peer communication (*e.g.,* as in MANETs) is considered more imperative than source-destination one. On the contrary, we follow the source-destination paradigm as the very essence of WMNs, where nodes are assumed totally selfish and non-cooperative. Second, the bargaining mechanism presented in this chapter is fully non-cooperative as compared to the incentive mechanism based on some imposition from outside the game. In [13], authors have used players bargaining for efficient spectrum utilization among WiFi Access Points. Their analytical results show that system level improvement in the data rate is achieved. One of the closest studies is that of Lili Cao *et al.* [24], where the authors have proposed an adoptive and distributed bargaining solution for spectrum allocation in MANETs. Their proposed solution is of too much importance where the channel re-allocation is performed with the change in the network topology due to the nodes movements. They have further optimized this re-allocation of channels by localizing the process. Joint channel and power allocation problem has been addressed by Q Ni *et al.* [25], where a cooperative bargaining game theoretical model has been presented for cognitive radio networks. The above proposed bargaining solutions [13, 24, 25] are cooperative and the nodes interaction is in the form of collusion. Besides, these research studies have assumed a single radio per primary and secondary user's device of the cognitive networks.

4.4 System Model

Since Wireless Mesh Networks consist of backbone routers connecting end users via Mesh Access Points (MAPs) to the Gateways, therefore the flow of data is always between the end users and gateways. However, the backbone routers do not generate data by themselves and act only as forwarding relays. Secondly, the multiple collision domain nature of the routers demands to re-consider the game theoretic models as studied before in [16-21]. WMNs provide wireless broadband across towns and there is a chance that multiple organizations will connect to the same backbone to relay their data for Internet access. In this chapter, we consider the scenario of a town-wide WMNs deployment, where users from different organizations are connected as shown in the Figure 4-2.

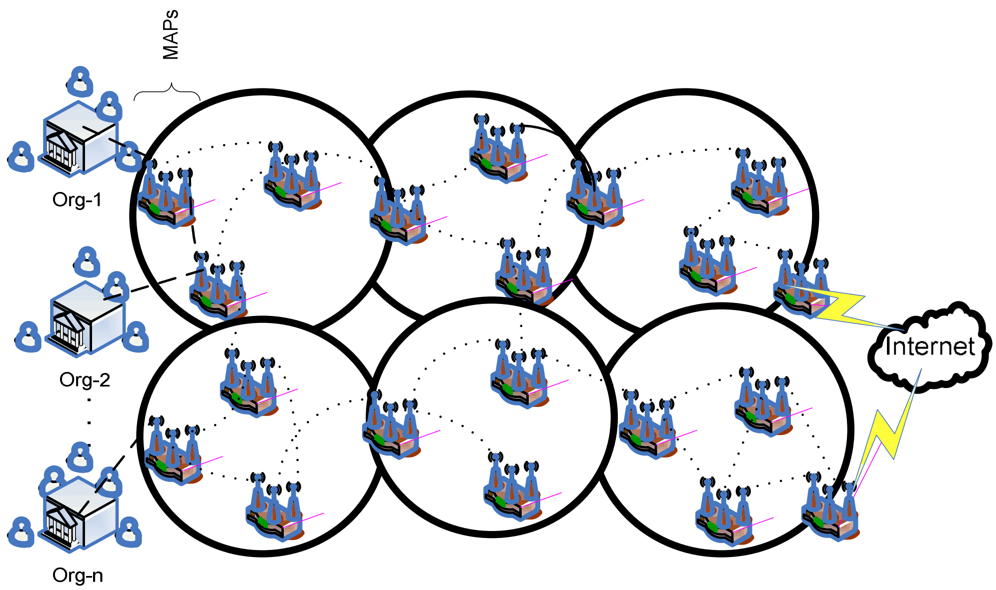


Figure 4-2 : A Wireless Mesh Network

4.5 Graph Theoretical Network Model

To visualize the WMNs topology and connectivity, concepts from graph theory [26] are used throughout this chapter. A graph G (V, E) generally represents the connectivity between multiple entities, called vertices, in terms of lines called edges. Any two vertices (v_1, v_2) ∈ V form an edge *e* ∈ E in a graph G (V,E), if and only if they are connected to each other through a line. Figure 4-3 shows the graphical representation of a WMN network. The network consists of 15 nodes, out of which the connected nodes in the network are represented by the edges in the graph representation. The set of vertices in the graph G (V, E) is V= {v_1, $v_{2\ldots}$, v_{15}} where each edge in the set of edges E= { e_1, e_2, ….., e_{20}}, represents the connectivity between two vertices from the set V.

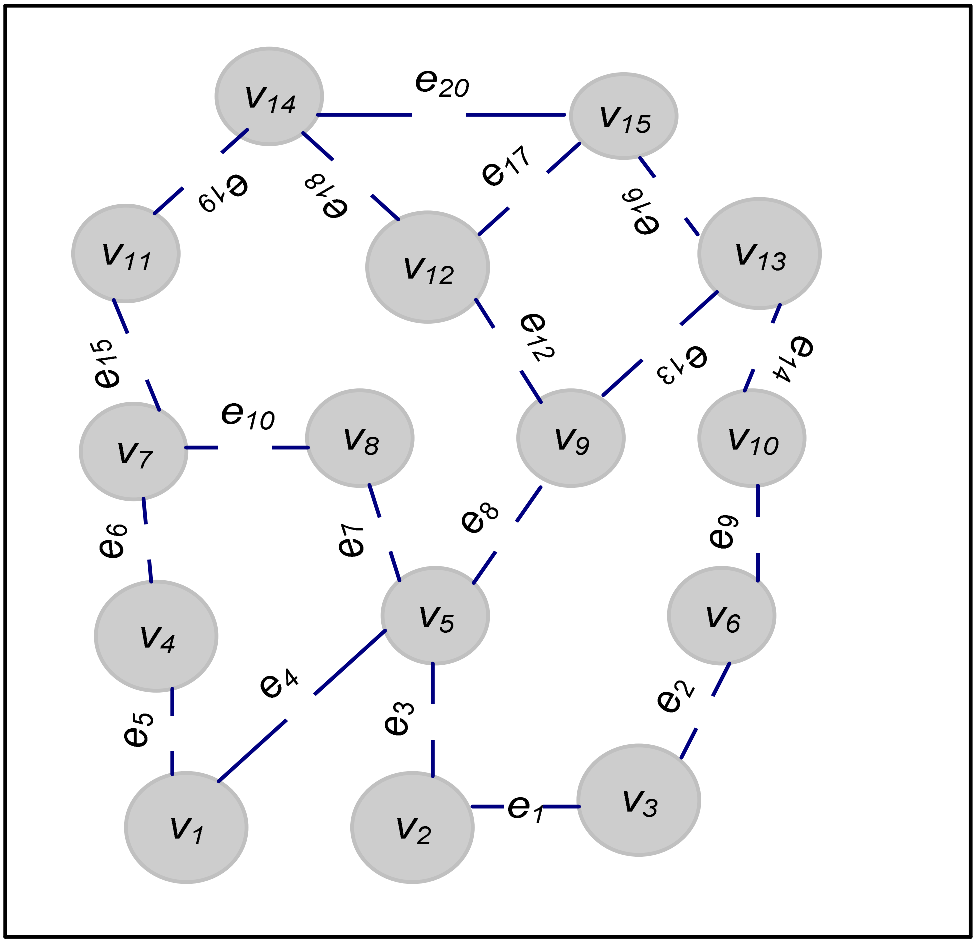


Figure 4-3: Graphical Representation of a WMN

Two wireless nodes can communicate if and only if they lie within each others transmission ranges. Transmission range of a radio is the range where it can receive a packet without any error from another radio. An associated concept is the interference range of a node which is the area around a receiver within which an unrelated transmission causes a packet drop. We assume that all nodes use the same transmission power as in IEEE 802.11/a/b/g/n [24, 25, 26] standards. Two nodes v_i an v_j ∈ V can successfully communicate with each others if and only if the Euclidian Distance between them is equal to or less than the total sum of their radii [21], *i.e:*

$$\mathrm{d}(v_i, v_j) \le r_{vi} + r_{vj}, \ for\ any(v_i, v_j) \in \mathrm{V} \tag{4.1}$$

Where r_{vi} and r_{vj} are the radii of vertices v_i and v_j in the graph G, respectively. In other words, they are in the transmission range of each other and can successfully communicate as shown in the Figure 4-4.

An edge between two nodes $(v_i,u_i) \in V$ exists if and only if a there is a communication session going on between them. We represent the set of communication links in the network graph G by L, where $L=\{ e_i =(v_i,u_i) \mid \forall\ v_i,u_i \in V$ and satisfies the Equation (4.1)}. Let the interference range of a node is represented by the outer circle as shown in the Figure 4-4, whose radii is twice that of smaller circle, then two set of nodes (v_1,u_1), $(v_2,u_2) \in V$ cannot communicate with each other if any of the following is true[21]:

$$d(u_1,v_2)<2(r_{u1}+r_{v2}) \text{ OR } d(v_1,v_2)<2(r_{v1}+r_{v2}) \text{ OR } d(u_1,u_2)<2(r_{u1}+r_{u2}) \text{ OR } d(v_1,u_2)<2(r_{v1}+r_{u2}) \quad (4.2)$$

In other words, two set of nodes (v_1,u_1), $(v_2,u_2) \in V$ cannot communicate with each other independently, if any node from the set is inside the interference range of any of the other node from another set and both links are using the same channel for communication [27].

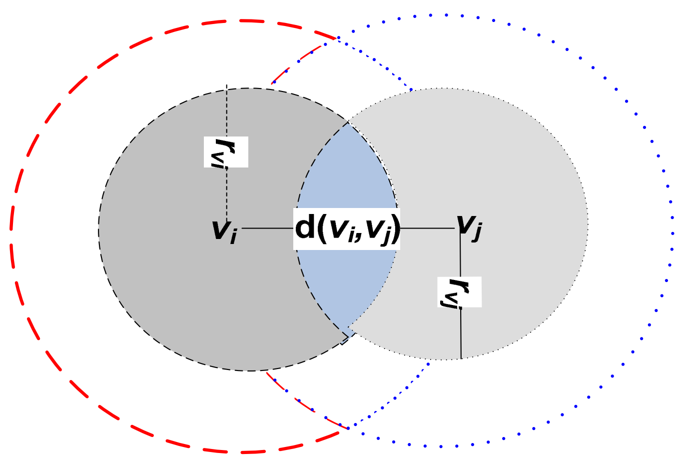


Figure 4-4: Transmission range and Interference ranges of two nodes

Due to the multi-hop nature of WMNs, multiple collision domains exist and a given link can potentially interfere with a sub set of links in total. In order to capture the interference phenomenon between the collision domain specific links, the network is further represented by a conflict graph G' (V_{CG}, E_{CG}) [28, 22]. The set V_{CG} represents nodes in G', where the edge e_{ij} ∈ G' exists if and only if two links (e_i, e_j) ∈ L interfere with each others in the generic network graph G. As shown in the Figure 4-5a, links e_1, e_4 and e_2 interfere with each others; similarly e_2, e_3 and e_5 interfere in the graph G. The vertices of the interference graph G' are e_1, e_2, e_3 e_4 and e_5 respectively. Figure 4-5b shows the conflict graph representation of the example in the Figure 4-5a, which shows the interference relationships between different links. Further, the generic and conflict graphs will always be referred to while formulating the game theoretic models in the next sub-section.

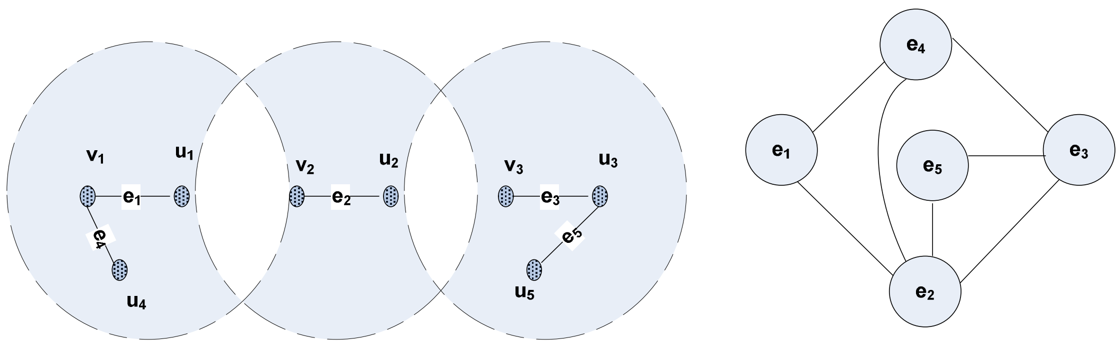


Figure 4-5: (a) Links interference graph G (b) Links conflict graph G'

Since, in the multiple collision domains, each link interferes with a sub-set of links in the network, therefore, conflict graph is an effective way to capture these collision domain specific interferences. However, in the complete non-cooperative environment, the competition for the channel resource is between the nodes instead of the links. To understand this phenomenon of competition among the individual nodes during channel assignment in the selfish environment, consider the graph representation of a network in the Figure 4-6(a), where two nodes v_1 and v_2 want to assign a channel, say C_i, to the potential link, e_{12}, between them. As can be seen from the Figure 4-6(b), link e_{12} interfere with the links set {e_{13}, e_{14}} and {e_{25}, e_{26}} independently. Considering the links of the network as players of the game in a non-cooperative MRMC WMNs, spanning multiple collision domains, is based on a fundamental assumption of binding the two nodes to be connected over a potential link by a default agreements as in [22, 20]. These are one sided agreements, where the other node in the pair over a shared link is considered always to be agreed on assigning a channel based on the link interference degree. This assumption leads to two problems. First, in a non-cooperative network and hence in a non-cooperative game, the agreements cannot be forced from outside the rules of the game [32]. Secondly, in a multi-radio setup, each node in the node pair =(v_i,v_j) might evaluate and experience different degree of interference for a channel C_i to be assigned to a potential link e_{ij} in L={ e_{ij} =(v_i,v_j) such that ∀ v_i,v_j) ∈ V}. This is because the two nodes might be possibly sharing disjoint set of neighbouring nodes, in their respective collision domains, and there are chances that these neighbours have assigned C_i to their interfaces in varying degrees.

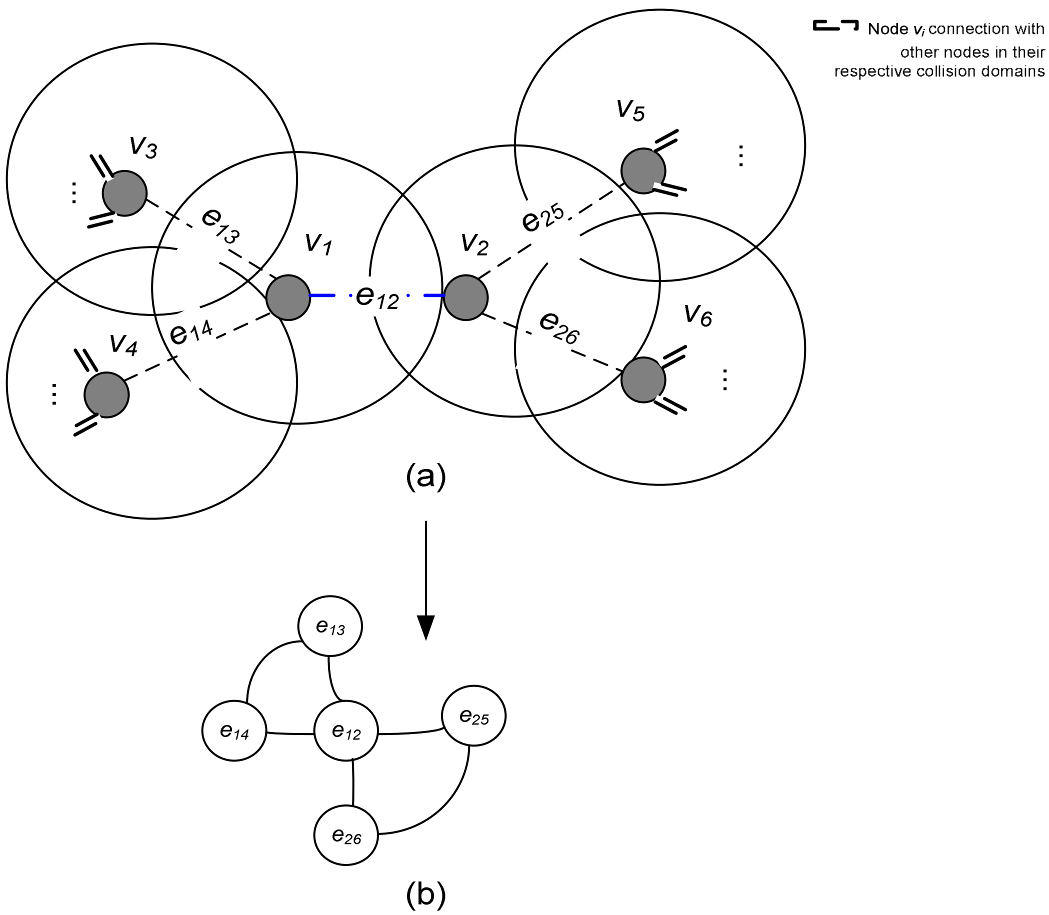


Figure 4-6: (a) Node interference graph G (b) Links conflict graph G'

For example, in the Figure 4-6(a), it is possible that the neighbours of v_1, *i.e,* v_3 and v_4, might have assigned C_i to their respective radios in more numbers than the neighbours of v_2, *i.e.,* v_3 and v_6. This means that v_1 essentially experience more interference as compared to v_2 for C_i being assigned to the link e_{12} between them. In a competitive environment, v_1 will prefer to assign another channel, say C_j, which causes it less interference over the potential link e_{12} with v_2. Further in next sections, the graph G, as shown in the Figure 4-3, will always be referred to determine the number of nodes interfering with the current node V_i as according to the rule outlined in the Equation (1) and the Figure 4-4. Similarly, the conflict graphs of the topology will always be referred to show the degree of interference experienced by a node.

4.6 Game Formulation and Concepts

In this section, the game formulation and the relevant concepts are presented.

4.6.1 Game Formulation

The channel assignment in the MRMC WMNs has been formulated as a non-cooperative game as follows. Each node of the network, as represented by the vertices of the graph in the Figure 4-3, is referred to as rational player of the game, represented by the non-empty finite set N= {N_1, N_2…, $N_{|N|}$}. The notion of player's set as discussed in the relevant work [16-20] and [22, 23] and the one presented in this Chapter is fundamentally different. When channel assignment to the multiple radios is considered in the single collision domain [16-20], it means that all nodes of the network can potentially interfere with each other if they try to simultaneously assign a similar channel to their respective links due to their existence in the same collision domain. While in multiple-collision domains [22, 23], the set of links which can potentially interfere with a subset of other links residing in the same collision domain are considered as players of the game. However, considering links as the unit of analysis has the shortcomings during the design of a non-cooperative game as discussed in the Section 4.5. We consider each individual node as the unit of analysis during the game formulation and hence the set of players are the nodes residing in the same collision domain. For example, refer to the Figure 4.6 (a), the set of players are in separate groups (collision domains), *i.e.,* the sets {v_1, v_2, v_3, v_4} represents the set of players with respect to the player v_1 , {v_1, v_2, v_5, v_6} with respect to player v_2, {v_1, v_3, v_4} with respect to players v_3,and v_4 and {v_1, v_2, v_5, v_6} with respect to players v_5 and v_6 respectively . Non-overlapping orthogonal channels, as present in IEEE 802.11 a/b/g/n, is denoted by the set C= {C_1, C_2,…., $C_{|C|}$} all having the same channel characteristics. Each node i is equipped with $k < |C|$ number of multiple radios of the same communication capabilities. The total achievable data rate on a channel c ∈C is represented by R_c which is equally shared by all the radios deployed on channel *c.* As in [14], the total number of channels where a player i has deployed all of its radios in the respective particular collision domains is represented by:

$$k_i = \sum_{c \in \mathrm{C}} k_{i,c} \tag{4.3}$$

Where $k_{i,c}$ is the number of radios assigned by player $i \in \mathrm{N}$ to the channel *c*. To avoid the co-radio interference, we assume that each player can assign only one radio to a particular channel at the same time, *i.e.,* $k_{i,c} = (1 \mid 0)\ \forall\, c \in \mathrm{C}, \forall\, i \in \mathrm{N}$. Any channel $c \in \mathrm{C}$ is evaluated differently by each node player for the reason mentioned earlier in the Section 4.5. Therefore, we define $n_i \subseteq \mathrm{N}$, representing the sub set of nodes which have an edge with i in the graph G including player i, *i.e., L*={ $e_{i,j}$ =(i, j)| $\forall\, i, j \in \mathrm{N}$} and satisfying the Equation (4.1). We define the potential degree of conflict of player i as $\varphi_i = [(e_{ij} + e_{jk}) - 1]$, where *L*={ $e_{i,j}$ =(i, j)| $\forall\ j \in n_i$} and *L*={ e_{jk} =(j, k)| $\forall\, k \in n_j$. It is assumed that all the nodes possess the same number of radios, *i.e.,* $k_i = k_j\ \forall\, i, j \in \mathrm{N}$. Accordingly, the total number of radios using a particular channel *c* in the collision domain of i^{th} player is represented by:

$$k_c^{i\text{th}} = \sum_{i \in n_i} k_{i,c} \tag{4.4}$$

Refer to the Figure 4-6a, if the same channel $c \in \mathrm{C}$ is assigned by all the players to all their respective radios, then $n_1 = \{v1, v2, v3, v4\}$, $n_3 = n_4 = \{v1, v3, v4\}$, $n_5 = n_6 = \{v2, v5, v6\}$ and $n_2 = \{v1, v2, v5, v6\}$ and accordingly $\varphi_1 = \varphi_2 = 8$, $\varphi_3 = \varphi_4 = 6$ and similarly $\varphi_5 = \varphi_6 = 6$. Similarly, $k_c^1 = k_c^2 = 9$, $k_c^3 = k_c^4 = 5$ and $k_c^5 = k_c^6 = 5$. The achievable data rate of a player *i* on a particular channel *c* is represented by:

$$R_{i,c} = \sum_{c \in \mathrm{C}} \frac{k_{i,c}}{k_c^{\mathrm{ith}}} \tag{4.5}$$

In a non-cooperative game [32], players interact with one another in a rational manner, keeping in view the actions of all other players. In order to study the strategic interaction of players in the channel assignment game, we define the strategy set which shows all the actions available to player *i*, represented by A_i as follows:

$$A_i = \{ k_{i,1}, k_{i,2}, k_{i,3}, \ldots, k_{i,|C|} \}$$

We represent the strategy profiles of all players by a strategy matrix **A**=[$A_1, A_2, \ldots, A_{|N|}$]$^{\mathrm{T}}$, where any row in **A** shows the action of a particular player. As a notation convenience in a strategic interaction, A_{-i} means the action of all players in the game less *i* and the pair (A_i, A_{-i}) shows the action of player *i* against the actions of all other players in a strategic setup. At the end of the game, each player $i \in \mathrm{N}$ gets benefit in the form of a real number (*R*) called payoff which is determined by the utility function U_i as: $U_i = A_i \rightarrow R$. We define the utility function of player *i* as the total data rate achieved by deploying all of its radios *i-e:*

$$U_i = \sum_{c=C_1}^{C_{|C|}} R_{i,c} + E(U^i) \tag{4.6}$$

Where $R_{i,c}$ is the achievable data rate of player *i* on a particular channel c, as defined in the Equation (4.5) and $E(U^i)$ its expected utility from the non-cooperative bargaining as discussed in the next sub-section, represented by the Equations (4.9-4.12). The bargaining utility, $E(U^i)$, is represented by $E(U^B)$ and $E(U^S)$ for the Buyer and Seller agents, respectively. The utility function in the Equation (4.6) calculates the sum of the gain, in terms of throughput, of a player *i* on each channel in its collision domain plus the expected utility earned if a player opt for bargaining if that is the case.

4.6.2 Non-Cooperative Bargaining

The bargaining process has received enormous attention in a variety of disciplines ranging from economics, industrial politics, applied mathematics to political science and psychology. In pure economics, bargaining is an alternative to the fixed price trading. It is common in several parts of the world, where the vendor's asking price is much higher than the actual value of the item or service [33]. This situation leads to an unfair trading, where sellers get buyers surplus money through price discrimination. Societies across the globe deal this exchange of goods and money with different bargaining strategies [34]. Bargaining problem involves two or more agents to negotiate and reach to an agreement keeping in view each one's own personal gains.

Bargaining can be viewed as a conflicting situation, where the cooperation of the parties involved is for some incentive. The rationality of both to get maximum share in the outcome makes it competitive and non-cooperative. Non-Cooperative bargaining is defined as a "situation involving two rational individuals/agents who have the opportunity to collaborate for mutual benefit in more than one way. Being rational, each agent can accurately compare his/her desires for various things and all have equal bargaining skills" [34]. Game theory has contributed much to this conflicting situation to solve the problem of bargaining in a strategic set up. John Nash [35, 36] was the first who formally defined bargaining as a non-zero sum game between two individuals. Later developments in bargaining ranges from developing models considering the completeness of information, risk assessment, ultimatums, timing and bargaining power [33, 37, 38, 39].

In a two person non-cooperative bargaining game, two rational players come into contact with each other and negotiate on some object or service. Being rational, the aim of each one will be to maximize its own benefit from the trade. Many factors can influence the bargaining process including the information available during the game, the timing, the position of the bargainers and their own evaluation of the item or service in trade [4].

As discussed earlier, two nodes can only communicate with each other if they are in each others hearing ranges and a common channel has been assigned to the link between them. Assigning a channel to a link involves two nodes and their agreement on the selection of a specific channel is necessary. This agreement is possible in the cooperative network, as the one discussed in the Chapter-3. However, in a non-cooperative WMNs, the agreements and hence cooperation between the nodes can not be taken as for granted. Since, each node of the network is considered as an individual selfish entity, therefore, a mechanism is needed to enforce this agreement, which is beyond the scope of non-cooperative games.

Consider, for example, the potential link e_{12} in, the Figure 4-7, to be shared by two nodes v_1, v_2 by assigning a channel C_1 to it. Since the nodes of the WMNs belong to different collision domains due to the multi-hop nature of the topology and hence, it is possible that node v_1 evaluates more interference for the channel C_1 as compared to the node v_2. In this case, node v_1 will not agree to assign channel C_1 to the link e_{12} if there is another channel, say C_2, which gives it more benefit if assigned to the link e_{12} under the given set up. To solve the similar situation of disagreements during the channel assignment in a MRMC WMNs, a bargaining mechanism based on the strategic alternating offers [41] has been proposed. In the alternating offer bargaining, the two players interact by offering and counter offering alternatively. As shown in the Figure 4-8, two entities, being the Seller and Buyer come into a contact via strategic interaction. Buyer offers an amount (or good) to the Seller. If the Seller agrees, the bargaining ends and both the entities update their respective utilities. However, if the Seller does not agree, it counter offer another amount (or good) to the Buyer. If the buyer agrees, the bargaining ends. This process of offer and counter offer is repeated till the specified time for the bargaining, T, ends. In the non-cooperative games, as the one presented in this chapter, the solution is the outcome called the Nash Equilibrium (NE). However, NE is not an optimal solution in the MRMC WMNs game due to the fact that the fairness of the system is compromised because the channels are evaluated differently by each nodes to be connected by a potential link. However, due to the limited knowledge of either nodes regarding each others evaluation of a specific channel to be assigned to a potential link between them, the system outcome remains sub-optimal.

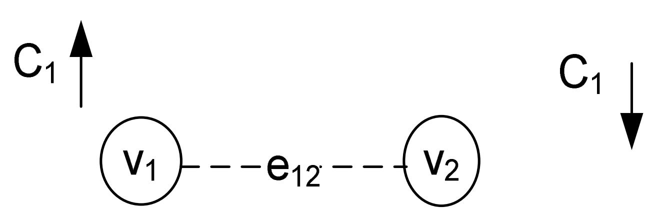


Figure 4-7: Channel assessment by nodes in different collision domains.

We define the two nodes to assign the channel *C* to the potential link between them as the set of bargaining agents S={S_1,S_2 }. During the bargaining process, one node becomes the buyer and the other as the seller. During the channel assignment, one node, *e.g,* S_1 , offers to S_2 to assign a channel, say c_i, to the potential link between them based on its own evaluation as outlined in the Section 1.7. The node S_2, based on its own evaluation of the offered channel c_i, either accepts or rejects.

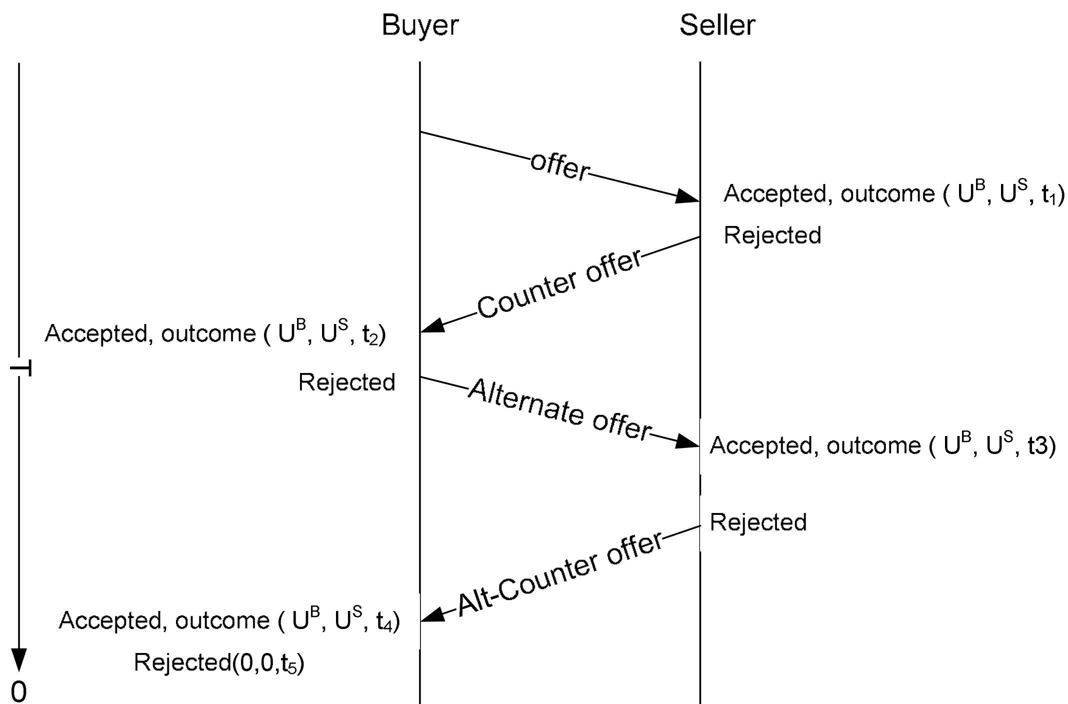


Figure 4-8: Alternating offers Bargaining

The offer will be accepted, if the current offered channel for the potential link earns high throughput to S_2. Otherwise, S_2 will offer to S_1 another channel, say c_j, from the set of available channels C, which earns it high throughput. This initializes the bargaining process as outlined in the Figure 4-8, because the offered channel c_j essentially earns S_1 low throughput as compared to c_i. In this case, S_1 becomes the seller and expect to get some monetary benefit from S_2, now being the buyer agent. It is assumed that each bargaining agent has some virtual currency, *p*, which can be used during the bargaining process. Being rational, each agent aims at to maximize its throughput, being the buyer or the amount of currency, being the seller. The result of bargaining is either in breakdown or success, where breakdown means both agents fail to reach at an agreement during the specific time. A success in the proposed bargaining model means assignment of the channel to the link between the two agents/node.

Next we present some of the important definition used as the solution for the non-cooperative game discussed in this chapter.

Definition 4.1: A strategy profile **A** is Nash Equilibrium (NE) if:

$$U_i(A_i, A_{-i}) \geq U_i(A'_i, A_{-i}) \ \ \forall \ i \in \mathrm{N}, \ \forall \ A'_i \in \mathbf{A} \quad (4.7)$$

The existence of NE guarantees the stability of the non-cooperative game in a sense that if any player changes its current strategy individually then this change will have no gain in the player's payoff. All players being rational stick to their NE strategies at the same time.

Definition 4.2: Negotiation-Proof Nash Equilibrium (N-PNE).

NE for a given strategy profile **A** is N-PNE if and only if there exists no single coalition in **A** which can make objection to the existing strategy profile in a way which can lead to another N-PNE giving benefits to all the members of the coalition [3].

This simply means that N-PNE is NE, i.e., for a strategy profile to be NPNE, it is a must that no individual deviation form the current strategy is possible, unilaterally. NPNE applies to the situations where there is a need for negotiation for a non-cooperative game before actually playing it. Since NE in its original form does not allow such a communication, being the solution concept of non-cooperative games, therefore, N-PNE is applied in such a situation to fill the gap. However, N-PNE only recognizes the possibility where the players are highly rational and the agreements are not binding[3]. The game model presented in this chapter is fully non-cooperative, however, taking the selfish nodes of the network as the players of the game needs some form of coordination, which is not possible in the pure non-binding solutions, such as the NE.

In the following section, we present the conditions for the existence of N-PNE and hence the NE. It should be noted that each NP-NE is essentially an NE, however, it is possible that a NE solution for a strategy profile may not be N-PNE. In our proposed model, the latter case can happen in a situation where there is no bargaining involved between any two player for a strategy profile **A**.

4.7 Existence of Negotiation-Proof Nash Equilibrium

4.7.1 N-PNE and existence conditions

Following are the necessary conditions for the existence of N-PNE and hence NE in a non-cooperative MRMC WMNs spanning multiple collision domains.

Lemma 4.1: *In a multiple-collision domain MRMC WMNs game for a strategy profile* **A** *to be N-PNE,* $k_i = \sum_{c \in C} k_{i,c} = k \ \forall \ i \in N$.

Proof: This lemma is proved by contradiction. Let a strategy profile **A** is NE where a player *i* has assigned $k_i < k$ radios to a set of channels $C_i \subseteq C$ in the i^{th} collision domain. Since $k < |C|$ and $k_{i,c} = (0 \mid 1)$ as per assumption in the Section 4.6, there exists at least one channel $c' = C \backslash C_i$ where $k_{i,c'} = 0$ and hence player *i* can assign at least one of its radio $k'_i = k - k_i$ to one of the channel $c' \in C \backslash C_i$ to increase its payoff. Therefore, the strategy profile **A** cannot be a NE under this condition. This essentially means that the given strategy profile can not be N-PNE either and hence the statement in lemma is true. This lemma is the necessary condition for NE in single as well as multiple collision domain MRMC WMNs as in the relevant work [16-23].

Let us take into consideration any two arbitrary channels $c,d \in C$, the difference of radios deployed on channel *c* and *d* in the i^{th} collision domain is represented by $\Omega_{i,c,d} = k_c^{ith} - k_d^{ith} \ \forall \ i \in N$. Next lemma 2 is defined as follows.

Lemma 4.2: *For a multiple-collision domain MRMC WMNs game, the strategy profile* **A** *is not a NE if:* $\Omega_{i,c,d} \geq 1$ *for* $k_{i,c}=1$, $k_{i,d}=0$ *for any arbitrary channels* $c,d \in C$, $\forall \ i \in N$.

Proof: Lemma 4.2 is proved by contradiction. Let us assume that the conditions given in lemma hold for strategy profile **A** for a player *i*. Since $\Omega_{i,c,d} \geq 1$, $k_{i,c}=1$and $k_{i,d}=0$, it means that channel *c* has been assigned to at least two more players than channel *d* in the collision domain of *i*. Therefore player *i* can effectively increase its utility by deviating from the current strategy by assigning channel *d* to its radio and hence the current strategy profile **A** cannot be a NE and essentially not a N-PNE.

Lemma 4.3: *For a multiple-collision domain MRMC WMNs game, the strategy profile* **A** *is a NE* $\forall$ $i \in \mathrm{N}$ *if* $\varphi_i \geq |\mathrm{C}|$ *then* $k_c^{i\mathrm{th}} \leq 1$

Proof: For a strategy profile **A**, let $k_{i,c}$=1 and $k_c^{i\mathrm{th}}$ >1, then it means that channel *c* is shared by at least two players in the collision domain of *i*. Let $\varphi_i < |\mathrm{C}|$ then there is at least one channel $d \in \mathrm{C}$ which has not been assigned by any player in the i^{th} collision domain and player *i* has an incentive to deviate from its current strategy. Therefore, the current strategy profile **A** is not a NE by contradiction and lemma 4.3 is a necessary condition for N-PNE. Lemmas (4.2) and (4.3) are also the necessary conditions for MRMC games in multi-hop networks when link is considered as the player of the game as in [22].

Lemma 4.4: *For a multiple-collision domain MRMC WMNs game, the strategy profile* **A** *is not N-PNE if for a player set* $(i,j) \rightarrow e_{ij} \in G', \varphi_{i,c} = \varphi_{j,c} \; \forall \, i,j \in \mathrm{N}$.

Proof: By contradiction, let the strategy profile **A** a N-PNE. This essentially means that there exists a channel $c \in \mathrm{C}$ where either $\varphi_{i,c} < \varphi_{j,c}$ *or* $\varphi_{i,c} > \varphi_{j,c}$. This implies that for assigning this channel $c \in \mathrm{C}$, both players $(i,j) \in \mathrm{N}$ enters into a bargaining setup, the success of which can lead to N-PNE. Since, $\varphi_{i,c} = \varphi_{j,c} \; \forall \, i,j \in \mathrm{N}$ as given in the condition and therefore the statement in the Lemma 4.4 is true. Lemma 4.4 leads to Proposition 4.1.

Proposition 4.1: *For a multiple-collision domain MRMC WMNs game, all NE need not necessarily N-PNE.*

Proof: For a multiple-collision domain MRMC WMNs game let the Lemmas (4.1-4.3) hold for a strategy profile **A.** Let $\varphi_{i,c} = \varphi_{j,c} \; \forall \, i,j \in \mathrm{N}$. This means that there is no such set of players $(i,j) \rightarrow e_{ij} \in G' \; \forall \, i,j \in \mathrm{N}$, where they can enter into the non-cooperative bargaining. Since the interference on all the channels experience by the both players is the same and the agreements are binding bilaterally.

Lemma 4.5: *For a multiple-collision domain MRMC WMNs game, the strategy profile* **A** *is not a N-PNE if for a player set* $(i,j) \rightarrow e_{ij} \in G'$*, if there exists a channel* $c \in \mathrm{C}$ *such* *that* $\varphi_{i,c} = \min(\varphi_{i,C\backslash\{c\}})$ *and* $\varphi_{j,c} = \min(\varphi_{j,C\backslash\{c\}})$ *and c is not assigned to* $e_{ij} \in G' \forall i, j \in N$.

Proof: Let the strategy profile **A** be the N-PNE. This means that both the players (i, j) has no way to increase their respective utilities/payoffs by deviating to a new strategy. From the statement, since, both the players (i, j) experience minimum interference on channel c as compared to the other channels $C\backslash\{c\}$ in their respective collision domains and hence this is a contradiction to the supposition. Therefore, the statement in the Lemma (4.5) is true.

4.7.2 Convergence to Nash Equilibrium

In the Section 4.7.1, the conditions for the N-PNE and NE existence have been proven for a game of channel assignment to multiple radios in competitive Wireless Mesh Networks, taking the individual selfish network nodes as the player of the game. The conditions, as outlined in the form of Lemmas (4.1-4.5), should be satisfied by all the nodes during their channel allocation moves. Any node, which deviates from these defined rules, will get no benefit from its unilateral move at the outcome of the game. All the individual players of the game are rational and hence their decision on their move from the current strategy depends on how much utility it can draw from it. Since the unilateral move of any player outside the rules of the game cannot benefit it individually as evident from the Lemmas (4.1-4.5) and the, therefore, the convergence to the NE is always ensured in the game. However, for convergence to N-PNE, the nodes enter into the bilateral non-cooperative bargaining, where they reach at an agreement based on the Algorithm 2 as shown in the Figure 4-10. In this section, a distributed algorithm, based on the perfect information available to all the nodes, is presented.

4.7.3 Distributed Algorithm for channel assignment in the MRMC WMNs

In this section, a distributed algorithm, which runs on each node player is presented. The information needed by the nodes is restricted to their own collision domains only. Each node needs to know about the number of channels available and the number of radios deployed on each specific channel in its own collision domain. This is again an example of perfect information in non-cooperative games. In distributed algorithm, however, nodes are not supposed to be under the authority of any central system and their moves in the game are expected to be simultaneous. It is assumed in the proposed model that there is some random channel assignment already present, which is not necessarily an NE and hence N-PNE. Each node runs the algorithm given in the Figure 4-9 and updates its current channel

Algorithm 1
Input: N={ N1,N2,N3, ….,N|N|}, A random channel allocation, {1,2, …. ,W}
Output: NE or N-PNE Channel Assignment

while(Not NE or N-PNE)
→get current channel assignment
***for** each* $e_{ij} \in G'$
***for** each* (i,j) ∈ N, where (i,j) → e_{ij} ∈ G′
if $backoff\_counter\ _i$==0
for k_i=1 to K
k_c= $k_{i\_current}$
calculate k_c^{ith} and k_c^{jth}
if ($k_c^{ith} - k_{c'}^{ith}$)>1 ∀c′ ∈ C\{c} and ($k_c^{jth} - k_{c'}^{jth}$)>1 ∀c′ ∈ C\{c}
and $\varphi_{i,c'} = \varphi_{j,c'}$
//NE move
remove k_i from *c*, remove k_j for $k_{j\_current}$
assign c′ to e_{ij}—→ (k_i, k_j) where $k_{c'}^{ith}$ is of min(∀*d*∈ C\(c∩ c′)) and $k_{c'}^{jth}$ is of min(∀*d*∈ C\(c∩ c′))
reset $backoff\_counter\ _i$ to a new value from W
elseif ($k_c^{ith} - k_{c'}^{ith}$)==0 and $\left(k_c^{jth} - k_{c'}^{jth}\right) == 0$ and $\varphi_{i,c} = \varphi_{j,c}$ ∀c′ ∈ C\{c}
Search for: a channel *d* ∈ C\{c} where *i* has minimum radios
if $(\varphi_{i,d} = \varphi_{j,d})$ // NE move
remove $k\ _i$ from *c*
assign *d* ∈ C to e_{ij}—→ (k_i, k_j)
reset $backoff\_counter\ _i$ to a new value from W
esle
Bargain (i,j,d)
end if
end if
next k_i
else
$backoff\_counter\ _i$= $backoff\_counter\ _i - 1$
end if
next $(\boldsymbol{i},\boldsymbol{j})$ (random)
do

Figure 4-9: Algorithm for channel assignment (Distributed and Perfect Information).

assignment accordingly for its own benefit. The inherent property of player's simultaneous moves in distributed channel assignment algorithm can lead to channel oscillation problem.

Since channels are assessed by each player independently, an under loaded channel can be assigned by multiple nodes simultaneously. In the next round, by knowing the previous wrong moves, every player will remove the current channel and update for

Algorithm 2
Input: players (i, j)
Output: N-PNE Channel Assignment
Bargain $(\boldsymbol{i}, \boldsymbol{j}, \boldsymbol{d})$
T={t_0 , t_1 , t_2, ……, t_n }
While $t \leq |T|$
1. *if* ($\varphi_{i,d} < \varphi_{j,d}$)
2. →Seller= j, Buyer= i
3. Buyer i offers with an amount (p') to Seller j
4. *if* (Seller accepts the offer)
5. Assign channel *d to* $e_{ij} \longrightarrow (k_i, k_j)$
6. **Return;**
7. *else (t=t+1)*
8. *end if*
9. Seller j counter-offers with an amount (q') to Buyer i
10. *if* (Buyer accepts the offer)
11. Assign channel *d to* $e_{ij} \longrightarrow (k_i, k_j)$
12. **Return;**
13. *else (t=t+1)*
14. *end if*
15. Buyer i alternate-offers with an amount (p_1') to Seller j
16. *if* (Seller accepts the offer)
17. Assign channel *d to* $e_{ij} \longrightarrow (k_i, k_j)$
18. **Return;**
19. *else (t=t+1)*
20. *end if*
21. Seller j alternate counter-offers with an amount(q_1') to Buyer i
22. *if* (Buyer accepts the offer)
23. Assign channel *d to* $e_{ij} \longrightarrow (k_i, k_j)$
24. **Return;**
25. *else (t=t+1)*
26. *end if*
27. *else* (Seller= i, Buyer= j) GoTo: line-3.
28. *end if*

Figure 4-10: Alternating offer Bargaining Algorithm between two nodes.

another. This process can repeat multiple times and the system will never converge to a stable NE state. To solve this problem and make the simultaneous moves sequential, a *backeoff* window as in [16, 20, 22], {1, 2, …., W}, similar to the one used in IEEE 802.11 [27-29] medium access *backeoff* mechanism is defined. Each player assigns a random value with a uniform probability distribution to its *backeoff_counter* variable from the set W. In each round, all players reduce the *backoff_counter* by one and only players whose *backoff* values reaches zero update their channel assignment, as shown in the Figure 4-9. Selling and buying agents evaluate their preference differently during the bargaining game. For seller, money is important in terms of virtual currency and so its whole dependency is on the variable *p*. For buyers, both currency *p* and channel benefit in terms of bandwidth gain worth during the evaluation process. A simple algorithm, similar to the one presented in [45], showing the interaction of a buying agent i and a selling agent j during alternating offer bargaining over time T is presented in the Figure 4-10. Alternating offers bargaining model starts with the buying agent i offering an amount $p^{'}$ lying within its acceptable region, at time t=0, to the selling agent j. If the offer is above selling agent's valuation line, it is accepted; otherwise the offer is rejected as being outside its feasible region [41] as shown in the Figure 4-11. Alternatively, selling agent j asks for an amount q' lying above its valuation line at time t_1. If this asking amount is below the buying agent valuation line, it is accepted; otherwise rejected. This procedure is continued by both buying and selling agents in another round each time incrementing time *t,* till both reach to the point which is mutually acceptable. The region containing all these acceptable points is called feasible set [41]. We exactly follow the alternating offer bargaining model as presented by [41]. The feasible set contains all those points which are common between the valuation lines of both selling and buying agents as shown in the bargaining solution space of the Figure 4-11. Since both players are highly rational and in non-cooperative environment, each one will try to maximize their own profit without caring for the others.

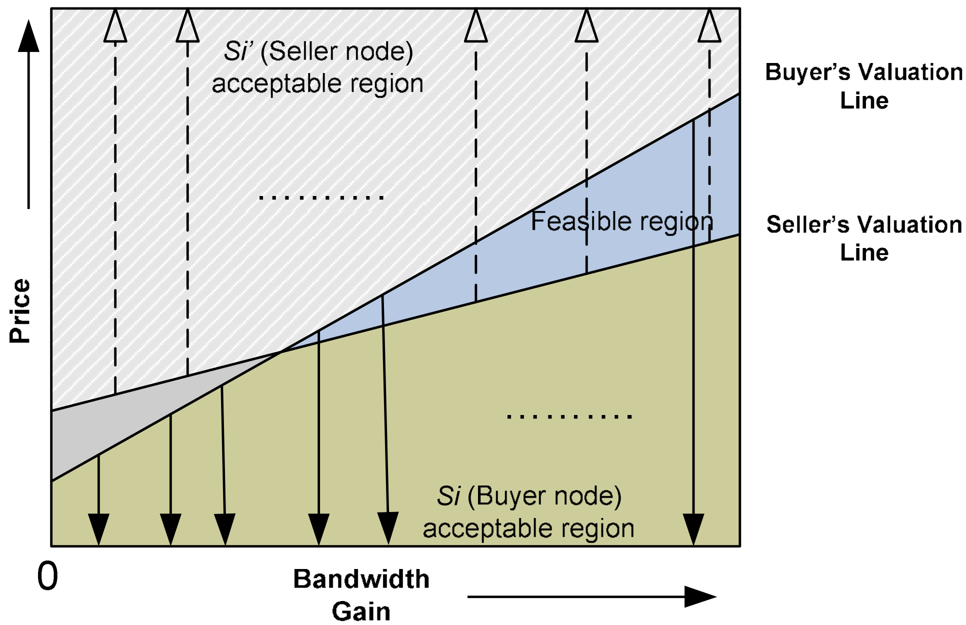


Figure 4-11: Solution Space (Feasible Region) [41].

The solution space is within the feasible region where the buyer is bound by the lower end of its valuation line *i.e,* buyer agent have high preference for the lower end of the valuation line so it will always try to pay less for the channel exchange. The seller agent, however, will always try to look for an offer nearer to its evaluation line's upper end.

The Utility of each agent is the share in the surplus generated during this non-cooperative bargaining process. Let x_i be the maximum amount of currency the buying agent is willing to pay and $x_{i'}$ be the minimum amount the selling agent will accept, then the maximum surplus can be defined as the difference between buyer's maximum buying price and the seller minimum threshold price:

$$\Delta(x_i, x_i') = x_i - x_i' \qquad (4.8)$$

Due to the strategic interaction of non-cooperative agents, the buyer will always try to offer a buying price (x_i - α) where (x_i - α) ≥ 0 by strictly preferring the points near the lower end of its valuation line; on the other hand, the selling agent will always try to offer ($x_{i'} + \partial$) preferring the upper end of its valuation line. In such a strategic interaction, the bargaining converges based on the alternating offers and counter offers as shown in the algorithm in the Figure 4-10 to find the solution space *i.e.,* the point where $x_{i'} + \partial \in \boldsymbol{A}$ or $x_i - \alpha \in \boldsymbol{A}$, where ***A*** is the set of points in the feasible region of solution space. To find such a point, we follow the method as presented in [45], where each agent accepts or rejects the offer from other based on some probability associated with it. As shown in the Table 4-1, buyer highly prefers (with zero probability of rejection) an offer from the seller demanding no payment and this preference weakens to maximum rejection when the seller's demanding offer is greater than or equal to x_i (the maximum currency the buying agent is willing to pay). Similarly, the seller highly prefers an offer from buyer which is equal to or greater than its own valuation of the channel. It is assumed that the seller knows the market value (m.v) of the channel and an offer from the buyer equal to or greater than the market value is highly preferred by the seller (offer rejected with zero probability). Buyer and seller associate a probability of rejection, based on their own evaluation, with each offer it receive from the opponent agent, as shown in the Table 4-1. Since both buying and selling agents are unaware of each other's reserved valuation, *i.e.* x_i and $x_i{}'$ following the approach in [38], the Expected Utilities of both agents are calculated from the Equation (4.8) as follows:

Buying agent's utility function when accepts seller's offer or seller accepts buyer's offer:

$$E(U^B) = (x_i - (1 - p(x_i' + \partial)) \tag{4.9}$$

$$E(U^B) = (x_i - \alpha) \tag{4.10}$$

Selling agent's utility function when it accepts buyers offer or buying agent accepts his offer:

$$E(U^S) = \left(x_i - p\left(x_i - \alpha\right) - x_i{}'\right) \tag{4.11}$$

$$E(U^S) = (x_i' + \partial) \tag{4.12}$$

Where $E(U^B)$ and $E(U^S)$ show the Expected utilities of buying and selling agents, respectively. $1 - p(x_i' + \partial)$ and $1 - p\left(x_i - \alpha\right)$ are the respective valuations probabilities of buying and selling agents which show the possibility of an offer acceptance from the opponent based on the probabilities of rejection in their respective decision tables as shown in the Table 4-1. It is clear from the Equations (4.9-4.12), that the utility functions of both buying and selling agents are derived based on the offers acceptance possibility. Each agent update their respective rejection probabilities to some lower values when its current offer is not accepted by the opponent. In this way, the bargaining game converges to the solution space during alternating offers and counter offers.

Table 4-1: Buyer and Seller Expected Value Evaluation

Offer from Seller	*Probability of rejection*	*Offer from Buyer*	*Probability of rejection*
$x_{i'} + \partial \geq x_i$	1	$x_i - \alpha \leq x_{i'}$	1
$x_{i'} + \partial_1 < x_i$	0.8	$x_i - \alpha_1 > x_{i'}$	0.8
$x_{i'} + \partial_2 < x_i$	0.6	$x_i - \alpha_2 > x_{i'}$	0.6
$x_{i'} + \partial_3 < x_i$	0.3	$x_i - \alpha_3 > x_{i'}$	0.3
$x_{i'} + \partial_4 < x_i$	0.1	$x_i - \alpha_4 > x_{i'}$	0.1
$x_{i'} + \partial_n = 0$	0	$x_i - \alpha_n \geq$ m.v	0

4.8 Sub-optimality and End Users Bargaining

Although, NE and further N-PNE are the efficient and stable outcomes for non-cooperative channel assignment games in single collision domain as in [16], the practical application scenario of WMNs consists of end user source nodes accessing Internet through multi-hop routers and Gateways. In this case, the existence of NE or N-PNE is not always an efficient solution as the end-to-end achieved data rate of any source destination pair is limited by the bottleneck link/links among the relay nodes across the path. Let R_{Si}^{e} be the end-to-end data rate achieved by a source node (Mesh Access Point), then:

$\mathrm{R_{Si}^{e}} = \mathrm{Min}(R_{l1,}R_{l2,} \ldots R_{lm})$, where *m* is the number of links between any two source destination pair (*Src_i, Dest_i*) across the multiple collision domains and $R_{l1,}R_{l2,} \ldots, R_{lm}$ are the data rates achievable on the individual links in the end-to-end path. As shown in the example of the Figure 4-12, source nodes (S_i) and relay nodes/routers are placed in two collision domains CD1 and CD2. Let the achievable data rate on a channel *c*, R_c, is normalized to 1 $\forall$ *c* $\in$ C, then the effective data rate for S_1 : $R_{S1}^{e} = Min(1.5, 1) = 1$, $R_{S2}^{e} = Min(1.5, 1) = 1$. Figure 4-13 shows a MRMC assignment as the outcome of a game fulfilling all the conditions mentioned in the Lemmas (4.1-4.5) for NE and N-PNE existence, in the first stage of the game. Although no player will deviate from the current channel assignment strategy individually, it is clear that the outcome is not social optimal in the source nodes prospective as node S_2 can do better off, if it exchanges its channel c_1 in its end-to-end path with the channel c_4 in the end-to-end path of S_1 at CD3. It is clear from the diagram that such an exchange does not affect the end- to-end data rate of S_1. The game so far studied in this chapter is non-cooperative in nature and such an exchange is not possible keeping in view the selfish nature of players.

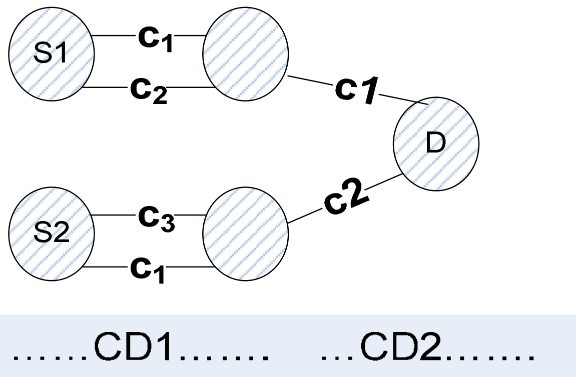
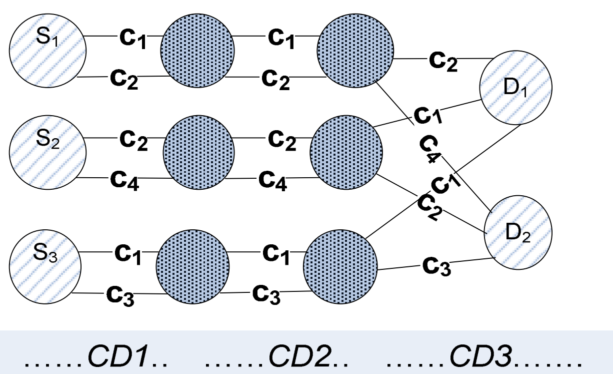


Figure 4-12: The effect of bottleneck links on end-to-end throughput



c_1	c_2	c_3	c_4
S_3	S_2		
S_1	S_1	S_3	S_2

c_1	c_2	c_3	c_4
S_3	S_2		
S_1	S_1	S_3	S_2

c_1	c_2	c_3	c_4
S_3	S_2		
S_2	S_1	S_3	S_1

Figure 4-13: An example NE/N-PNE Channel Assignment

4.8.1 End Users Bargaining Game Design

Similar to the bargaining mechanism as discussed in the Section 1.7.3, we introduce a Non-Cooperative alternating offer bargaining mechanism has been introduced in this sub-section.

We define the source nodes as the set of bargaining agents S={S_1,S_2,..,$S_{|S|}$}, where |S| shows the cardinality of the set S being the Mesh Access Points (MAPs) of WMNs at different sites as shown in the Figure 4-2, Section 4.4. The MAPs are assumed to be in the same collision domain or are connected with each other via multi-hop fashion. It is assumed that each bargaining agent has some virtual currency, *p*, which can be used during the bargaining process. Being rational, each agent aims to maximize its end-to-end data rate, being the buyer or the amount of currency, being the seller. The result of bargaining is either in breakdown or success, where breakdown means both agents fail to reach an agreement during the specific time. A success in the bargaining process means an exchange of channel between the buyer and seller in the end-to-end paths across the WMNs backbone in a mutual beneficial way. All agents are assumed to have full knowledge of the network topology in the form of a Global Link Topology Matrix (GLTM) *i.e.,* all links, associated interferences, and the channels assigned to them in the form of the outcome of the game in first stage. The bargaining process is scheduled just after the NE or N-PNE outcome of the non-cooperative game and is performed in a pre-determined equally spaced time T={t_1,t_2,t_3,…,t_n}. Each agent S_i reveals its end-to-end data rate, R^e_{Si}, along with the channel across the end-to-end sessions, at the process initialization. After computing R^e_{Si} againstR^e_{-Si}, an agent signals either 1 or 0 in a broadcast message to show its willingness for the bargaining. Those agents who signal 0 are excluded from the agents set. We model the non-cooperative bargaining process as an alternating offers game as defined in [38], where two agents, S_i and $S_{i'}$, enter into a negotiation as buyer and/or seller and reach to an agreement on certain point for a bargaining game. The seller agent S_i negotiates an amount of currency p'≤ p, with the buyer S_i', and upon agreement, an exchange of channels (c_i <- ->$c_{i'}$) takes place in the Global Link Topology Matrix. The bargaining process ends when the pre-determined time T elapses.

Selling and buying agents evaluate their preference differently during the bargaining game. For seller, money is important in terms of virtual currency and so its whole dependency is on the variable *p*. For buyers, both currency *p* and channel benefit in terms of end-to-end bandwidth gain worth during the evaluation process. Alternating offers bargaining model starts with the buying agent S_i offering an amount p^0 lying within its acceptable region, at time t=0, to the selling agent $S_{i'}$. If the offer is above selling agent's valuation line, it is accepted; otherwise the offer is rejected as being outside its feasible region. Alternatively, selling agent $S_{i'}$ asks for an amount q^1 lying above its valuation line at time t_1. If this asking amount is below the buying agent S_i valuation line, it is accepted; otherwise rejected.

This procedure is continued by both buying and selling agents in another round each time incrementing time *t,* till both reach to the point which is mutually acceptable feasible set [38]. Considering both players are highly rational and in non-cooperative environment, each one will try to maximize their own profit without caring for the others.

The solution space is within the feasible region where the buyer is bound by the lower end of its valuation line *i.e,* buyer agent have high preference for the lower end of the valuation line so it will always try to pay less for the channel exchange. The seller agent, however, will always try to look for an offer nearer to its evaluation line's upper end.

As in the previous section, the Utility of each agent is the share in the surplus generated during this non-cooperative bargaining process. Let y_i be the maximum amount of currency the buying agent is willing to pay and $y_{i'}$ be the minimum amount the selling agent will accept, then the maximum surplus can be defined as the difference between buyer's maximum buying price and the seller minimum threshold price:

$$\Delta(y_i, y_i') = y_i - y_i' \tag{4.13}$$

Due to the strategic interaction of non-cooperative agents, the buyer will always try to offer a buying price (y_i - α) where (y_i - α) ≥ 0 by strictly preferring the points near the lower end of its valuation line; on the other hand, the selling agent will always try to offer ($y_{i'} + \partial$) preferring the upper end of its valuation line. In such a strategic interaction, the bargaining converges based on the alternating offers and counter offers as shown in the algorithm in the Figure 4-10 to find the solution space *i.e.,* the point where $y_{i'} + \partial \in \boldsymbol{A}$ or $y_i -$

$\alpha \in \boldsymbol{A}$, where $\boldsymbol{A}$ is the set of points in the feasible region of solution space. To find such a point, each agent accepts or rejects the offer from other based on some probability associated with it. Since both buying and selling agents are unaware of each other's reserved valuation, *i.e.* y_i and $y_i{}'$ following the approach in [38], the Expected Utilities of both agents are calculated from the Equation (4.13) as follows:

Buying agent's utility function when accepts seller's offer or seller accepts buyer's offer:

$$E'(U^B) = (y_i - (1 - p(y_i' + \partial)) \quad (4.14)$$

$$E'(U^B) = (y_i - \alpha) \quad (4.15)$$

Selling agent's utility function when it accepts buyers offer or buying agent accepts his offer:

$$E'(U^S) = \left(1 - p\left(y_i - \alpha\right) - x_i{}'\right) \quad (4.16)$$

$$E'(U^S) = (y_i' + \partial) \quad (4.17)$$

Where $E'(U^B)$ and $E'(U^S)$ show the Expected utilities of buying and selling agents, respectively. $1 - p(y_i' + \partial)$ and $1 - p\left(y_i - \alpha\right)$ are the respective valuations probabilities of buying and selling agents which show the possibility of an offer acceptance from the opponent based on the probabilities of rejection in their respective decision tables. It is clear from the Equations (4.14-4.17), that the utility functions of both buying and selling agents are derived based on the offers acceptance possibility. Each agent update their respective rejection probabilities to some lower values when its current offer is not accepted by the opponent. In this way, the bargaining game converges to the solution space during alternating offers and counter offers.

4.9 Simulation Setup and Performance Evaluation

This section presents the performance evaluation of the proposed game theoretic models and show their numerical results in terms of nodes individual fairness and comparative throughputs. The comparison is performed between the proposed game theoretic model and a similar approach in the multiple collision domains [22]. In the second subsection, we investigate the effect of end-to-end non-cooperative bargaining on the QoS provisioning and its effect on end nodes (clients) in terms of their measured and expected throughputs.

4.9.1 Throughput and Fairness Analysis at Game Convergence

For simulation purposes, the proposed Game Theoretic models were implemented in MATLAB [42]. Throughout simulations, IEEE 802.11a [27] standard is considered with the default value of C=8 orthogonal channels. A network topology consisting of 20 nodes was considered, each having *K*=2 radios.

Figure 4-12 shows the simulation setup for the case of the proposed multiple collision domain topology. The nodes are placed in an area of 300 x 300 meters. A distance of 50 units between the nodes was considered as their transmission range. Similarly, the interference range was considered as twice (100 meters in each direction) of the transmission range. In the multiple collision domain topologies, nodes experience the interference from only those nodes, which are inside their interference range. Simulation parameters (Number of channels, radios, achievable data rate on each channel) were kept for both the approaches during simulation. The simulation setup was run 40 times and the average results were plotted.

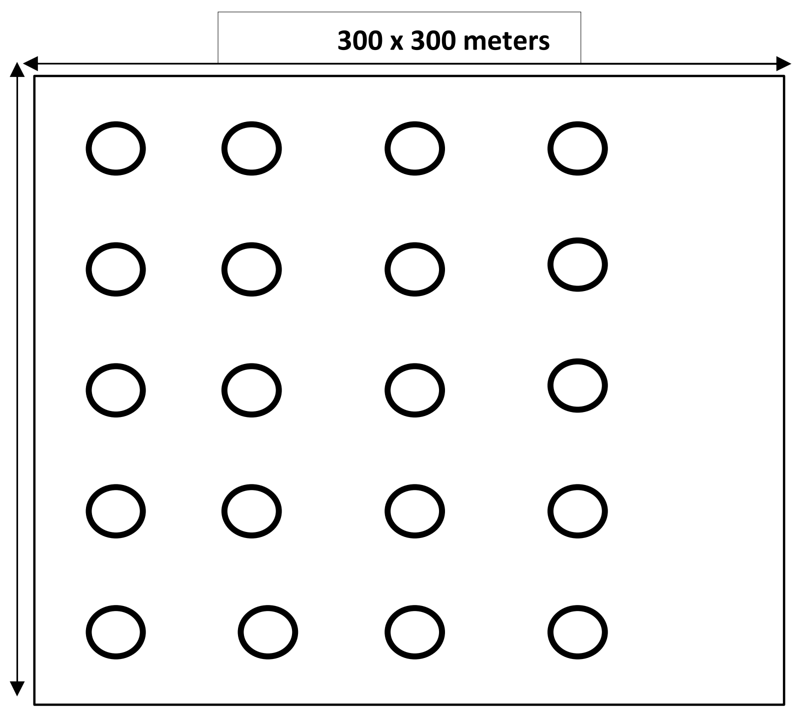


Figure 4-14: Simulation scenarios for MRMC models in competitive WMNs.

Figure 4.13 compares the individual payoffs in terms of total throughputs achieved by each node of the network using the proposed distributed algorithm against the one proposed in one of the relevant work with perfect information [22]. The results were obtained when both the systems converge to the NE [22] and NE or N-PNE (proposed). The results show that the proposed distributed algorithm significantly outperforms the one presented in [22], in terms of achieved throughput per player. The reason is that the proposed model considers the nodes as the players of the game instead of the network links. This gives a possibility to the nodes to assess the channel conditions more accurately in their respective collision domains. Further, the improvement in the throughput is due to the fact that each node opt for bargaining where there is a chance to increase its data rate. Whereas, in the case of NE, channel assignment decisions are one sided binding considering the common link as the player of the game. It may be the case that the node, which binds the channel assignment agreements with a neighbouring node, might not have the same knowledge of the channel interferences as experienced by its neighbour. However, in some cases, *e.g.* nodes 15 and 16, both approaches yield the same results. This might be due to the reason that in the proposed N-PNE there was no bargaining involved for these nodes.

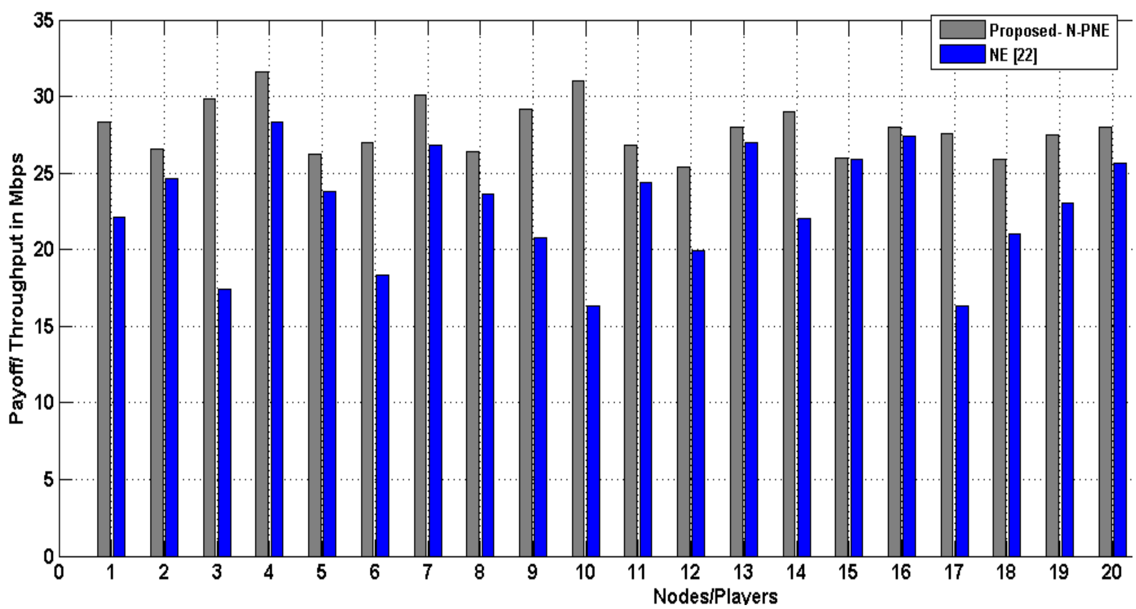


Figure 4-15: Nodes Throughput Comparison

Figure 4-14 compares the max-min throughput/payoff difference of the proposed bargaining game theoretic solution with the scheme as presented in [22]. Max-min throughput difference is defined as the “difference between the flow which gets maximum throughput and the flow that gets minimum throughput” in a given setup [19]. The simulation setup was run for different group of players ranging from 5 to 30 in step 5.It can be observed from the results that the proposed game theoretical scheme, when converge to N-PNE, outperforms the NE solution of the distributed algorithm presented in [22], both with perfect information. The max-min difference is low and almost the same for both the systems when the number of nodes are less. However, when the number of nodes in the topology increases, an exponential growth in the max-min difference is observed for the NE. The proposed scheme also shows a similar behaviour when converge to N-PNE. This is because, for small group of nodes, there is high possibility that each node gets the same share of channel resource. However, when the number of players increases in the game, the max-min payoff difference increases. Since, more players mean more competition and more chances of players being subjected to varying degrees of interference and therefore it results in more max-min payoff difference. Comparatively, the proposed scheme outperforms the one in [20] when the number of players in the game increases. This is because, in the proposed scheme, more nodes mean more chances of non-cooperative bargaining and thus it leads to a more fair channel resource share across the backbone of the network.

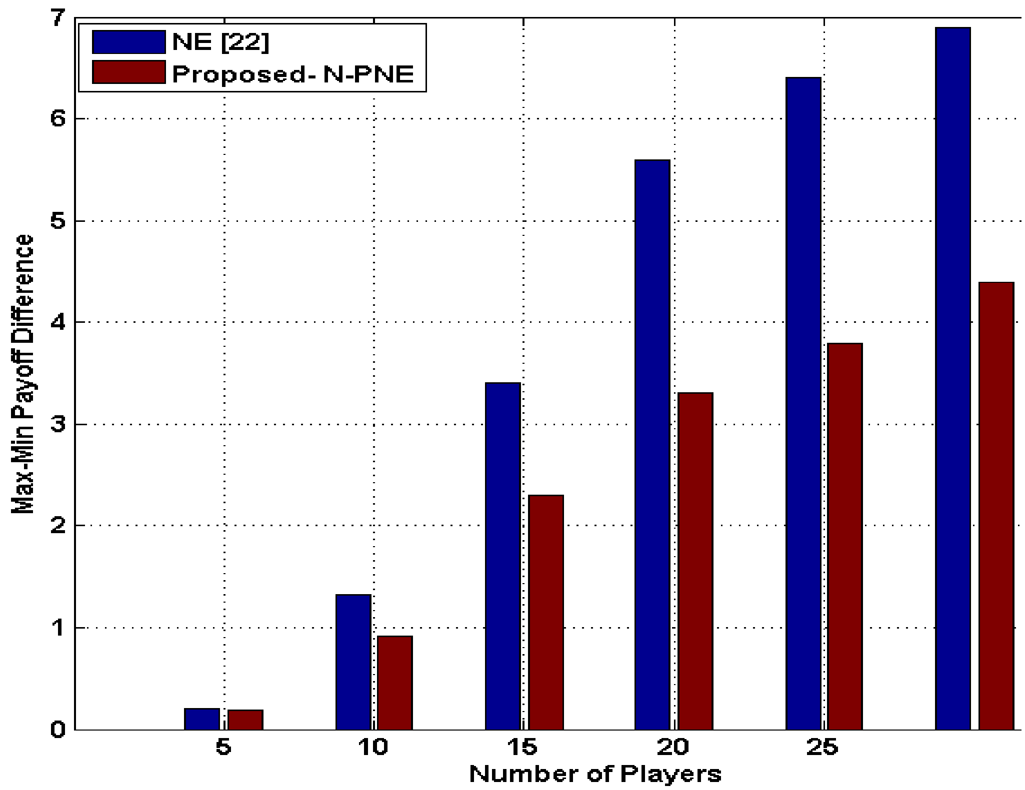


Figure 4-16: Max-Min Payoff Difference

The fairness of both proposed algorithm was computed and compared with the centralized and distributed (perfect information) algorithms of [22] by using Jain Fairness Index [43] using the following equation.

$$\text{Jain Fairness Index}=\frac{\left(\sum_{i=1}^{n} \mathrm{x}_i\right)^2}{n.\sum_{i=1}^{n} \mathrm{x}_i^2} \tag{4.13}$$

Jain Fairness Index varies from 0 being the worst to 1 being the best.

Using Jain Fairness Index, the results were plotted for 15 independent rounds for a network of 20 nodes, each for both the proposed as well as the centralized and distributed algorithms of [20]. Each round is the average of 40 simulation runs. As depicted in the Figure 4-15, the comparative results show that the nodes get fairer share of the channel resources in the case of the centralized algorithm at NE [22], as compared to the proposed as well as the distributed algorithm at NE presented in [22]. This is because centralized algorithm runs under a single authority with a perfect sequential order. On the other hand, distributed algorithm runs on each node independently and the arbitration between the players moves is achieved through the *backoff* window W, which is based on probability and is not always perfect. For some round, *e.g,* round 9, the comparative Fairness Index for is almost equal for the centralized algorithm and our proposed scheme. This is because, the distributed algorithm sometimes performs as good as the centralized one in certain situations. In the presented result, the good performance of distributed algorithm might be due to the reason that the information available with the nodes are as complete as for a centralized authority. The same behaviour has been reported in the research work while comparing the centralized and distributed algorithms in [41]. The weak point of the centralized algorithm is that it needs to know the whole network topology and the links interferences details. Other disadvantage is the failure of the central authority causes the system a standstill.

The proposed bargaining solution performed better at N-PNE than that of the distributed algorithm at NE in [22], both with perfect information. This is because the proposed scheme uses node as the unit of analysis and therefore have more perfect information regarding the interference in the vicinity. On the other hand, the distributed algorithm, as presented in [22], when converges to NE might not yield the fairer outcome because of the imperfection in the information. Since the distributed algorithm presented in [22] considers the link as the unit of analysis and hence the player of the game, while the proposed N-PNE scheme uses node as the unit of analysis. This gives added advantage to the proposed scheme to capture the interference phenomenon more accurately and hence resulting in more fair share of the channel resource after bargaining. Results for fairness index shows that on average, very good fairness averaging 0.87 is achieved in the case of centralized algorithm [22]. While, good to moderate fairness averaging 0.79 and 0.748 is achieved by both the proposed scheme and the distributed algorithm as presented in [22].

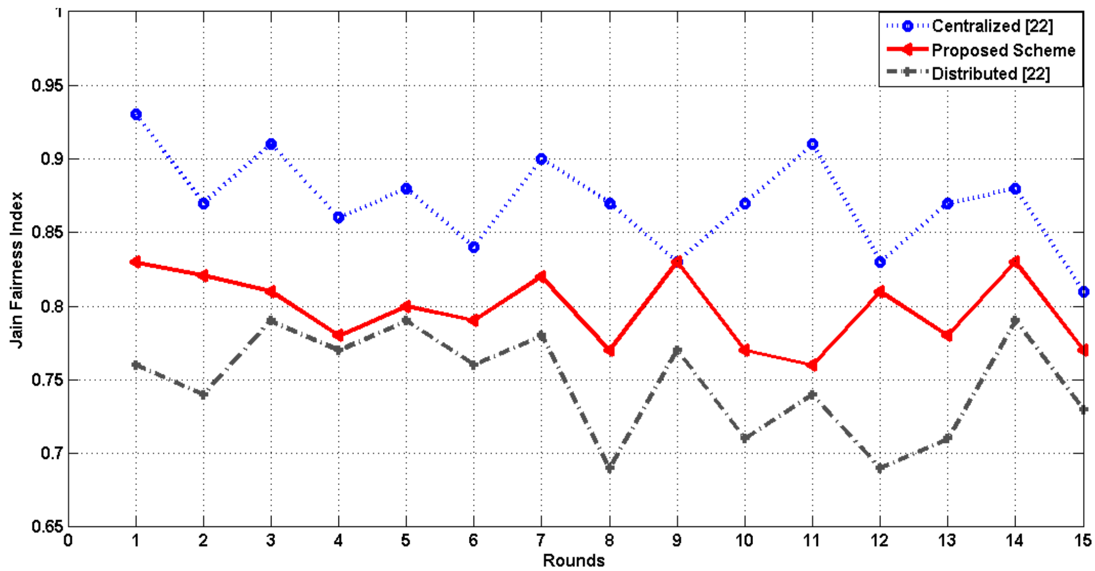


Figure 4-17: Fairness index in rounds

Figure 4-16 shows the effect of varying the number of radios, per node, on the throughput of individual nodes. It should be noted that only 10 nodes are selected randomly to show this effect. As shown in the Figure 4-16, the throughput increases for all nodes with an increase in the number of radios. The main reason of this increase in throughput is the very characteristic of the MRMC. More radios in a topology mean more connections and hence more chances to occupy the bandwidth keeping in view the number of orthogonal channels.

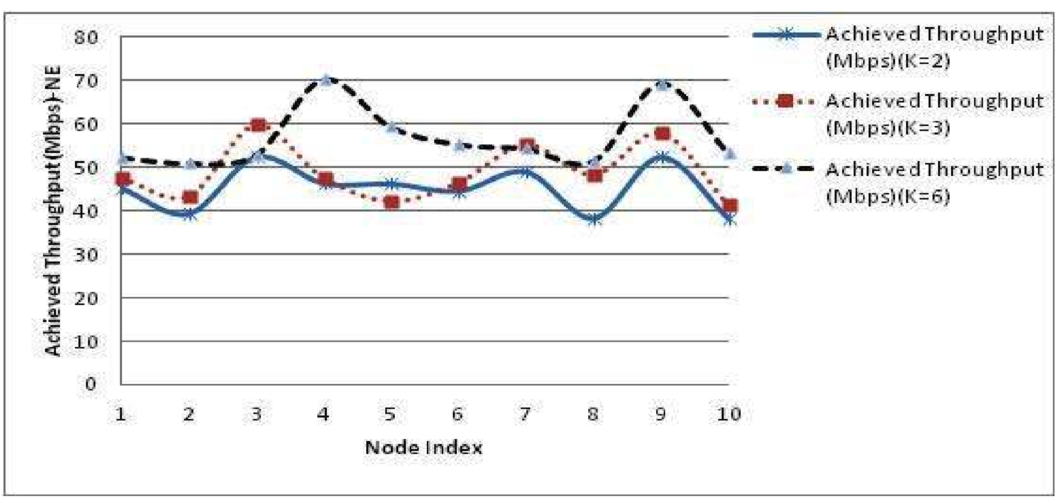


Figure 4-18: Varying number of radios per node

4.9.2 Throughput and QoS Analysis at Bargaining Equilibrium

As mentioned in the Section 4.8, the end-to-end date rate of the originating source nodes depend on the quality of channels in their session paths. End user's non-cooperative game was implemented with a alternative offer bargaining strategies. This algorithm, however, was only implemented on the end users *i.e,* the MAPs after the establishing of N-PNE. Figure 4-17 shows the results for a simulation setup when the end users come in a strategic bargaining set up. The figure compares the end-to-end throughput of end nodes at N-PNE (stage-1) with that of the end-users bargaining at the stage-2 of the game. As shown in the Figure 4-17, two end nodes (node 5 and 4) increase their end-to-end throughput by coming in a bargaining contact with other nodes from the same set. This should be noted, however, that this bargaining does not affect the end-to-end throughput of the seller agent.

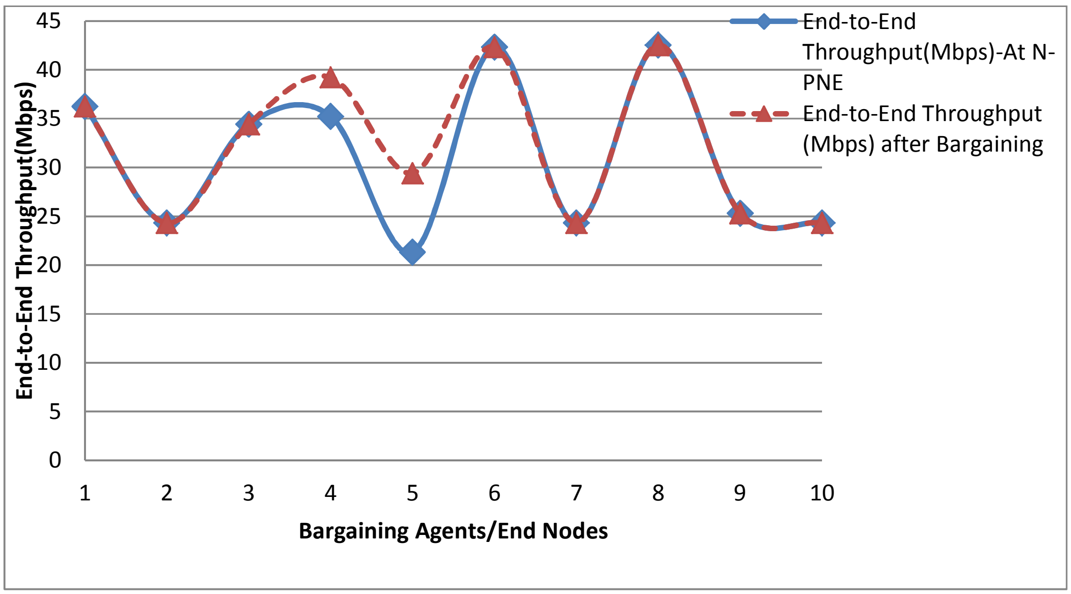


Figure 4-19: Bargaining gain

To show the significance of end users bargaining, a simulation setup was run for 10 end node bargaining agents (MAPs). The network density was kept the same as in the Section 4.9.1, with each node having two radios. A separate script was written in MATLAB to record of the quality of service requirements in terms of confirmed service of 64kbps to be run only on those nodes that go for bargaining. 15 client nodes (those user nodes who access the WMN's backbone through Mesh Access Points, as shown in the Figure 4-2, in the lower tier) were setup for the experiment.

The result in the Figure 4-18 shows Quality of Expectation (QoE) of clients which is constant as 64kbps, shown by the constant blue line in the graph. Bargaining outperform N-PNE in terms of QoS with a significant margin. The reason is that after end-users bargaining, the buyer gets extra end-to-end confirmed bandwidth and hence can serve it's more clients with their requirements comparatively.

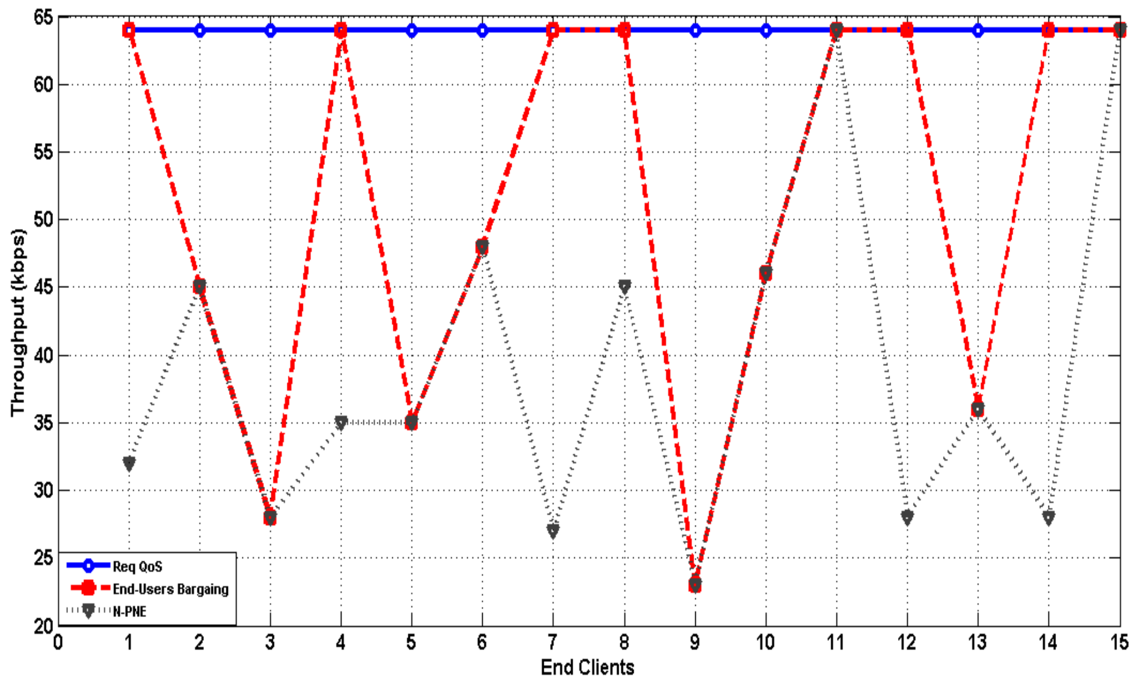


Figure 4-20: End-clients QoS provisioning in Bargaining

4.10 Summary

This chapter presents a two non-cooperative game theoretical model and studies the interaction of WMN's nodes during channel assignment and re-assignment, in a strategic setup. In stage 1, sufficient conditions have been derived for the existence of NE and N-PNE. Each node of the WMN has been considered as they unit of analysis during the game, *i-e.,* the player of the game. Since NE is not a system optimal solution, therefore, a bargaining mechanism has been developed to enable the rational nodes for pre-play communication. Based on perfect information, a distributed algorithm was developed for channel assignment in competitive environment, where network nodes achieve a good fairness (based on Jain Fairness Index=0.79), on average. It is analytically proved that the N-PNE, and hence NE, is not a social optimal solution in the end users' prospective. In the second stage of the game, the end users Mesh Access Points (MAPs) come into contact with each others and bargain on the channels in their end-to-end paths. Two MAPs bargain with each other when the channel exchange in their end-to-end paths has an advantage for one MAP in terms of throughput and for the other in terms of money. This channel exchange has been modelled with a non cooperative bargaining game, where both bargaining agents have imperfect information during the strategic interaction. The non-cooperative bargaining mechanism proved to further improve the end-to-end achievable data rate of source nodes as compared to NE for their QoS requirements.

4.11 References

[1] I. F. Akyildiz, X. Wang and W. Wang, "Wireless mesh networks: a survey," Computer Networks, vol. 47, pp. 445-487, 2005.

[2] I. Shah, S. Jan, K. K. Loo and C. E. A. Campbell, "Selfish Flow Games in Non-Cooperative Multi-Radio Multi-Channel Wireless Mesh Networks With Interference Constraint Topology," International Journal on Advances in Telecommunications, vol. 4, pp. 172-182, 2011

[3] L. Xue, "Negotiation-proof Nash equilibrium," International Journal of Game Theory, vol. 29, pp. 339-357, 2000..

[4] J. Sutton, "Non-cooperative bargaining theory: An introduction," The Review of Economic Studies, vol. 53, pp. 709, 1986.

[5] M. Perry and P. J. Reny, "A non-cooperative bargaining model with strategically timed offers," J. Econ. Theory, vol. 59, pp. 50-77, 1993.

[6] L. Santhanam, B. Xie and D. Agrawal, "Selfishness in mesh networks: wired multihop MANETs," Wireless Communications, IEEE, vol. 15, pp. 16-23, 2008.

[7] S. Basagni, M. Conti, S. Giordano and I. Stojmenović, Mobile Ad Hoc Networking. Wiley-IEEE Press, 2004.

[8] I. Katzela and M. Naghshineh, "Channel assignment schemes for cellular mobile telecommunication systems: A comprehensive survey," Personal Communications, IEEE, vol. 3, pp. 10-31, 1996.

[9] K. Marina, S. R. Das, and A. P. Subramanian, "A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks," Computer Networks, vol. 54, pp. 241-256, 2010.

[10] A. Raniwala and T. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in Proceedings IEEE INFOCOM 2005. 24th

Annual Joint Conference of the IEEE Computer and Communications Societies, Miami USA, pp. 2223-2234, 2005.

[11] M. Alicherry, R. Bhatia, and L. E. Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks," in Proceedings of the 11th Annual International Conference on Mobile Computing and Networking, Cologne, Germany , pp. 58 - 72 . 2005.

[12] D. Niyato and E. Hossain, "Competitive pricing for spectrum sharing in cognitive radio networks: Dynamic game, inefficiency of nash equilibrium, and collusion," Selected Areas in Communications, IEEE Journal on, vol. 26, pp. 192-202, 2008.

[13] M. M. Halldórsson, J. Y. Halpern, L. E. Li and V. S. Mirrokni, "On spectrum sharing games," in Proceedings of the Twenty-Third Annual ACM Symposium on Principles of Distributed Computing, pp. 107-114, 2004.

[14] R. Zhang and Y. C. Liang, "Exploiting multi-antennas for opportunistic spectrum sharing in cognitive radio networks," Selected Topics in Signal Processing, IEEE Journal of, vol. 2, pp. 88-102, 2008.

[15] Z. Ji and K. J. R. Liu, "Cognitive radios for dynamic spectrum access-dynamic spectrum sharing: A game theoretical overview," Communications Magazine, IEEE, vol. 45, pp. 88-94, 2007.

[16] M. Felegyhazi, M. Cagalj, S. Bidokhti, J. P. Hubaux, and L. EPFL, "Non-cooperative multi-radio channel allocation in wireless networks," in IEEE INFOCOM 2007. 26th IEEE International Conference on Computer Communications, Alaska, USA, pp. 1442-1450, 2007.

[17] F. Wu, S. Zhong and C. Qiao, "Globally optimal channel assignment for non-cooperative wireless networks," in INFOCOM 2008. the 27th Conference on Computer Communications. IEEE, pp. 1543-1551, 2008.

[18] F. Wu, S. Zhong and C. Qiao, "Strong-incentive, high-throughput channel assignment for noncooperative wireless networks," Parallel and Distributed Systems, IEEE Transactions on, vol. 21, pp. 1808-1821, 2010.

[19] T. Chen and S. Zhong, "Perfectly fair channel assignment in non-cooperative multi-radio multi-channel wireless networks," Comput. Commun., vol. 32, pp. 1058-1061, 2009.

[20] L. Gao and X. Wang, "A game approach for multi-channel allocation in multi-hop wireless networks," in Proceedings of the 9th ACM International Symposium on Mobile Ad Hoc Networking and Computing, Hong Kong, China, pp. 303-312, 2008.

[21] J. Xiao, N. Xiong, L. T. Yang, and Y. He, "A joint selfish routing and channel assignment game in wireless mesh networks," Comput. Commun., vol. 31, pp. 1447-1459, 2008.

[22] R. D. Vallam, A. A. Kanagasabapathy and C. S. R. Murthy, "A non-cooperative game-theoretic approach to channel assignment in multi-channel multi-radio wireless networks," Wireless Networks, vol. 17, pp. 411-435, 2011.

[23] T. Chen, F. Wu and S. Zhong, "On Designing Protocols for Non-cooperative Multi-Radio Channel Assignment in Multiple Collision Domains," A technical report: *www.cse.buffalo.edu/tech-reports/2011-05.pdf* Last accessed: 10/01/2012

[24] L. Cao and H. Zheng, "Distributed spectrum allocation via local bargaining," in Proc. IEEE SECON, 2005

[25] Q. Ni and C. C. Zarakovitis, "Nash Bargaining Game Theoretic Scheduling for Joint Channel and Power Allocation in Cognitive Radio Systems," Selected Areas in Communications, IEEE Journal on, vol. 30, pp. 70-81, 2012.

[26] J. van den Heuvel, R. A. Leese, and M. A. Shepherd, “Graph labelling and radio channel assignment,” Journal of Graph Theory 29:263-283, 1998.

[27] http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=6606, last accessed: 21/06/2010

[28] IEEE 802.11b/g: www.ieee.org/, last accessed: 22/12/2010

[29] IEEE 802.11n; www.ieee.org/, last accessed: 22/12/2010

[30] K. Xu, M. Gerla and S. Bae, "How effective is the IEEE 802.11 RTS/CTS handshake in ad hoc networks," in Global Telecommunications Conference, 2002. GLOBECOM'02. IEEE, pp. 72-76 vol. 1, 2002.

[31] K. Jain, J. Padhye, V. N. Padmanabhan and L. Qiu, "Impact of interference on multi-hop wireless network performance," Wireless Networks, vol. 11, pp. 471-487, 2005.

[32] M. J. Osborne and A. Rubinstein, A Course in Game Theory. The MIT press, 1994.

[33] S. B. Bacharach and E. J. Lawler, Bargaining: Power, Tactics and Outcomes. Jossey-Bass Inc., 433 California Street, San Francisco, CA 94104, 1981

[34] A. Muthoo, Bargaining Theory with Applications. Cambridge Univ Pr, 1999.

[35] K. Binmore, A. Rubinstein and A. Wolinsky, "The Nash bargaining solution in economic modelling," Rand J. Econ., pp. 176-188, 1986.

[36] J. F. Nash Jr, "The bargaining problem," Econometrica: Journal of the Econometric Society, pp. 155-162, 1950.

[37] A. Rubinstein, "A sequential strategic theory of bargaining," Advances in Economic Theory, T.Bewley (Ed.), Cambridge University Press, London, pp. 197-224, 1987.

[38] R. H. Wagner, "A noncooperative solution to a two-person bargaining game," Theory Decis., vol. 21, pp. 311-335, 1986.

[39] C. Mudgal and J. Vassileva, "Bilateral negotiation with incomplete and uncertain information: a decision-theoretic approach using a model of the opponent,"

Cooperative Information Agents IV-the Future of Information Agents in Cyberspace, pp. 1-43, 2000.

[40] K. Chatterjee and L. Samuelson, "Bargaining with two-sided incomplete information: An infinite horizon model with alternating offers," The Review of Economic Studies, vol. 54, pp. 175, 1987.

[41] P. Winoto, G. McCalla and J. Vassileva, "An extended alternating-offers bargaining protocol for automated negotiation in multi-agent systems," On the Move to Meaningful Internet Systems 2002: CoopIS, DOA, and ODBASE, pp. 179-194, 2002.

[42] MATLAB v. R2007a: www.mathworks.com/products/matlab/ , Last accessed: 24/02/2012

[43] R. Jain, A. Durresi and G. Babic, "Throughput fairness index: An explanation," in ATM Forum Contribution 99, 1999.

[44] Celandroni, N., Ferro, E., and Potort´ı, F., “Comparison between distributed and centralised demand assignment TDMA satellite access schemes.” International Journal of Satellite Communications V. 14, No. 2 (Mar.–Apr. 1996), pp. 95–111.

[45] P. Ghosh, N. Roy, S. K. Das and K. Basu, "A pricing strategy for job allocation in mobile grids using a non-cooperative bargaining theory framework," Journal of Parallel and Distributed Computing, vol. 65, pp. 1366-1383, 2005.

CHAPTER 5

Flow Routing in Competitive Wireless Mesh Networks

5.1 Introduction

As the technology evolved, Wireless Mesh Networks (WMNs) routers are nowadays equipped with multiple interfaces/radios due to their static nature and availability of permanent power supplies. This added advantage enables them to achieve parallel communication sessions among nodes. Assigning distinct non-overlapping channels to each set of communicating radio-link increases network connectivity and throughput. On the other hand, the performance of wireless networks is always limited by the inter-flow and intra-flow interference [1] phenomena among the concurrent transmission sessions. The topology of WMNs is interference constrained due to the limited non-overlapping available channels [2], selfishness of end users to transport their data further degrades individual fairness and affects overall network performance due to their protocol deviation in a non-cooperative environment [3].

In this chapter, a non-cooperative game theoretical model is proposed in a MRMC WMNs [38], based on the competing end users who route their data flows in an interference constrained topology. The end user nodes are selfish and compete for the channel resources across the WMNs backbone aiming to maximize their own benefit, without taking care for the overall system optimization. End-to-end throughput achieved by the flows of an end node and interference experienced across the WMNs backbone are considered as the performance parameters in the utility function. Theoretical foundation has been drawn based on the concept from Game Theory and necessary conditions for the existence of Nash Equilibrium have been extensively derived. A distributed algorithm running on each end node with imperfect information has been implemented to assess the usefulness of the proposed mechanism.

The analytical results have proven that a pure strategy Nash Equilibrium exists with the proposed necessary conditions in a game of imperfect information. Based on a distributed algorithm, the game converges to stable state in finite time and all channels are perfectly load-balanced at the end of the game. Simulation results show that standard deviation of player's throughputs is less than that of random channel selection scheme in long run. Furthermore, the Price of Anarchy of the system is close to one showing the efficiency of the proposed scheme.

5.2 Related Work

Application of game theory to networks is not new and a huge amount of literature can be found at different layers of the protocol stack. In [4], for example, congestion control has been analyzed using game theory while the studies of [5, 6, 7] have addressed network routing games in general. Power control games have been extensively studied in [8, 9], while Medium Access Control has been analyzed by using game theoretical analysis in [10, 11]. A detailed survey targeting the telecommunication problems using game theory can be found in [12]. Similarly, game theory applications in wireless networks can be found in [13].

Due to the practical importance of WMNs, considerable amount of research efforts have been made for designing an intelligent MRMC technique. In [14], authors have addressed MRMC with a graph theoretic approach while A. Raniwala *et al.* [15] have presented MRMC models based on flows. The work of M. Alicherry *et al.* [16] addresses routing and channel assignment as a combined problem. Although all of the above research work have tackled MRMC from different aspects but they have considered that all the nodes cooperate with each other for system wide throughput optimization and selfish behavior has been explicitly ignored.

In one of their pioneering work, Felegyhazi *et al.* [17] have proven the existence of Nash Equilibrium in a non-cooperative multi radio multi channel assignment. They have formulated channel assignment as a game where nodes, equipped with multiple radios, compete for shared multiple channels in a conflict situation and the result shows that the system converges to a stable Nash Equilibrium where each player gets equal and fair share of the channel resources. The work of Chen *et al.* [18] is an extension of [17] where perfect fairness has been provided to all players by improving the max-min fairness. Despite the interesting results, their work is limited to single collision domain. However multi-hop networks like WMNs, span multiple collision domains and hence all the above cited work cannot be applied to this scenario. In one of the recent study presented by Gao *et al.* [19], have provided a more practical approach by extending the number of hops in the mesh backbone. They have proved that allowing coalition among players can lead to node level throughput improvement. They have provided a coalition-proof Nash Equilibrium and algorithms to reduce the computational complexity of equilibrium convergence; their solution considers cooperation among the nodes inside the coalition and hence cannot be applied to a fully non-cooperative WMNs environment. More importantly, it is more apposite to consider end users generating flows as players of the game [18] because of their competition for the common channel resource across the wireless mesh backhaul. In such a situation, channel assignment and flow routing may be tackled simultaneously. It is worth mentioning here that all of the above cited studies have tackled the channel assignment problem only in the MRMC wireless networks.

A class of game theoretical model for routing in transportation networks has been presented by Rosenthal. [20]. The author has considered *n* players in a competitive environment, each wants to ship one unit from source to destination while minimizing its transportation cost. The existence of pure strategy Nash Equilibrium has been proven in this model. In [21, 22], authors have provided game theoretic solutions based on end users flows to control congestion inside the communication network. Their work is more related to the transport layer TCP of the TCP/IP protocol stack. Routing in general wired networks has been studied as a non-cooperative game in [23, 24, 25, 26, 27], where conditions for the existence of Nash Equilibrium has been derived. Banner *et al.* [28] have extensively studied the non-cooperative routing problem in wireless networks based on split-able and unsplit-able flows. Although, they have proven the existence of Nash Equilibrium for both classes of flow problems; their solution is not applicable to MRMC WMNs. Selfish routing over the Internet has been studied in [29] where authors have incorporated link load and link delays as their cost metric in the utility function. Although, their work is more relevant, however, they have ignored the interference constraint due to the wired nature of the network model considered. In [30], selfish routing and channel assignment in wireless mesh networks is formulated as a Strong Transmission Game, where it is assumed that selfish nodes at the user premises assign channels, in a strategic setup, to their end to end paths. While they have solved channel assignment and routing problem in a non-cooperative environment from the end users selfish prospective, the strong assumption of non-interference among channels needs a large set of orthogonal frequencies which is limited by the fewer channels available in the IEEE 802.11 a/b/g/n standards [31, 32, 33]. In practice, channel assignment is always an interference constrained phenomena due to the availability of fewer channels in the orthogonal frequency set of ISM band [34] and large backbone size of WMNs. This work looks at the routing in a MRMC WMNs from the selfish end users of the network. To the best of our knowledge, this is the first work in the area of flow routing in a MRMC WMNs with interference constrained topology.

5.3 System Model and Concepts

As shown in the Figure 5-1, mesh routers having multi radio capabilities reside in multiple collision domains. It is assumed that channels are assigned to the multiple radios of

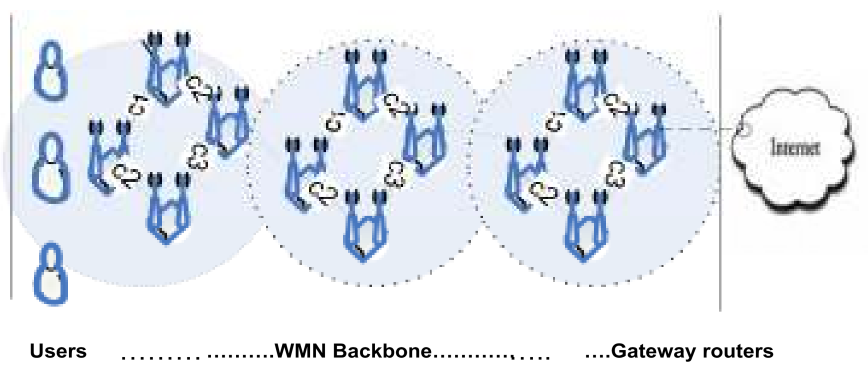


Figure 5-1: WMNs Components

the mesh routers as in the Chapter 4 and there is always a chance of channel usage conflict across the mesh backbone. Each end user uses the WMNs backbone for Internet access having specific flows to transfer from users premises to the Internet via WMNs gateways, as shown in the Figure 5-2.

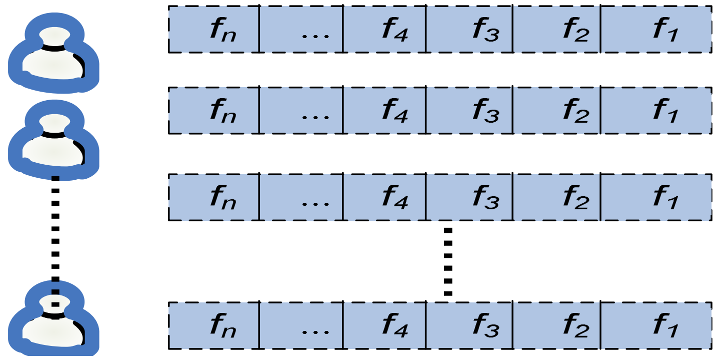


Figure 5-2: WMNs end users flows

5.3.1 Network Model

Multi-hope WMNs spanning multiple collision domains is presented with a Graph G (V, E) [35], where the sets V and E represent mesh backhaul routers and their associated links accordingly in the graph G. It is assumed that each mesh router uses same transmission power on all of its radios, as described in IEEE 802.11 a/b/g/n standards [31, 32, 33]. Any two mesh routers v_i and v_j ∈ V can communicate with each other successfully, if the Euclidian Distance between them is less than the sum of their radii, *i. e*. for any two routers $(v_i, v_j) \in V$:

$$\mathrm{d}\left(v_i, v_j\right) < r_{vi} + r_{vj} \tag{5.1}$$

where $\mathrm{d}\left(v_i, v_j\right)$ is the Euclidian distance between the vertices v_i and v_j whereas r_{vi} and $r_{vj}$are their respective radii. In other words, they are in the transmission range of each others; as shown in the Figure 5-3 by smaller circles around the vertices. Let the interference range of a node is represented by the outer circle, whose radius is twice as that of smaller circle, then two set of nodes(v_1, u_1), (v_2, u_2) cannot communicate with each other if either [30]:

$$\mathrm{d}(u_1,v_2)<2(r_{u1}+r_{v2}) \mid \mathrm{d}(v_1,v_2)<2(r_{v1}+r_{v2}) \mid \mathrm{d}(u_1,u_2)<2(r_{u1}+r_{u2}) \mid \mathrm{d}(v_1,u_2)<2(r_{v1}+r_{u2}) \tag{5.2}$$

Two nodes can communicate with each other if and only if they are within each other transmission ranges and a common channel is assigned to their radios. Two communication links between two pairs of communicating nodes can potentially interfere with each other if they are using a common channel and lie within the interference ranges of each other as according to the Equation (5.2) [30].

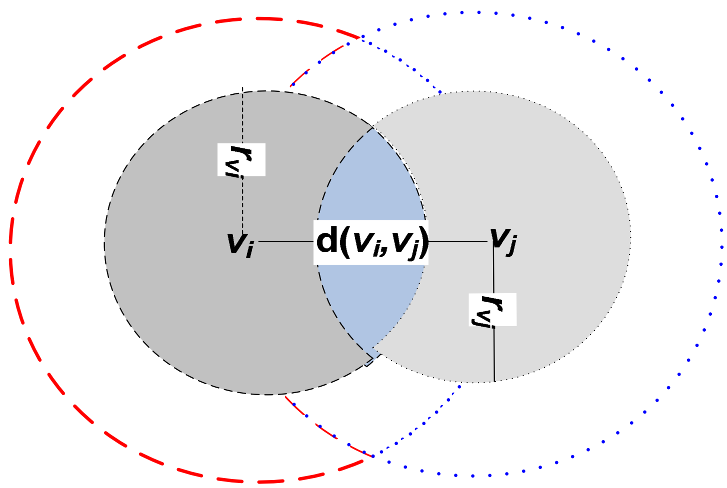


Figure 5-3: Transmission and Interference Range

To capture this interference phenomenon among the links within the WMNs, the generic graph G is further represented by a conflict graph G' as discussed in the Chapter 4. Flow routing across WMNs is the same phenomenon as putting weights on the edges of a conflict graph while considering their degree of conflict as the decision parameter.

5.3.2 Game Theoretic Model

The game theoretic model is formulated by considering competitive end users as the players of the game and each player has imperfect information in a MRMC multi-collision domain WMNs as follows. The core of the mesh network is divided into a set of multiple collision domains D={1 , 2,3,…|d|}, where |d| is the cardinality of the set D. The set of non-overlapping orthogonal channels, as present in the IEEE 802.11a/b standards [31, 32, 33], are represented by $C=\{C1, C2, C3, \ldots, C|C|\}$, where |C| represents the cardinality of the set C, as shown in the Figure 5-4. We refer to any channel C_i in a specific collision domain j by C_{ij}, where $C_i \in C$ and $\in D$, respectively. The maximum achievable data rate on a channel C_i

$\in$ C is represented by R_{C_i}. It is assumed that the maximum achievable capacity on all the channels is the same, *i.e:*

$$\boldsymbol{R_{C_i} = R_{C_j}}\ , \forall\ \boldsymbol{C_i, C_j} \in \mathbf{C}$$

(5.3)

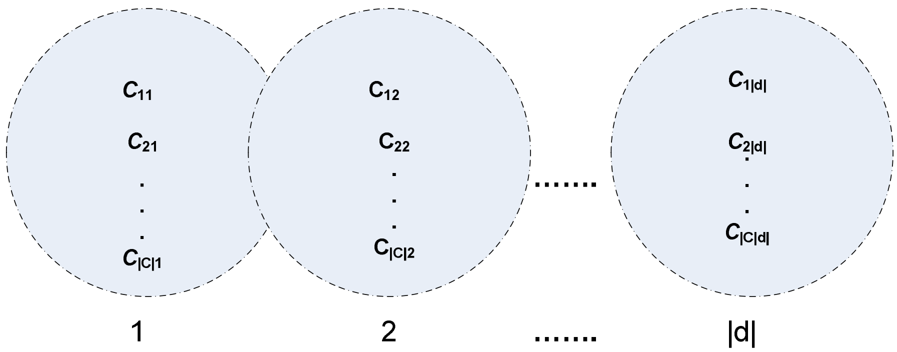


Figure 5-4: Channel Distribution in Multiple Collision Domains

A limited set of channels are considered as according to the IEEE 802.11 a/b/g/n standards and there is a chance that a channel assigned to a link might potentially interfere with other links in its sensing range according to the conditions given in the Equation (5.2). The degree of interference of a link having channel C_k ∈C being assigned is defined as $\varphi_{C_{kj}}$ which shows the number of links which have been assigned the same channel C_k in the same collision domain $j \in \mathrm{D}$.

Nodes originating flows from the user premises are the players of the game represented by a finite non-empty set $\mathrm{N} = \{N_1, N_2, N_3, \dots . N_{|\mathrm{N}|}\}$, where N_n is any player belonging to the set N and |N| shows the cardinality of the set N. The number of flows generated by any player N_n ∈ N is represented by a non-empty set f={f_1,f_2,…,$f_{|f|}$}, where f_n ∈ f represents any flow generated by player N_n ∈ N. Assuming packet as the basic unit of data transmission at the network level, the sequence of packets originated by an end-node N_n∈N is considered as a flow. The strategy of a player N_n ∈N is defined as the channels/links selection vector for each of its flows across the multiple collision domains. *i.e*:

$$A_n = \{f_{1,Ci}\,, f_{2,Ci}\,, \dots.,\ f_{|f|,Ci}\} \quad (5.4)$$

where $f_1, f_2, \ldots f_{|f|} \in$ f are the flows of player N_n and $C_i \in$C is the arbitrary channel in the channel set across collision domains 1, 2, …., |d ∈D.

Accordingly, the strategy profile of all players is represented by:

$$\mathrm{A} = \left(A_1, A_2, \ldots, A_{|\mathrm{N}|}\right)^T \tag{5.5}$$

The n^{th} row of the vector in the Equation (5.5) shows the strategy of player N_n, *i.e.,* A_n as in the Equation (5.4). Each player, $N_n \in$ N, takes a rational decision by selecting an end-to-end path across the core of the network towards the Gateways of the mesh by maximizing its utility function. The utility function of a player N_n is formulated as follows:

$$U_n = \sum_{f_{n \in f}, C_{i \in C, j=1}}^{|d|} \left(\frac{1}{\varphi_{C_{ij}}} \left(\frac{f_n}{F_{ij}} \right) . R_{C_{ij}} \right) \tag{5.6}$$

where C_{ij} denotes the channel $C_i \in C$ assigned to a link and selected by player $N_n \in$ N for its flow $f_n \in$ f in j^{th} collision domain and F_{ij} is the total number of flows on the link assigned channel C_{ij} as defined in the Equation (5.7). $R_{C_{ij}}$ is the maximum achievable data rate on the specific link assigned channel C_i ∈C in collision domain $j \in$ D, which is equal for all the channels as defined in the Equation (5.3). It is assumed that all users generate CBR (Constant Bit Rate) flows, therefore the parameter F_{ij} represents the number of flows on a specific link assigned channel $C_i \in C$ in any collision domain, $j \in$ D, and is is defined as:

$$F_{ij} = \frac{Q\left(C_{ij}\right)}{\tau(CBR)} \tag{5.7}$$

where $Q\left(C_{ij}\right)$is the queue length associated with the link to which channel C_{ij} has been assigned showing the length of the queue in terms of total flows selected this current link/channel (C_{ij}) and $\tau(CBR)$ is the constant bit rate of any flow. Ideally, F_{ij} determines the number of flows or the load on a specific channel. The strategy of a rational player will be to select the end-to-end path having links least loaded by other flows and the channels assigned to these links are least interfered. The parameter $\varphi_{C_{ij}}$ in the Equation (5.6), as defined before, shows the degree of interference on a specific link to which channel $C_i \in C$ has been assigned in the j^{th} collision domain and is determined from the conflict graph. Each end node is configured as a self maximiser in terms of bandwidth and self minimiser in terms of interference across the end-to-end path. In such a selfish and competitive environment, game theory provides a realistic solution towards the stability of the system by reaching at a point where no flow can move to any other channel/link across the complete end-to-end path, unilaterally. This stable point is called Nash Equilibrium (NE) and is defined below [36].

Definition 5.1: A strategy profile A* is called Nash Equilibrium if for each player $N_n \in \mathrm{N}$:

$$U_n\left(A_n^{*},\ A_{-n}\right) \geq\ U_n\left(A_n, A_{-n}\right),\ \forall A_n \in \mathrm{A} \tag{5.8}$$

where $U_n(A_n^*,\ A_{-n})$ is the payoff, according to the utility function defined in the Equation (5.6), of player N_n by selecting the strategy A_n^* against the strategy of all other players A_{-n} as in the Equation (5.5). In other words, in NE, every player is playing its best response to everyone else in the game. It is the point where no player can get any benefit by unilaterally deviating from its current strategy.

5.4 Existence of Nash Equilibrium

To check the existence of NE in the proposed model, two types of links are assumed in any collision domain. Links with channels having maximum number of flows are represented by C_{max} and the category of links assigned channels having minimum number of flows as C_{min}. The parameter σ_{ik} , which is the difference of the number of flows on any two channels C_i , $C_k \in$ C within a specific collision domain $j \in \mathrm{D}$, is defined as:

$$\sigma_{ik} =\ F_{ij}(max) -\ F_{kj}(min) \tag{5.9}$$

where $F_{ij}(max)$ and $F_{kj}(min)$ are the number of flows on C_{max} and C_{min} respectively. Another term $\omega(C_i, C_k)$, which defines the difference in degree of interference between two links assigned channels $C_i, C_k \in$ C within a specific collision domain $j \in \mathrm{D}$, is defined as:

$$\omega(C_i, C_k) = \varphi_{C_i} - \varphi_{C_k} \tag{5.10}$$

where φ_{C_i} and φ_{C_k} are the degrees of interference on channel C_i and C_k respectively as defined in the Section 5.3.2. Being rational, the objective of each player is to maximize its utility by selecting an end-to-end path with channels assigned to links having minimum number of load and minimum interference on it. Following, the necessary conditions for the this competitive environment are proved for the existence of the Nash Equilibrium.

Lemma 5.1: For a MRMC multi-collision domain WMN, for $\omega(C_i, C_k)$=0, if $\left(\frac{nf_n}{F_{ij}}\right).R_{C_{ij}} = 1 \;\forall\, f_n \in \mathrm{N}_n$ AND $\forall\, f_m \neq f_n \in \mathrm{N}_m, \left(\frac{f_m}{F_{ij}}\right).R_{C_{ij}} = 0$ with $\sigma_{ik} \geq 1 \;\forall\, C_i \in C_{max}, C_k \in C_{min}$ for any *j* ∈ D, then the strategy profile A^* is not a Nash Equilibrium.

If all the flows of any player N_n selects any link assigned channel $\boldsymbol{c_i} \in \boldsymbol{c_{max}}$ in any collision domain while flows of all other users N_m put their flows on $\boldsymbol{c_m} \in \boldsymbol{c_{min}}$, then player N_n will have an incentive to unilaterally deviate from his strategy and this can no longer be a Nash Equilibrium. As shown in the Figure 5-5, player N_1 selects a link assigned Channel C_1 for all its four flows in collision domain *j*. It can increase its utility if one of the flows is transferred to other links assigned channels (C_2, C_3 or C_4) in the same collision domain.

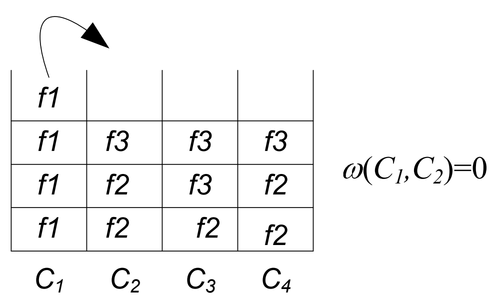


Figure 5-5: Example of homogenous flows on one channel

Proof: Let α_n be the gain of player N_n deviating from its current strategy which has defined all its flows $n.f_n$ on one of channel $C_{ij} \in C_{max}$. Let F_{ij} be the total flows on $C_{ij} \in C_{max}$ and F_{ik} be the total flows on $C_{kj} \in C_{min}$.

Then:

$\alpha_n = U'_n - U_n$, where U'_n is the new payoff of player N_n after deviating from its current strategy which was giving it a utility U_n .

We represent $\theta \in N_n$ as one of the flow, which player N_n redirect to another channel $C_{kj} \in C_{min}$ in any collision domain $j \in$D and calculate the benefit of change along the path as follows.

$$\alpha_n = \sum_{f_{n\in f, C_{i\in C, j=1}}}^{|j-1|} \left[\frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}}\right] + \frac{1}{\varphi_{C_{ij}}}\left(\frac{(n-\theta)f_n}{F_{ij}-\theta}\right).R_{C_{ij}} + \left(\frac{1}{\varphi_{C_{kj}}}\left(\frac{\theta f_n}{F_{kj}+\theta}\right).R_{C_{kj}}\right)$$

$$-\left(\frac{1}{\varphi_{C_{ij}}}\left(\frac{nf_n}{F_{ij}}\right).R_{C_{ij}}\right) + \sum_{f_{n\in f, C_{i\in C, j=j+1}}}^{|d|} \frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}} \tag{5.11}$$

By considering only $j\in$D collision domain:

$$= \frac{1}{\varphi_{C_{ij}}}\left(\frac{(n-\theta)f_n}{F_{ij}-\theta}\right).R_{C_{ij}} + \left(\frac{1}{\varphi_{C_{kj}}}\left(\frac{\theta f_n}{F_{kj}+\theta}\right).R_{C_{kj}}\right) - \left(\frac{1}{\varphi_{C_{ij}}}\left(\frac{nf_n}{F_{ij}}\right).R_{C_{ij}}\right)$$

Since $R_{C_{ij}} = R_{C_{kj}}$, $F_{kj} + \theta = F_{ij}$ and $\varphi_{C_{ij}} = \varphi_{C_{kj}}$ as per assumption of $\omega(C_i, C_k) = 0$

Therefore:

$$= \frac{1}{\varphi_{C_{ij}}}\left[\left(\frac{(n-\theta)f_n}{F_{ij}-\theta}\right).R_{C_{ij}} + \left(\frac{\theta f_n}{F_{ij}}\right).R_{C_{ij}} - \left(\frac{nf_n}{F_{ij}}\right).R_{C_{ij}}\right]$$

After simplification:

$$\alpha_n = \frac{1}{\varphi_{C_{ij}}}\left[\left(\frac{\theta f_n(n-\theta)}{F_{ij}(F_{ij}-\theta)}\right).R_{C_{ij}}\right] \tag{5.12}$$

$\alpha_n >$ 0 in the Equation (5.12) as $n-\theta$ and $F_{ij}-\theta$ are positive. Hence, the strategy profile A* cannot be a Nash Equilibrium.

Lemma 5.2: In a MRMC multiple-collision domain WMN, for $\omega(C_i, C_k) = 0$, in any collision domain $j \in$D along the end-to-end path of flows, if $\sigma_{ik} > 1$ for any $C_i \in C_{max}, C_k \in C_{min}$, then the strategy profile A* is not a Nash Equilibrium.

Let $\sigma_{ik} > 1$ in any collision domain $j \in$D along the end-to-end path of flows then it essentially means that there exists a channel $C_{kj} \in C_{min}$ in $j \in$D for which $\left(\frac{Q(C_{ij})}{\tau\,(CBR)} - \frac{Q(C_{kj})}{\tau\,(CBR)}\right) > 1$, and hence at least one of the flow $f_n \in N_n$ on $C_{ij} \in C_{max}$ has incentive to change for its benefit. As shown in the Figure 5-6, N_2 can unilaterally switch one of its flows to C_1, C_2 or C_4.

Proof: Let a user N_n changes its flow, f_n, from $C_{ij} \in C_{max}$ to $C_{kj} \in C_{min}$ in $j \in D$ collision domain along the end-to-end path. The gain of change is calculated as follows:

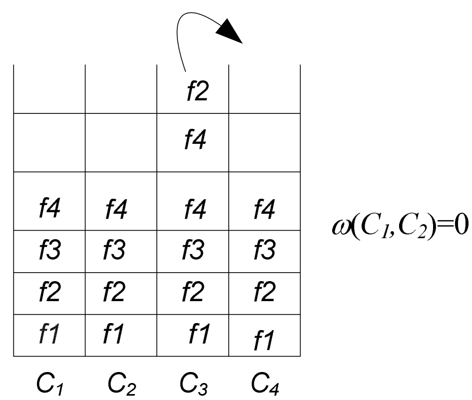


Figure 5-6: Flow distribution on channels where σ >1

$$\alpha_n = \sum_{f_{n \in f, C_{i \in C, j=1}}}^{|j-1|} \left[\frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}}\right] + \frac{1}{\varphi_{C_{kj}}}\left(\frac{f_n}{\frac{Q(C_{kj})}{\tau\,(CBR)}}\right).R_{C_{kj}} - \frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{\frac{Q(C_{kij})}{\tau\,(CBR)}}\right).R_{C_{ij}}$$

$$+ \sum_{f_{n \in f, C_{i \in C, j=j+1}}}^{|d|} \frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}} \tag{5.13}$$

By considering the j^{th} collision domain only, the first and last summation terms become irrelevant and hence by simplification, we get:

$$= \frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{\left(\frac{Q(Ckj)}{\tau\,(CBR)}+1\right)}\right).R_{C_{kj}} - \frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{\frac{Q(Cij)}{\tau\,(CBR)}}\right).R_{C_{ij}}$$

Since $\varphi_{C_{ij}} = \varphi_{C_{kj}}$ as $\omega(C_i, C_k) = 0$, therefore:

$$= \frac{1}{\varphi_{C_{ij}}}\left[\left(\frac{f_n}{\left(\frac{Q(C_{kj})}{\tau\ (CBR)}+1\right)}\right).R_{C_{kj}} - \left(\frac{f_n}{\frac{Q(C_{kj})}{\tau\ (CBR)}+\sigma}\right).R_{C_{kj}}\right]$$

$$\alpha_n = \frac{1}{\varphi_{C_{ij}}}\left[\frac{\sigma.\tau(CBR) - \tau(CBR)}{\tau(C_{kj}) + \tau(CBR).(\tau(C_{kj}) + \sigma.\tau(CBR)}\right].f_n R_{C_{kj}} \qquad (5.14)$$

α_n>0 in the Equation (5.14), as $\sigma > 1$. Since player N_n has an incentive to change from its current strategy to the new one, and hence the current strategy profile A* cannot be a Nash Equilibrium.

Lemma 5.3: In a MRMC Multiple-Collision domain mesh network, for $\omega(C_i, C_k) = 0$, for any player N_n if $\forall f_n C_{ij} - \forall f_n C_{kj} > 2$ and σ_{ik} ≥1 in any collision domain j ∈D, $\forall C_{ij} \in C_{max}$, $\forall C_{kj} \in C_{min}$, then the strategy profile A* is not a Nash Equilibrium.

As shown in the Figure 5-7, difference of flows of N_2 on C_2 and C_3>2, although it does not deviate from the lemma 5.2, player N_2 has incentive to switch one of its flow from C_2 to C_3.

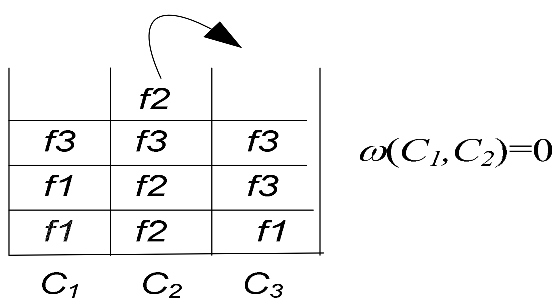


Figure 5-7: Homogenous flows difference on two channels>2

Proof: Let $\theta_1, \theta_2 \in$ N_n are the number of flows of player N_n on C_{max} and C_{min} channels, respectively. The parameter $\Delta\theta_{1,2} = \theta_1 - \theta_2$ is defined as the flow difference of any player on two C_{max}, C_{min} channels. Let N_n redirect one of its flows from C_{max} to C_{min} in any collision domain $j \in \mathrm{D}$ along the end-to-end path. Then the gain of change is given by:

$$\alpha_n = \sum_{f_{n\in f, C_{i\in C, j=1}}}^{|j-1|}\left[\frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}}\right] + \frac{1}{\varphi_{C_{ij}}}\left(\frac{(\theta_1 - 1)f_n}{F_{ij} - 1}\right).R_{C_{ij}} + \frac{1}{\varphi_{C_{kj}}}\left(\frac{(\theta_2 - 1)f_n}{F_{kj} + 1}\right).R_{C_{kj}}$$

$$-\frac{1}{\varphi_{C_{ij}}}\left(\frac{\theta_1 f_n}{F_{ij}}\right).R_{C_{ij}}-\frac{1}{\varphi_{C_{kj}}}\left(\frac{\theta_2 f_n}{F_{kj}}\right).R_{C_{kj}}+\sum_{f_{n\in f,C_{i\in C,j=j+1}}}^{|d|}\frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}} \qquad (5.15)$$

We suppose that the change of end-to-end path for N_n accurse in the j^{th} collision domain only and hence by eliminating the first and last summation terms. Since $F_{ij} = F_{kj} - \sigma$ before flow switch from C_{ij} to C_{kj} and $F_{kj} + 1 = F_{ij}$ after flow switch by assuming $\sigma = 1$, by substituting appropriate terms:

$$\alpha_n = \frac{1}{\varphi_{C_{ij}}}\left(\frac{(\theta_1-1)f_n}{F_{ij}-1}\right).R_{C_{ij}}-\frac{1}{\varphi_{C_{ij}}}\left(\frac{\theta_1 f_n}{F_{ij}-1}\right).R_{C_{ij}}+\frac{1}{\varphi_{C_{ij}}}\left(\frac{(\theta_2+1)f_n}{F_{ij}}\right).R_{C_{ij}}$$

$$-\frac{1}{\varphi_{C_{ij}}}\left(\frac{\theta_2 f_n}{F_{ij}-\sigma}\right).R_{C_{ij}}$$

Since $\varphi_{C_{ij}} = \varphi_{C_{kj}}$ as $\omega(C_i, C_k) = 0$ and by further simplification:

$$\alpha_n = \frac{1}{\varphi_{C_{ij}}}\left(\frac{\theta_1-(\theta_2+1)f_n}{F_{ij}(F_{ij}-1)}\right).R_{C_{ij}} \qquad (5.16)$$

The term $\theta_1 - (\theta_2 + 1)$ and $F_{ij} - 1 > 0$ as $\Delta\theta_{1,2} > 2$

∴ $\alpha_n > 0$ and A^* cannot be a Nash Equilibrium under such condition.

Lemma 5.4: In a MRMC Multiple-Collision domain mesh network, for $\omega(C_i, C_k) \geq 1$, for any player N_n if $\forall f_n C_{ij} - \forall f_n C_{kj} = 1$ and $\sigma_{ik} \geq 1$ n any collision domain j ∈D, $\forall C_{ij} \in C_{max}$, $\forall C_{kj} \in C_{min}$, then the strategy profile A* is not a Nash Equilibrium.

As shown in the Figure 5-8, difference of flows of N_2 on C_2 and C_3>2, although it does not deviate from lemma2, player N_2 has incentive to switch one of its flow from C_2 to C_3.

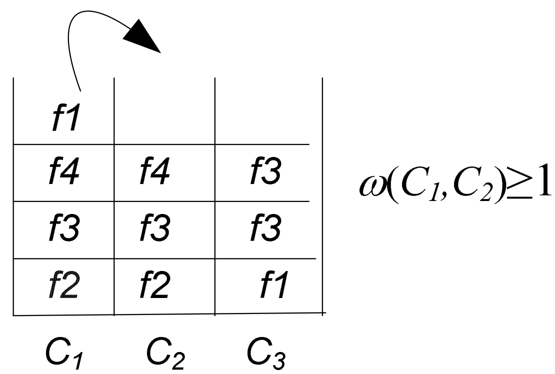


Figure 5-8: An interference difference

Proof: The proof of this lemma is straightforward. Let $f_n \in$ f be the only flow of player $N_n \in$ N on C_{max}. It essentially means that there are no flows defined by player N_n on channel C_{min} in any collision domain $j \in$D along the end-to -nd path. The gain of change is given by:

$$\alpha_n = \sum_{f_{n\in f, C_{i\in C, j=1}}}^{|j-1|} \left[\frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}}\right] + \frac{1}{\varphi_{C_{kj}}}\left(\frac{f_n}{F_{kj}+1}\right).R_{C_{kj}} - \frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}}$$

$$+ \sum_{f_{n\in f, C_{i\in C, j=j+1}}}^{|d|} \frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}} \quad (5.17)$$

It is supposed that the change of end-to-end path for N_n accurse in the j^{th} collision domain only and hence by eliminating the first and last summation terms.

$$= \frac{1}{\varphi_{C_{kj}}}\left(\frac{f_n}{F_{kj}+1}\right).R_{C_{kj}} - \frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}}$$

Since $F_{kj} + 1 \le F_{ij}$ and $R_{C_{ij}} = R_{C_{kj}}$, by substituting the appropriate terms and further simplification:

$$= \frac{1}{\varphi_{C_{kj}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}} - \frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}} = \left(\frac{\varphi_{C_{ij}} - \varphi_{C_{kj}}}{\varphi_{C_{ij}}.\varphi_{C_{kj}}}\right)\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}}$$

$$\alpha_n = \left(\frac{\omega(C_i, C_k)}{\varphi_{C_{ij}}.\varphi_{C_{kj}}}\right)\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}} \quad (5.18)$$

Here we only consider the case $F_{kj} + 1 = F_{ij}$ for simplicity. This can be proved further for $F_{kj} + 1 < F_{ij}$, which will have the same result.

Since the difference of interference between the two channels C_i, C_k ∈ C is more than or equal to one, therefore the term $\omega(C_i, C_k) \geq 1$ in the Equation (5.18) earns the player a gain in the utility as $\alpha_n > 0$ and A* cannot be a Nash Equilibrium under such a condition.

Proof of NE existence: In a MRMC Multiple-Collision domain mesh network, if $\sigma_{ik} \leq$ 1<=1 $\forall j$ ∈ D and lemma 5.1 and 5.3 do not hold then the strategy profile A* is a Nash Equilibrium. From the Equation (5.14) of lemma 5.2, let $\sigma_{ik} = 1$ and we assume that lemma 5.1 and 5.3 do not hold, then:

$$\alpha_n = \frac{1}{\varphi_{C_{ij}}}\left[\frac{\tau(CBR) - \tau(CBR)}{\tau(C_{kj}) + \tau(CBR).(\tau(C_{kj}) + \sigma.\tau(CBR)}\right].f_n R_{C_{kj}} = 0 \tag{5.19}$$

Also for $\sigma_{ik} = 0$:

$$\alpha_n = \frac{1}{\varphi_{C_{ij}}}\left[\frac{-\tau(CBR)}{\tau(C_{kj}) + \tau(CBR).(\tau(C_{kj}) + \sigma.\tau(CBR)}\right].f_n R_{C_{kj}} < 0 \tag{5.20}$$

Also from the Equation (5.18) of lemma 5.4, let $\omega(C_i, C_k) \geq 1$:

$$\alpha_n = \left(\frac{-\omega(C_i, C_k)}{\varphi_{C_{ij}}.\varphi_{C_{kj}}}\right)\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}} < 0 \tag{5.21}$$

Both the negative sign and zero results in the Equations (5.19, 5.20 and 5.21) show that no player has any incentive to deviate from its current strategy and hence the current strategy profile is a Nash Equilibrium.

Theorem 1: A strategy profile A* is Nash Equilibrium, if:

1) $\forall f_n \in \mathrm{N}_n, \left(\frac{nf_n}{\boldsymbol{F_{ij}}}\right) RC_{max} < 1, \exists \left(\frac{f_m}{\boldsymbol{F_{ij}}}\right) R_{C_{max}} > 0 \; for \; \sigma \geq 1,$
   $\forall j, \forall C_{max}, C_{min}, \omega(C_{max}, C_{min}) = 0$
2) $\forall C_{max}, C_{min}, 1 \geq \sigma \geq 0, \forall j \in D, \; \omega(C_{max}, C_{min}) = 0$
3) $\Delta\theta_{C_{max},C_{min}} \leq 2$ for $\ell \geq 1, \forall f_n \in N_n, \forall N_n \in \mathrm{N}, \forall j \in D, \omega(C_{max}, C_{min}) = 0$
4) $\omega(C_{max}, C_{min})$<1, $\forall C_{max}, C_{min}$, $if \; \sigma \geq 1$, $if \; \theta_1 f_n - \theta_2 f_n \geq 1$ for θ_1 on C_{max}, θ_2 on C_{min} for any player $N_n \in$ N.

5.5 Convergence to Nash Equilibrium

In the previous section, It was proved that a pure strategy NE exists in a selfish routing flow game in MRMC WMNs with interference constraint topology. In this section, we present a distributed algorithm running on each end node with imperfect information. As shown in the Figure 4-9, each player has information about each channel usage inside all collision domains but no player knows the strategy of it opponent players, thus a game of imperfect information. Using Algorithm 5.1, each player $N_n \in$ N selects channels for all its flows $f_n \in$ f in each collision domain across the end to end path in a distributed manner. Lines 5, 9, 13 and 17 of the algorithm are sufficient conditions for convergence to the NE. Furthermore, each node keeps a record of its channel usage, $C_{ij}\_f_{nCount}$, in each collision domain for a necessary check at lines 5, 9 and 13. Players in this game move simultaneously without having information about the past histories. With this imperfect information, the game converges to stable NE in a non-cooperative environment.

Algorithm 5.1

1. *for* each $N_n \in$ N (independently)
2. *for* each $f_n \in$ f (do)
3. *for* j=1 to |d|
4. *for* i=1 to $C_{|c|}$
5. *if* Q(C_{ij}) ≤Q($C_{min(j)}$) & $\varphi_{C_{ij}} \le \varphi_{C_{min(j)}}$
6. Select channel C_i for flow f_n
7. $C_{ij}\_f_{nCount}$=$C_{ij}\_f_{nCount}$+1
8. exit;
9. *elseif*($C_{ij}\_f_{nCount}$ - $C_{(rem)}\_f_{nCount}$) ≤ 2 & $(\frac{nf_n}{F_{ij}}) R_{C_{ij}} \neq 1$ & C_{ij}-$C_{(rem)j}$≤1
10. Select channel C_i for flow f_n
11. $C_{ij}_f_n$Count= $C_{ij}_f_n$Count +1
12. exit;
13. *elseif*(Q($C_{rem(j)}$)-Q(C_{ij})≥1 & ω($C_{rem(j)}$, C_{ij}) ≥1
14. Select channel C_i for flow f_n
15. $C_{ij}_f_n$Count= $C_{ij}_f_n$Count +1
16. exit;
17. *else*
18. *next i*
19. *end if*

20. → $next\ j$
21. → $while(f_n)$

→ $next\ N_n$

Figure 5-9: Algorithm for Nash Equilibrium convergence using imperfect information

5.6 Performance Evaluation

In this section, we evaluate our proposed algorithm and show its results in terms of individual fairness and Price of Anarchy (*PoA*) and its associated Cumulative Distribution Function (CDF). In the second subsection, we investigate and compare the throughput difference of the proposed scheme with a random channel selection scheme by varying the number of players. All the experiments were conducted in MATLAB version R2007a [37] to test the performance and effectiveness of the proposed scheme.

5.6.1 Price of Anarchy, Cumulative Distribution Function and Individual Fairness

In this subsection, the individual fairness of end users nodes and *PoA* and its associated normal CDF have been investigated.

5.6.1.1 Price of Anarchy

In this subsection, the individual fairness of end users nodes and *PoA* and its associated normal CDF have been investigated. The *PoA* is formulated as in [30] and is defined as the ratio of throughput achieved by individual players in case of worst NE to the throughput achieved in the best NE *i.e,*

$$PoA = \frac{\Gamma_n(NE_{worst})}{\Gamma_n(NE_{best})}, n = 1, 2..., N_{|N|} \tag{5.22}$$

where Γ_n is the end-to-end throughput of player $N_n \in \mathrm{N}$.

In the simulation, 40 nodes are deployed randomly in a rectangular area of 600X600 units. The transmission range is considered 50 units and interference range is taken as twice of the transmission range. On the left hand side of the topology, 12 nodes were configured as the players of the game who want to route their flows across the MRMC WMNs backbone. At the right hand side of the topology, 3 nodes were configured as the Gateways, being the destinations for the source nodes. Each node generates 10 CBR flows of 64Kbps during each run of the game. Simulation was carried out by considering IEEE 802.11a [31], where 8 non-overlapping channels were selected for parameter set C across 5 collision domains. Each node is configured with two radios, each for transmission and reception. All players move simultaneously having no information of one another past histories. With this imperfect information, we investigate the performance of the proposed scheme in terms of *PoA*. As shown in the Figure 5-10, the *PoA* is in the range of 0.71 and 1 for all the players. This shows a very strong indication that the individual throughput is not degraded even if the system converges to a worst NE.

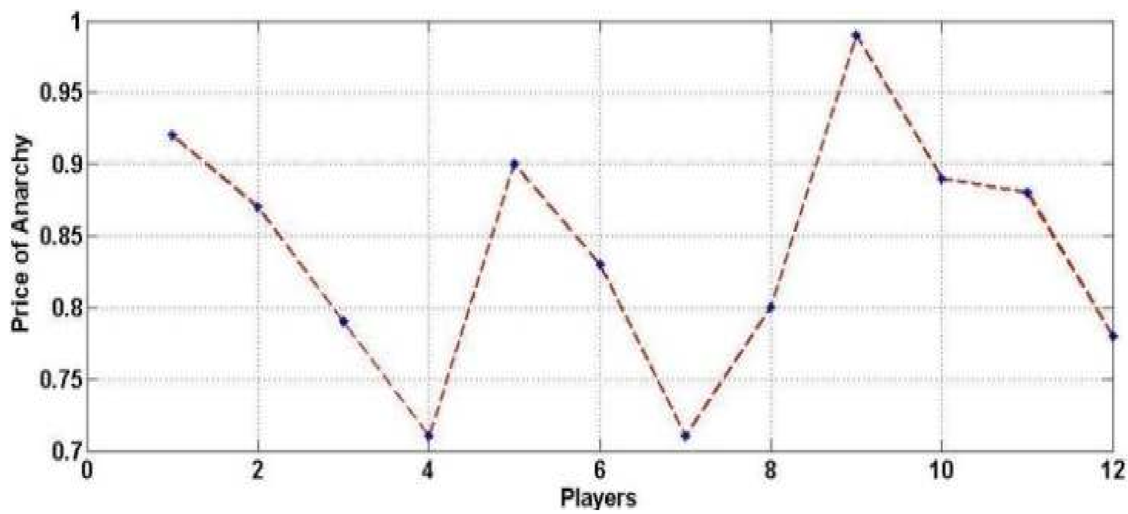


Figure 5-10: Price of Anarchy with D=5,C=8, N=12, f=10 and CBR=64Kbps

5.6.1.2 Statistical Analysis and Cumulative Distribution Function of PoA

Definition 5.2: For a real number *x*, the Cumulative Distribution Function for a random variable X is given by:

$$CDF(x) = \int_{-\infty}^{x} f(x)dx \tag{5.23}$$

The Cumulative Distribution Function defines the probability of a random variable X from $-\infty$ till the real value variable x. It shows the area under the curve from a lower limit ($theoritically\ -\infty$) till an upper limit (x).

The mean of PoA as presented in the Figure 5-10 is 0.8392, while the Standard Deviation is 0.0848. This shows the *PoA* outcome for each individual players is not far from the average and hence low variance.

The CDF over the *PoA* dataset was computed to show the expected occurrences of the individual random values in the data set limits. As shown in the Figure 5-11, the CDF increases from the lower values to the upper values of *PoA*. This shows that in the proposed system, the probability of high value *PoA* occurrence is highly likely as compared to the small values of *PoA*. In other words, the *PoA* always tend to 1 in the proposed system.

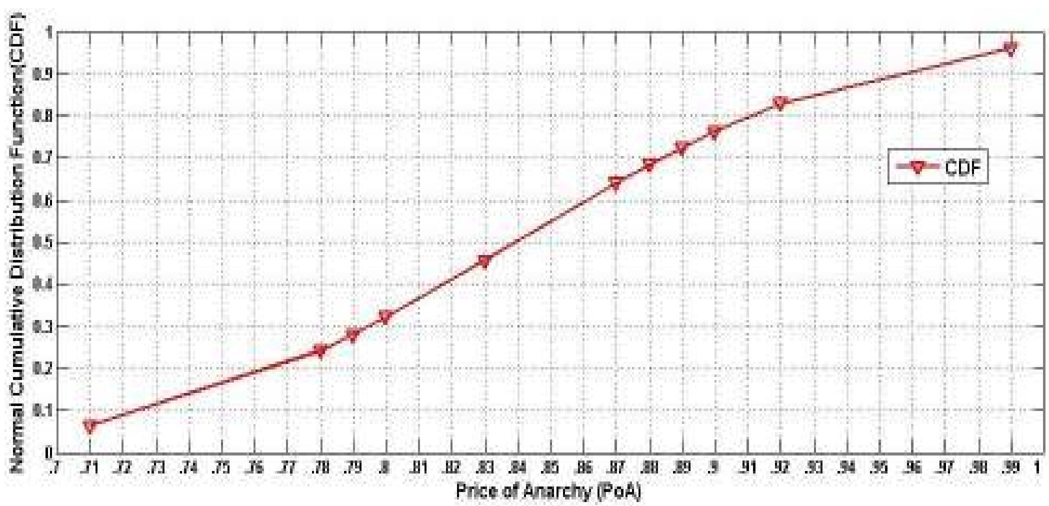


Figure 5-11: CDF for PoA

5.6.2 Individual Fairness

Fairness among players was measured at the end of the game. As shown in the Figure 5-12, individual players achieve end-to-end data rate with a mean 121.6 Mbps and a standard deviation of 2.19Mbps, with imperfect information, at the end of the game. This shows that using the proposed algorithm, players achieve fair end-to-end data rate across multiple collision domains when game converges to NE. The reason is that when the game ends up with NE, each player is playing its best response of its strategies to every other player of the game and hence has no incentive to deviate individually from its current strategy. A set of simulations were carried out for the scenarios with the same set of parameters, where nodes deviate from the proposed algorithm and select the channels/links of the end-to-end paths randomly.

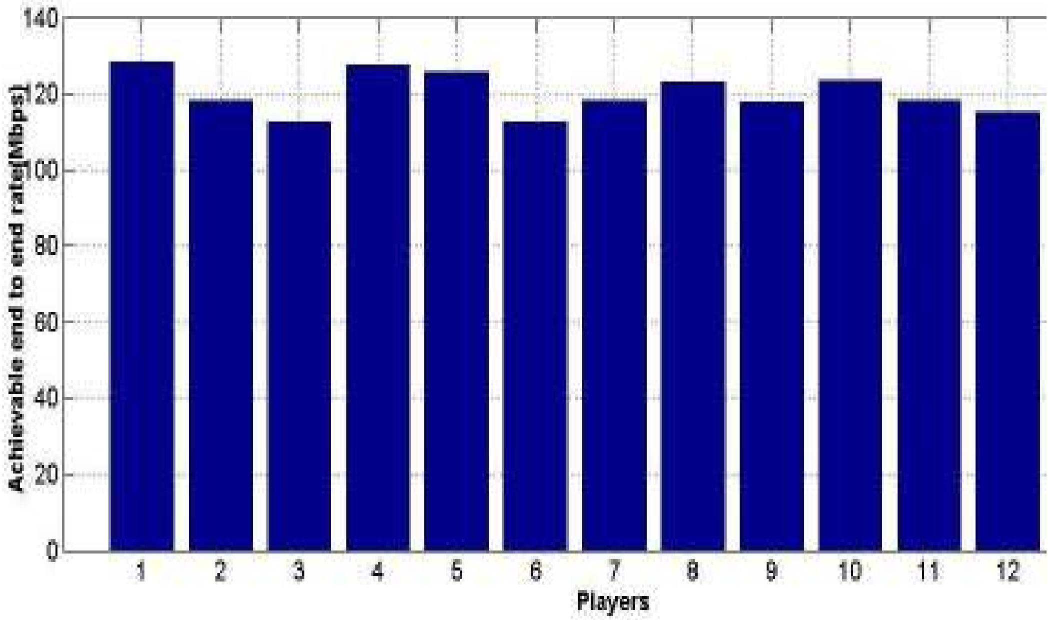


Figure 5-12: Total End to End rate of individual players with imperfect information with D=5,C=8, N=12, f=10 and CBR=64Kbps

As shown in the Figure 5-13, although some nodes perform better comparatively to our scheme by achieving high end-to-end throughputs; the mean of the system was measured was 127.3 Mbps and the standard deviation is 3.74Mbps among the achieved throughputs for the random channel selection scheme. This shows that some of the selfish nodes get access to less interfered channels while leaving the crowded channels for others. This selfish behaviour leads to individual unfairness of the system as compared to the proposed scheme.

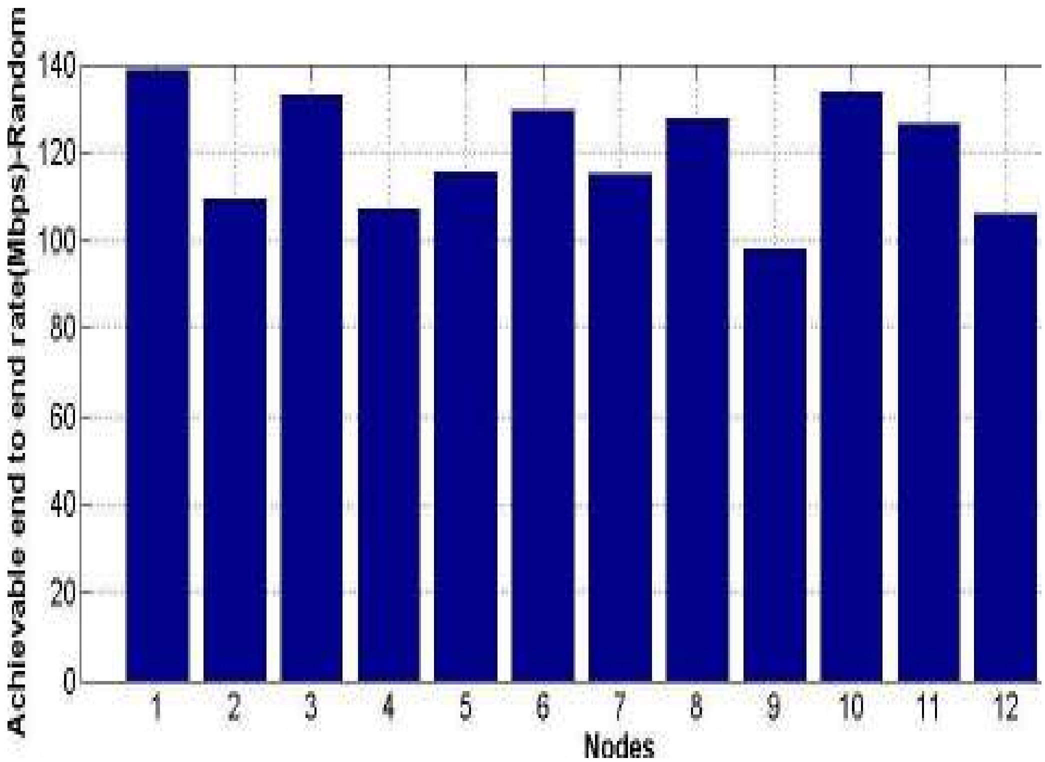


Figure 5-13: Total End to End rate of individual players with imperfect information with D=5,C=8, N=12, f=10 and CBR=64Kbps

5.6.3 Standard Deviation and Max-Min throughput Difference

In second scenario, 100 nodes are deployed in a rectangular area of 1000X1000 units. The transmission range is taken 25 units and the interference range as twice of the transmission range. Variance among players throughputs was measured by varying the set of players, N, from 5 to 40 in 5 steps. The proposed scheme was compared with random channel/link selection where flows select channels across multiple collision domains arbitrarily. Figure 5-14 compares max-min throughput difference by of the proposed selfish routing game theoretical model with random channel selection scheme. Max-min throughput difference is the difference between the flow which gets maximum throughput and flow that gets minimum throughput, as in Chen *et al.* [18]. It can be observed that the game theoretical scheme outperforms random channel selection for each set of players by having minimum max-min throughput difference. The max-min difference is higher for both systems at beginning but as the number of players increases, max-min throughput difference of the proposed scheme either decreases or remains constant when the game ends up with NE. This shows the stability of the flow routing scheme at NE. The max-min throughput difference for random selection does not remain stable with varying number of players, as shown in the Figure 5-14. This is because of the reason that the selfish end nodes, being rational, select less crowded channels across multiple collision domains and thus increase their end-to-end throughputs while leaving more crowded channels for other nodes.

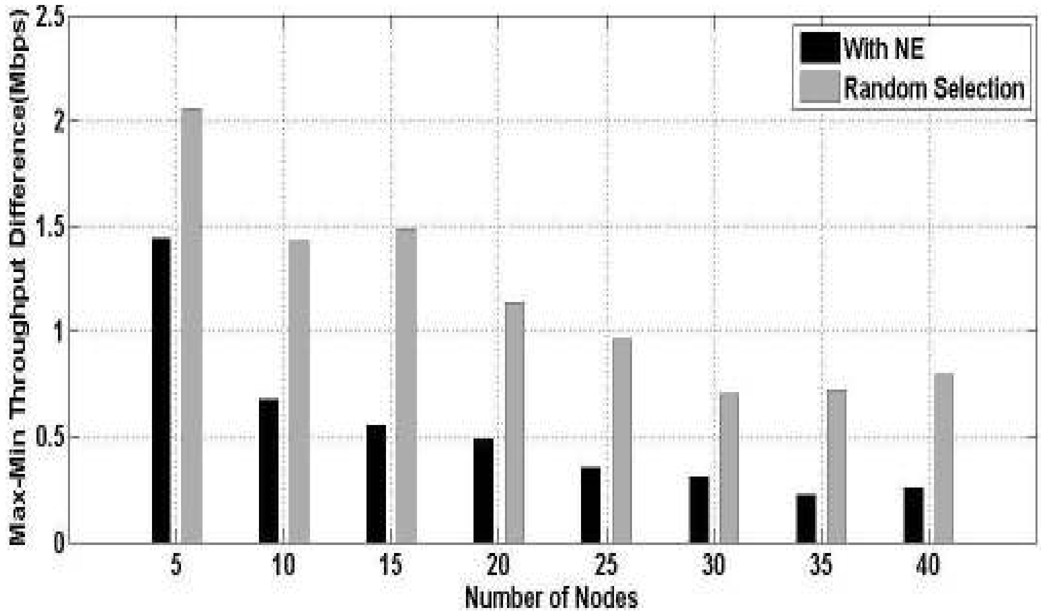


Figure 5-14: Max-Min Throughput Difference by varying number of players with imperfect information. D=5,C=8,N=5:5:40, f=10,CBR=64Kbps

Figure 5-15 shows the standard deviation comparison of player's throughputs in the proposed scheme against that of random selection. The values for collision domains (D), Channels (C), number of flows per node and CBR were kept same in both schemes while number of players/nodes was varied from 5 to 40 in step 5. Results in Fig. 5-15 suggest that the proposed game theoretic scheme always performed better than random selection irrespective of the number of players. When number of nodes is lower, some selfish players have always incentive to select less crowded channels across multiple collision domains and hence variance among players throughputs is high leading to high standard deviation. With the increase in the number of players, the proposed system shows a constant and predictable decrease in standard deviation while random selection scheme is unpredictable.

This means that the proposed scheme achieves good fairness in long run when the system converges to NE.

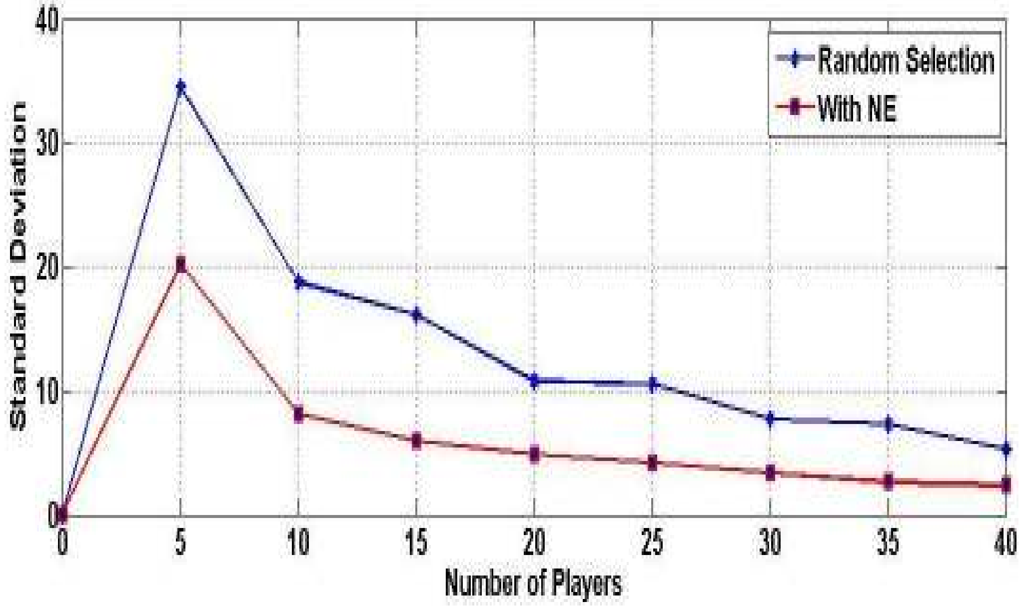


Figure 5-15: Standard Deviation among players throughput with D=5,C=8,N=5:5:40, f=10,CBR=64Kbps

5.7 Summary

In this Chapter, a flow routing game theoretical model is developed in a non-cooperative multiple-collision domain Multi-Radio Multi-Channel Wireless Mesh Networks. An interference constrained topology is considered due to the limited available orthogonal channels. The analytical results have proven that a pure strategy Nash Equilibrium exists with the proposed necessary conditions in a game of imperfect information. Based on a distributed algorithm, the game converges to stable state in finite time and all channels are perfectly load-balanced at the end. Simulation results show that standard deviation of player's throughputs is less than that of random channel selection scheme in long run. Furthermore, the Price of Anarchy of the system is close to one showing the efficiency of the proposed scheme.

5.8 References

[1] A. P. Subramanian, M. M. Buddhikot and S. Miller, "Interference aware routing in multi-radio wireless mesh networks," in *Wireless Mesh Networks, 2006. WiMesh. 2nd IEEE Workshop on,* pp. 55-63, 2006.

[2] M. Kodialam and T. Nandagopal, "Characterizing achievable rates in multi-hop wireless mesh networks with orthogonal channels," *IEEE/ACM Transactions on Networking (TON),* vol. 13, pp. 868-880, 2005.

[3] L. Santhanam, B. Xie and D. Agrawal, "Selfishness in mesh networks: wired multihop MANETs," Wireless Communications, IEEE, vol. 15, pp. 16-23, 2008.

[4] T. Alpcan and T. Basar, "A game-theoretic framework for congestion control in general topology networks (I)," in IEEE Conference On Decision and Control, Maui, USA, pp. 1218-1224, 2002.

[5] A. A. Economides and J. A. Silvester, "A game theory approach to cooperative and non-cooperative routing problems," in Proc. IEEE International Telecommunications Symposium, pp. 597-601.

[6] A. Blum, E. Even-Dar, and K. Ligett, "Routing without regret: On convergence to Nash equilibria of regret-minimizing algorithms in routing games," in Proceedings of the Twenty-Fifth Annual ACM Symposium on Principles of Distributed Computing, Denver, Colorado, USA , pp. 45 – 52, 2006.

[7] D. Fotakis, S. Kontogiannis, E. Koutsoupias, M. Mavronicolas, and P. Spirakis, "The structure and complexity of Nash equilibria for a selfish routing game," Automata, Languages and Programming, pp. 785-785.

[8] C. U. Saraydar, N. B. Mandayam, and D. J. Goodman, "Efficient power control via pricing in wireless data networks," IEEE Trans. Commun., vol. 50, pp. 291-303, 2002.

[9] C. W. Sung and W. S. Wong, "A noncooperative power control game for multirate CDMA data networks," IEEE Transactions on Wireless Communications, vol. 2, pp. 186-194, 2003.

[10] Cui, L. Chen and S. Low, "A game-theoretic framework for medium access control," Selected Areas in Communications, IEEE Journal on, vol. 26, pp. 1116-1127, 2008.

[11] L. Chen, S. H. Low and J. C. Doyle, "Random access game and medium access control design," Networking, IEEE/ACM Transactions on, vol. 18, pp. 1303-1316, 2010.

[12] E. Altman, T. Boulogne, R. El-Azouzi, T. Jimenez, and L. Wynter, "A survey on networking games in telecommunications," Comput. Oper. Res., vol. 33, pp. 286-311, 2006.

[13] M. Felegyhazi and J. P. Hubaux, "Game theory in wireless networks: A tutorial," Submitted to ACM Computing Surveys, , 2006.

[14] K. Marina, S. R. Das, and A. P. Subramanian, "A topology control approach for utilizing multiple channels in multi-radio wireless mesh networks," Computer Networks, vol. 54, pp. 241-256, 2010.

[15] A. Raniwala and T. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in Proceedings IEEE INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies, Miami USA, pp. 2223-2234, 2005.

[16] M. Alicherry, R. Bhatia, and L. E. Li, "Joint channel assignment and routing for throughput optimization in multi-radio wireless mesh networks," in Proceedings of the 11th Annual International Conference on Mobile Computing and Networking, Cologne, Germany , pp. 58 - 72 . 2005.

[17] M. Felegyhazi, M. Cagalj, S. Bidokhti, J. P. Hubaux, and L. EPFL, "Non-cooperative multi-radio channel allocation in wireless networks," in IEEE

INFOCOM 2007. 26th IEEE International Conference on Computer Communications, Alaska, USA, pp. 1442-1450, 2007.

[18] T. Chen and S. Zhong, "Perfectly fair channel assignment in non-cooperative multi-radio multi-channel wireless networks," Comput. Commun., vol. 32, pp. 1058-1061, 2009.

[19] L. Gao and X. Wang, "A game approach for multi-channel allocation in multi-hop wireless networks," in Proceedings of the 9th ACM International Symposium on Mobile Ad Hoc Networking and Computing, Hong Kong, China, pp. 303-312, 2008.

[20] R. W. Rosenthal, "A class of games possessing pure-strategy Nash equilibria," International Journal of Game Theory, vol. 2, pp. 65-67, 1973.

[21] E. Altman, "Flow control using the theory of zero sum Markov games," Automatic Control, IEEE Transactions on, vol. 39, pp. 814-818, 1994.

[22] Y. A. Korilis and A. A. Lazar, "On the existence of equilibria in noncooperative optimal flow control," Journal of the ACM (JACM), vol. 42, pp. 584-613, 1995.

[23] R. J. La and V. Anantharam, "Optimal routing control: Repeated game approach," Automatic Control, IEEE Transactions on, vol. 47, pp. 437-450, 2002.

[24] A. Orda, R. Rom and N. Shimkin, "Competitive routing in multiuser communication networks," IEEE/ACM Transactions on Networking (TON), vol. 1, pp. 510-521, 1993.

[25] H. Kameda, "How harmful the paradox can be in the Braess/Cohen-kelly-jeffries networks," in INFOCOM 2002. Twenty-First Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings. IEEE, pp. 437-445 vol. 1, 2002.

[26] E. Altman, T. Basar, T. Jimenez, and N. Shimkin, "Competitive routing in networks with polynomial costs," Automatic Control, IEEE Transactions on, vol. 47, pp. 92-96, 2002.

[27] T. Roughgarden and É. Tardos, "How bad is selfish routing?" Journal of the ACM (JACM), vol. 49, pp. 236-259, 2002.

[28] R. Banner and A. Orda, "Bottleneck routing games in communication networks," Selected Areas in Communications, IEEE Journal on, vol. 25, pp. 1173-1179, 2007.

[29] A. Czumaj, "Selfish routing on the internet," in HANDBOOK OF SCHEDULING: ALGORITHMS, MODELS, AND PERFORMANCE ANALYSIS, CHAPTER 42, 2004, .

[30] J. Xiao, N. Xiong, L. T. Yang, and Y. He, "A joint selfish routing and channel assignment game in wireless mesh networks," Comput. Commun., vol. 31, pp. 1447-1459, 2008.

[31] http://ieeexplore.ieee.org/xpl/mostRecentIssue.jsp?punumber=6606, last accessed: 21/06/2010

[32] IEEE 802.11b/g: www.ieee.org/, last accessed: 22/12/2010

[33] IEEE 802.11n; www.ieee.org/, last accessed: 22/12/2010

[34] M. Biggs, A. Henley and, T. Clarkson, "Occupancy analysis of the 2.4 GHz ISM band," IEE Proceedings Communications, vol. 153, issue 6 , pp. 481-488, 2004.

[35] J. van den Heuvel, R. A. Leese, and M. A. Shepherd, “Graph labelling and radio channel assignment,” Journal of Graph Theory 29:263-283, 1998.

[36] M. J. Osborne and A. Rubinstein, A Course in Game Theory. The MIT press, 1994.

[37] http://www.mathworks.co.uk/products/matlab/ [Accessed August 2010].

[38] I. Shah, S. Jan, K-K Loo, "Selfish Flow Games in Non-cooperative Multi-radio Multi-channel Wireless Mesh Networks with Imperfect Information," 6th International Conference on Wireless and Mobile Communications, pp. 219-225, 2010

CHAPTER 6

Conclusions and Future Work

This chapter presents the main conclusion and summarises the major contributions of this thesis. The future work section highlights those research areas where the findings of this research can further be investigated for new research directions.

6.1 Conclusion

This thesis has investigated the issues of channel assignment and routing in the emerging IEEE 802.11 based Wireless Mesh Networks (WMNs) [1, 2, 3] by considering both the cooperative and competitive behaviour of the network nodes. The main reason for solving the channel assignment and routing jointly in the cooperative setup was the interdependencies of these two problems on each others. The provision of Quality of Service (QoS) assurance on an end-to-end path is not only determined by the routing protocols but the quality of the individual links matters as well. A minimum interference channel assignment scheme was proposed for assigning the multiple non-overlapping channels, as present in the IEEE 802.11a [4] and IEEE 802.11b/g standards [5], to the multiple radios of the mesh backbone routers. The channel assignment scheme is distributed and dynamic. This means that each node of the network runs a copy of the proposed channel assignment algorithm and the channel re-assignment occurs based on some specific events related to routing load on the links, nodes mobility and failures. Unlike some of the previous approaches [6, 7], the proposed channel assignment scheme is flexible and can be initiated by any node or set of nodes inside the WMNs backbone. This approach, therefore, gives freedom to the network planners for initiating the process based on the network load in a specific region of the WMNs backbone. It is capable to record and maintain accurately the bi-directional link quality by measuring the delay incurred on specific associated links between any two nodes. The delay associated with any bi-directional link is measured frequently in terms of the queue length, *backoff* time, packet losses and the transmission time of the link. This delay metric is further utilized by the routing protocol for determining the end-to-end path across the WMNs backbone on the source-destination basis. The channel assignment scheme quickly responds to the routing load, mobility and nodes failures by re-assigning the channels when and where required.

The routing problem is solved jointly with the above mentioned channel assignment to provide QoS support to the end users in term of end-to-end path delays. The scheme is based on the Ad-hoc On Demand Distance Vector (AODV) [8] routing protocol and paths are established whenever it is necessary. The inherited problem of network wide flooding associated with on demand routing protocols was controlled with selective forwarding on those specific interfaces, which qualify the delay guarantees demanded by the end users applications. The routing protocol combined with the channel assignment module ensures an end-to-end path according to the end users delay requirements. This scheme enhances the packet delivery ratio and minimizes the overall network latency by eliminating a major part of the flood of unnecessary route request packets and ensuring the quality end-to-end paths based on the delay metric proposed. This further provides a mechanism of load balancing across the WMNs backbone by avoiding the already congested links to establish routes for the delay sensitive applications between end users and the Gateway destinations. The performance of the of the proposed Quality of service based Multi-Radio AODV (QMR-AODV) was evaluated against AODV-MR, where a performance gain was observed in terms of packet delivery, latency and routing overhead.

The thesis has presented a two stage non-cooperative game theoretic model developed for assigning multiple non-overlapping channels to the multiple radios of the WMNs backbone routers. The WMNs routers are assumed to be in multiple collision domains and the interference phenomena is captured by using the concepts from graph theory [9]. Conflict graphs [9] were used to partition the WMNs backbone into multiple collision domains. In the non-cooperative environment, nodes behave selfishly to increase their payoffs during the channel assignment process according to their utility function by increasing their data rates on each individual channel. Since individual selfish nodes are considered as the unit of analysis during the game design, therefore, a non-cooperative bargaining scheme has been proposed for mutual agreements between the nodes who want to share a channel over a potential link. A distributed algorithm was implemented based on the rules of non-cooperative game derived for the competitive channel assignment scheme. The game was solved by providing the necessary condition for the existence of NE and N-PNE. The Nash Equilibrium and N-PNE were analytically proved to be sub-optimal in the end-users prospective. Therefore, the proposed model was further enhanced by considering the end users Mesh Access Points (MAPs) non-cooperative bargaining scheme. In the second stage of the game, end users MAPs come into contact with each other and bargain on the channels in their end to end paths. Two MAPs bargain with each other when the channel exchange in their end-to-end paths has an advantage for one in terms of throughput and for other in terms of money. Keeping the non-cooperative nature of the model, the channel exchanges at the end-to-end paths was modelled with a non cooperative bargaining game, where information is considered as imperfect. A distributed algorithm was developed to find out the solution space inside the feasible region [10] and hence the mixed strategy Nash Equilibrium in this game. Evaluation of the proposed scheme shows that through non-cooperative bargaining, end nodes achieve an increase in the end-to-end throughputs. This, however, does not affect other node's end-to- end throughputs.

The thesis has further presented a flow based routing scheme in non-cooperative multiple radio multiple channels WMNs. End users nodes of the network are selfish and non-cooperative aiming to route their flows across the end to end path of the WMNs backbone with high utility. The non-cooperative game theoretic model provides a solution to balance the traffic on individual links. The selfish routing over multi radio multiple channels was modelled using the non-cooperative games. The necessary conditions for the existence of Nash Equilibrium were derived. A distributed algorithm running on each node was implemented which aims to establish links across the end to end path from source to destination. The fairness issues were addressed in the model.

6.2 Future work

There are several recommendations which can be used for future research directions in the area of channel assignment and routing in both cooperative as well as competitive WMNs.

6.2.1 Channel Assignment and QoS based Routing in Cooperative Wireless Mesh Network

Channel assignment and routing play a vital role in the performance of WMNs as the connectivity, throughput, delays and other QoS provision are directly related with both these interdependent issues. In this thesis, the channel assignment scheme was developed by considering the protocol model [11], where the interference phenomenon between any two links is captured based on the packet exchange. However, the protocol model is not an accurate measure of the wireless networks interference. For further research, the protocol can be developed by considering the physical model [11] to accurately capture the interference between the nodes. This method, however, needs existence of expensive and sophisticated equipment in the network [12, 13] for measuring the accurate signal strength and interference. In our proposed QoS routing model, if the RREQ packet does not reach the intended destination, the RREP is not initiated obviously. For this, the route requesting node initiates a fresh RREQ with an incremented ID as the default procedure of AODV. This procedure, however, has been modified and in the next route request the source node reduces the requested QoS bound *i-e* delay demand from the end to end path in this case. The proposed solution solves the problem to the point of getting the RREQ through the backbone with the new reduced QoS. However, for realistic scenarios, a cross layer design [14] for the explicit information exchange between the routing and application layers is highly desirable. This information exchange can inform the application layer modules to send the data with different delay requirements by using some upper layers delay reducing techniques.

The QoS based scheme can also be further investigated for multipath routing across the WMNs backbone. In multipath routing [15,16], a source requests for multiple paths and the destination returns two or more paths which can be used by the source node either as backup paths or using them all simultaneously by splitting data of the same session. Looking at the multi-path problem at the proposed QMR-AODV can enhance the service and network functionality with total guarantees. In this thesis, the proposed QMR-AODV's decision on end to end path is based on delay of the links. For more QoS metrics, several alternatives such as end to end bandwidth and the channel diversity across the routing path can be investigated in the future studies.

6.2.2 Channel Assignment in Competitive Wireless Mesh Networks

The competitive channel assignment scheme proposed in chapter-4 assumes perfect information in a non-cooperative game. This assumption means that each node knows exactly about the number of links interfering with its own link in the same collision domain. The same problem, however, can be further investigated by considering imperfect information in a non-cooperative game. During the channel assignment, the bargaining was achieved through the pre-play negotiation. However, the current model does not consider the cheat proof mechanism and hence this can be explored in future. Further, the non-cooperative bargaining game was played among the end-user MAPs for one time and in a static environment by considering all the MAPs in the same collision domains. The realistic scenarios can be different where the MAPs belonging to different organizations are spread over multiple collision domains. In this case, modelling the bargaining game to spread the bargaining request across multiple collision domains of the users premises can be one of the possible extension to the present solution. The problem can also be looked at by assuming the cooperative bargaining as in [17, 18]. Further, the existing model assumes the full knowledge of all the channels assigned to all the links in the network topology. This increases the complexity in terms of memory and processing. How to design such a bargaining game with imperfect information can be an interesting future study. The game theoretic model developed achieves a good fairness among the competing nodes; however, it is not perfect. The reason is that network nodes are spread across multiple collision domains and the achieved throughput by each node depends on the quality of the channel. It is possible that a node in some collision domain have access to quality channels due to the less number of neighbouring nodes, while another node in the same network can face a dense neighbourhood and thus the effective throughput varies among the nodes in different collision domains of the same WMNs. A potential research study will be to approach this problem by solving the game of channel assignment with non-cooperative flow routing as a combined problem.

6.2.3 Flow Routing in Competitive Wireless Mesh Networks

A flow routing game theoretical model is developed over an interference constrained WMNs topology in a non-cooperative setup. The solution for the game has been derived from the non-cooperative game theory, where each node is self maximizer by routing its flow through the network in a strategic setup. The model assumes that the competing nodes have imperfect information regarding the decision of each others. However, the information of individual links/channel load is known to each node and the utility is derived based on this information. The routing game as discussed in chapter-5 can be further extended by solving it jointly with the channel assignment in the same interference constrained network topology. This can be achieved by first establishing the shortest end to end path in a strategic setup as in [19] and then assigning the non-overlapping channels while considering the interference phenomenon among the channels in the path, using concepts from game theory.

6.3 References

[1] Akyildiz, I. F., Wang, X., & Wang, W., Wireless mesh networks: A survey. Computer Networks, 47(4), 445-487, 2005.

[2] Bruno, R., Conti, M., & Gregori, E., Mesh networks: Commodity multihop ad hoc networks. Communications Magazine, IEEE, 43(3), 123-131, 2005.

[3] Lee, M. J., Zheng, J., Ko, Y. B., & Shrestha, D. M., Emerging standards for wireless mesh technology. Wireless Communications, IEEE, 13(2), 56-63, 2006.

[4] "IEEE 802.11a Standard"; standards.ieee.org/, last accessed: 21/06/2010

[5] "IEEE 802.11b/g Standard"; standards.ieee.org/, last accessed: 22/12/2010

[6] A. Raniwala and T. Chiueh, "Architecture and algorithms for an IEEE 802.11-based multi-channel wireless mesh network," in INFOCOM 2005. 24th Annual Joint Conference of the IEEE Computer and Communications Societies. Proceedings IEEE, pp. 2223-2234 vol. 3, 2005.

[7] S. M. Das, H. Pucha, D. Koutsonikolas, Y. C. Hu and D. Peroulis, "DMesh: Incorporating practical directional antennas in multichannel wireless mesh networks," Selected Areas in Communications, IEEE Journal on, vol. 24, pp. 2028-2039, 2006.

[8] S. Das, C. Perkins and E. Royer, "Ad hoc on demand distance vector (AODV) routing," Mobile Ad-Hoc Network (MANET) Working Group, IETF, 2002.

[9] K. Jain, J. Padhye, V. N. Padmanabhan and L. Qiu, "Impact of interference on multi-hop wireless network performance," Wireless Networks, vol. 11, pp. 471-487, 2005.

[10] K. Chatterjee and L. Samuelson, "Bargaining with two-sided incomplete information: An infinite horizon model with alternating offers," The Review of Economic Studies, vol. 54, pp. 175, 1987.

[11] P. Gupta and P. R. Kumar, "The capacity of wireless networks," Information Theory, IEEE Transactions on, vol. 46, pp. 388-404, 2000.

[12] K. N. Ramachandran, E. M. Belding, K. C. Almeroth and M. M. Buddhikot, "Interference-aware channel assignment in multi-radio wireless mesh networks," in INFOCOM 2006. 25th IEEE International Conference on Computer Communications. Proceedings, pp. 1-12, 2006.

[13] aeroflex 6970 FR Power Meters: http//www.aeroflex.com [Accessed: 02/12/2011]

[14] S. Shakkottai, T. S. Rappaport and P. C. Karlsson, "Cross-layer design for wireless networks," Communications Magazine, IEEE, vol. 41, pp. 74-80, 2003.

[15] N. S. Nandiraju, D. S. Nandiraju and D. P. Agrawal, "Multipath routing in wireless mesh networks," in Mobile Adhoc and Sensor Systems (MASS), 2006 IEEE International Conference on, pp. 741-746, 2006.

[16] M. Mosko and J. Garcia-Luna-Aceves, "Multipath routing in wireless mesh networks," in Proc. IEEE Workshop on Wireless Mesh Networks (WiMesh), Santa Clara, USA, 2005, .

[17] Q. Ni and C. C. Zarakovitis, "Nash Bargaining Game Theoretic Scheduling for Joint Channel and Power Allocation in Cognitive Radio Systems," Selected Areas in Communications, IEEE Journal on, vol. 30, pp. 70-81, 2012.

[18] D. Niyato and E. Hossain, "Spectrum trading in cognitive radio networks: A market-equilibrium-based approach," Wireless Communications, IEEE, vol. 15, pp. 71-80, 2008.

[19] J. Xiao, N. Xiong, L. T. Yang, and Y. He, "A joint selfish routing and channel assignment game in wireless mesh networks," Comput. Commun., vol. 31, pp. 1447-1459, 2008.

List of Publications

Journal Papers

1) **I. Shah**, S. Jan, I. Khan and S. Qamar, "An Overview of Game Theory and its Applications in Communication Networks," International Journal of Multi-Disciplinary Sciences and Engineering. VOL. 3, NO. 4, issn:2045-7057, 2012
2) **I. Shah**, S. Jan and I. Khan, "Optimized Placement of Gateways for Routing Protocols in Wireless Mesh Networks," International Journal of Computer Science and Telecommunications Volume 3, Issue 4, ISSN 2047-3338, 2012.
3) **Ibrar Shah**, Sadaqat Jan, Kok-Keong Loo, "Selfish Flow Games in Non-Cooperative Multi-Radio Multi-Channel Wireless Mesh Networks in Interference constrained topology ", International Journal of Advances in Telecommunications. Volume 4, Number 2, issn: 1942-2601, 2011.
4) S. Jan, Maozhen Li, G. Al-Sultany, Hamed Al-Raweshidy and **I. A Shah** "Semantic file annotation and retrieval on mobile devices" Journal of Mobile Information Systems. Volume 7, Number 2, 2011 .
5) Campbell Carlene E-A, **Shah Ibrar** A,Loo Kok-Keong "Medium Access Control and Transport protocol for Wireless Sensor Networks: An overview", International Journal of Applied Research on Information Technology and Computing Volume : 1, Issue : 1 Print ISSN : 0975-8070. Online ISSN : 0975-8089, Year : 2010

Conference Papers

1) **Ibrar Shah**, Sadaqat Jan, Kok-Keong Loo, "Selfish Flow Games in Non-Cooperative Multi-Radio Multi-Channel Wireless Mesh Networks With Imperfect Information", The Sixth International Conference on Wireless and Mobile Communications (ICWMC), Valencia, Spain, Pages: 219 – 225, Year of Publication:2010, Print ISBN: 978-1-4244-8021-0
2) **I.A.Shah**, S.Jan, S.A.Mahmud, H. S. Al-Raweshidy , "Optimal Path Discovery with Mobility Management in Heterogeneous Mesh Networks" Proceedings of

the 2009 International Conference on Future Computer and Communication, Malysia Pages: 57-61 Year of Publication: 2009 ISBN:978-0-7695-3591-3

3) Sadaqat Jan, **I.A.Shah**, Hamed Al-Raweshidy "Performance Analysis of Proactive and Reactive Routing Protocols for Mobile Ad-hoc Grid in e-health Applications", 2009 International Conference on Communication Software and Networks, Macau, China February 27-February 28 ISBN: 978-0-7695-3522-7

4) S. Hamad, H. Noureddine, N. Radhi, **I. Shah** and H. Al-Raweshidy, "Efficient flooding based on node position for mobile ad hoc network," in Innovations in Information Technology (IIT), 2011 International Conference on, 2011, pp. 162-166.

Submitted Papers

1) **Ibrar Shah**, Sadaqat Jan, Sofian Hamad, and Hamed Al-Raweshidy, "Channel Assignment and QoS Routing in Wireless Mesh Netowrks", Springer Journal of Networks and Management.

2) **Ibrar Shah**, Sadaqat Jan, Sofian Hamad, and Hamed Al-Raweshidy, "Channel Assignment in Competitive Wireless Mesh Networks with End Users Non-Cooperative Bargaining Games", IEEE Transaction on Vehicular Technologies.

3) **Ibrar Shah**, Sadaqat Jan, Sofian Hamad, and Hamed Al-Raweshidy, "A Review of Channel Assignment Schemes in Non-Cooperative Multi-Radio Networks", EURASIP Journal on Wireless Communications and Networking

4) **Ibrar Shah**, Sadaqat Jan, Sofian Hamad, and Hamed Al-Raweshidy, "Selection of Appropriate Radio Technology for IEEE 802.11 Multi-Radio Wireless Mesh Networks- A Comparative Study", IETE Technical Review

5) Sofian Hamad, **Ibrar Shah**, Sadaqat Jan and Hamed Al-Raweshidy, "Route Discovery by Candidate Neighbour to Rebroadcast the RREQ for MANETs", Springer Journal of Networks and Management.

Appendix-1: Proof of Lemma 5.1, Equation (5.11).

Lemma 5.1: For a MRMC multi-collision domain WMN, for $\omega(C_i, C_k)$=0, if $\left(\frac{nf_n}{F_{ij}}\right).R_{C_{ij}} = 1\ \forall\ f_n \in \mathrm{N}_n$ AND $\forall\ f_m \neq f_n \in \mathrm{N}_m$, $\left(\frac{f_m}{F_{ij}}\right).R_{C_{ij}} = 0$ with $\sigma_{ik} \geq 1\ \forall\ C_i \in C_{max}, C_k \in C_{min}$ for any *j* ∈ D, then the strategy profile A* is not a Nash Equilibrium.

Proof: Let α_n be the gain of player *N_n* deviating from its current strategy which has defined all its flows *n.f_n* on one of channel $C_{ij} \in C_{max}$. Let F_{ij} be the total flows on $C_{ij} \in C_{max}$and F_{ik} be the total flows on $C_{kj} \in C_{min}$.

Then:

$\alpha_n = U'_n - U_n$, where U'_n is the new payoff of player N_n after deviating from its current strategy which was giving it a utility U_n .

We represent θ ∈N_n as one of the flow, which player N_n redirect to another channel $C_{kj} \in C_{min}$ in any collision domain *j* ∈D and calculate the benefit of change along the path as follows.

$$\alpha_n = \sum_{f_{n\in f, C_{i\in C, j=1}}}^{|j-1|} \left[\frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}}\right] + \frac{1}{\varphi_{C_{ij}}}\left(\frac{(n-\theta)f_n}{F_{ij}-\theta}\right).R_{C_{ij}} + \left(\frac{1}{\varphi_{C_{kj}}}\left(\frac{\theta f_n}{F_{kj}+\theta}\right).R_{C_{kj}}\right)$$

$$-\left(\frac{1}{\varphi_{C_{ij}}}\left(\frac{nf_n}{F_{ij}}\right).R_{C_{ij}}\right) + \sum_{f_{n\in f, C_{i\in C, j=j+1}}}^{|d|} \frac{1}{\varphi_{C_{ij}}}\left(\frac{f_n}{F_{ij}}\right).R_{C_{ij}} \qquad App: 1.1$$

By considering only *j*∈D collision domain, the first and last summation terms become irrelevant:

$$= \frac{1}{\varphi_{C_{ij}}}\left(\frac{(n-\theta)f_n}{F_{ij}-\theta}\right).R_{C_{ij}} + \left(\frac{1}{\varphi_{C_{kj}}}\left(\frac{\theta f_n}{F_{kj}+\theta}\right).R_{C_{kj}}\right) - \left(\frac{1}{\varphi_{C_{ij}}}\left(\frac{nf_n}{F_{ij}}\right).R_{C_{ij}}\right)$$

Since $R_{C_{ij}} = R_{C_{kj}}$ as in the Equation (5.3) Chapter 5, $F_{kj} + \theta = F_{ij}$ as per condition in the Lemma 5.1 and $\varphi_{C_{ij}} = \varphi_{C_{kj}}$ as per assumption of $\omega(C_i, C_k) = 0$ in the Lemma 5.1:

Therefore substituting the $R_{C_{kj}}$ with $R_{C_{ij}}$, substituting $F_{kj}+\theta$ with F_{ij} and substituting $\varphi_{C_{kj}}$ with $\varphi_{C_{ij}}$:

$$= \frac{1}{\varphi_{C_{ij}}}\left(\frac{(n-\theta)f_n}{F_{ij}-\theta}\right).R_{C_{ij}} + \left(\frac{1}{\varphi_{C_{ij}}}\left(\frac{\theta f_n}{F_{ij}}\right).R_{C_{ij}}\right) - \left(\frac{1}{\varphi_{C_{ij}}}\left(\frac{n f_n}{F_{ij}}\right).R_{C_{ij}}\right)$$

Taking out the common terms $.R_{C_{ij}}$ and $\frac{1}{\varphi_{C_{ij}}}$:

$$= \frac{1}{\varphi_{C_{ij}}}\left[\frac{(n-\theta)f_n}{F_{ij}-\theta} + \frac{\theta f_n}{F_{ij}} - \frac{n f_n}{F_{ij}}\right].R_{C_{ij}}$$

$$= \frac{1}{\varphi_{C_{ij}}}\left[\frac{n f_n.F_{ij} - \theta f_n.F_{ij} + \theta f_n.F_{ij} - \theta^2 f_n.F_{ij} - n f_n.F_{ij} + \theta n f_n}{F_{ij}.(F_{ij}-\theta)}\right].R_{C_{ij}}$$

After simplification by crossing the opposite equal terms with each other:

$$= \frac{1}{\varphi_{C_{ij}}}\left[\frac{-\theta^2 f_n.F_{ij} + \theta n f_n}{F_{ij}.(F_{ij}-\theta)}\right].R_{C_{ij}}$$

After further simplification:

$$\alpha_n = \frac{1}{\varphi_{C_{ij}}}\left[\left(\frac{\theta f_n(n-\theta)}{F_{ij}(F_{ij}-\theta)}\right).R_{C_{ij}}\right] \qquad App{:}\ 1.2$$

$\alpha_n > 0$ in the Equation (*App*: 1.2) as $n-\theta$ and $F_{ij}-\theta$ are positive. Hence, the strategy profile A* cannot be a Nash Equilibrium.