Partially Overlapping Channel Assignment in Multi-Radio Multi-Channel Wireless Mesh Networks

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Approval

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Abstract

Multi-radio Multi-channel (MRMC) Wireless Mesh Networks (WMNs) have made rapid progress in recent years to become a preferred option for end users due to its reliability, scalability and extending the network connectivity on the last mile. Although WMNs have already been deployed but still the capacity of WMNs is limited due to non-coordinated interference (nCO) among channels. To minimize non-coordinated interference among channels and maximize network capacity; channel assignment has always been a key issue in WMNs. Assigning IEEE 802.11b non-overlapping or Orthogonal Channels (OCs) minimize channel interference but they constraint network capacity as they are limited in number and lead to co-channel interference. On the other hand channels whose spectrum interferes with each other are considered as partially overlapping channels in IEEE 802.11b. These partially overlapping channels are not used for transmission as they result in transmission losses due to adjacent channel interference. Recent studies have shown that Partially Overlapping Channels ($POCs$) are not harmful and they can be used to further improve network performance and can utilize IEEE 802.11b spectrum more efficiently. In this thesis, we propose an optimization model that maximizes network capacity and minimizes non-coordinated interference using both non-overlapping and partially overlapping channel assignment in MRMC-WMNs. We also propose an infrastructure heuristic channel assignment algorithm POCA (*Partially Overlapping Channel Assignment*) where a central node keeps and distributes all the channel assignment information. The proposed model assigns both non-overlapping and partially overlapping channels and finds the optimum channel assignment strategy. Simulation results show that POC assignment performs *17%* better than traditional non-overlapping channel assignment in sparse WMN topologies where the non-coordinated interference is high. For dense WMN network environments, where the non-coordinated interference is not high, POC performs *9%* better than OC assignment.

Certificate of Originality

I hereby declare that this submission is my own work and to the best of my knowledge it contains no materials previously published or written by another person, nor material which to a substantial extent has been accepted for the award of any degree or diploma at National University of Sciences & Technology (NUST) School of Electrical Engineering & Computer Science (SEECS) or at any other educational institute, except where due acknowledgement has been made in the thesis. Any contribution made to the research by others, with whom I have worked at NUST SEECS or elsewhere, is explicitly acknowledged in the thesis.

I also declare that the intellectual content of this thesis is the product of my own work, except for the assistance from others in the project's design and conception or in style, presentation and linguistics which has been acknowledged.

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Sadiq Shah

Contents

List of Abbreviations

Abbreviations	**Descriptions**
WMN	Wireless Mesh Network
MR-MC	Multi-Radio Multi-Channel
OC	Orthogonal Channel
POC	Partially Overlapping Channel
AMPL	A Mathematical Programming Language
OPNET	Optimized Network Engineering Tools
SDR	Software Defined Radios
Mbps	Mega bits per second

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Chapter 1

Introduction

1.1 Wireless Mesh Network

Multi-Radio Multi-Channel Wireless Mesh Networks (MRMC-WMNs) consist of wireless mesh routers and clients. Some wireless mesh routers work as a gateway to relay traffic towards other heterogeneous networks. MRMC-WMNs have made progress rapidly in recent years and have become a preferred option for end users due its reliability, scalability and extending the network connectivity on the last mile. MRMC-WMNs provide high throughput because of its multi-radio technology and multi-hop backbone architecture. A WMN can be divided into three levels [1]. First level consists of gateways. These gateways or gateway routers work as a bridge to connect WMNs to internet as shown in Figure 1.1. There can be more than one gateway routers in a WMN. On the second level we have wireless mesh routers which relay traffic inside the WMNs on behalf of the end users. These routers are also called nodes and are static. Third level of WMN architecture comprised of wireless LANs or mesh clients. These end users are the actual senders and consumers of data. Mesh routers or nodes can only communicate if they operate on same IEEE 802.11b frequency channel.

Mesh routers can be equipped with single or multiple radios. In case of single radio WMNs nodes can't utilize multiple channels efficiently. The radio need to be switched very frequently due to dynamic traffic demands [1]. This switching creates significant delays during data transmission. These delays can be in milliseconds and even leads to link disconnection. On the other hand multi-radio architecture which is used in current deployments is very useful. Here each node is equipped with multiple radios instead of one radio. Multiple frequency channels can be activated on the same node at the

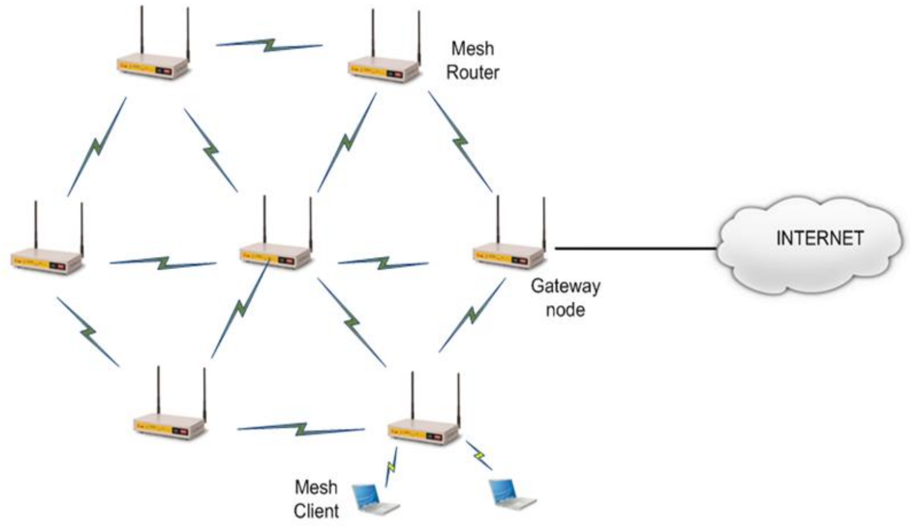


Figure 1.1: Wireless Mesh Network

same time that leads to higher network capacity.

In WMNs every node (mesh router) has its own transmission and carrier-sensing range. Two nodes communicate only if they are in the transmission range of each other and they are operating on the same frequency channel. Apart from transmission range every node in a WMN has a carrier-sensing range. Inside this carrier-sensing range nodes can create interference if they are operating on the same frequency channel. Figure 1.2 shows difference between transmission and carrier-sensing ranges. The outer dotted circle represents the carrier-sensing range while the inner solid circle represents the transmission range of L1. When interference occurs it causes transmission losses and also degrades WMN performance.

1.2 Interference and its classification in WMN

Interference in wireless mesh networks is categorized as coordinated (CO) and non-coordinated (nCO) interference [2]. Two links are coordinated(CO) interfering links if their source nodes are in each other's carrier-sensing range. Fig 1.2 shows CO interference relationship between link *L1* and *L2*. In case of non-coordinated (nCO) interference source nodes need not to be in carrier-sensing range. Non-coordinated (nCO) interference is further divided into three types i.e.

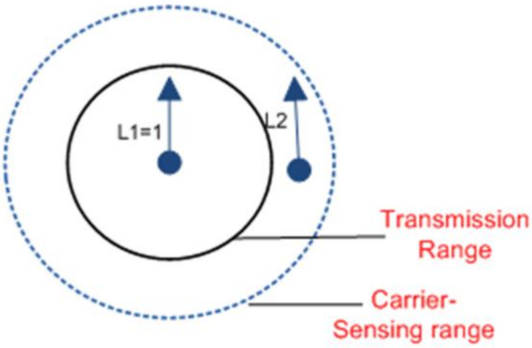


Figure 1.2: Coordinated interference: The source of *L2* is inside the carrier-sensing range of *L1*. Both the links can share channel 1.

i) *Information asymmetry*,
ii) *Near-hidden terminal*
iii) *Far-hidden terminal*.

Figure 1.3 presents all the three types of non-coordinated interference. If two links *L1(s1,d1)* and *L3(s3,d3)* are active on the same channel then for information asymmetry(IA) interference the following condition need to be true. Let d represents the physical distance among nodes then:

- $d(s1,\ s3) > Cs$
- $d(d1,\ s3) < Cs$
- $d(s1,\ d3) > Cs$

Source nodes *s1* and *s3* are outside each other carrier sensing ranges *Cs*. Similarly *s1* and *d3* are also outside each other carrier-sensing range but *s3* and *d1* are inside each other carrier-sensing ranges. In such case flow on *L1(s1, d1)* can be reduced due to interference from *L3(s3,d3)*. For near-hidden(NH) interference the following condition must be satisfied: According to Figure 1.3 if *L1* and *L2* are two links then:

- $d(s1,\ s2)> Cs$
- $d(d1,\ s2) < Cs$
- $d(s1,\ d2) < Cs$

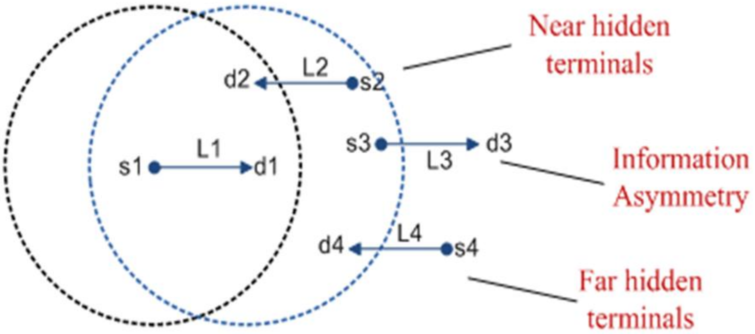


Figure 1.3: Non-coordinated interference categories

Both the source nodes *s1* and *s2* are outside each other carrier-sensing range *Cs*. But the receivers of both the links are inside the sensing range of each other's source node. Both these links interfere each other in case of transmission on the same frequency channel.

Far-hidden(FH) is the third type of non-coordinated interference. Following constraints hold for the Far-hidden interference among links:

- $d(s1, s4) > Cs$
- $d(d1, s4) > Cs$
- $d(d1, d4) < Cs$

In case of *FH* only the receivers of *L1* and *L4* can sense each other. So if transmission on the same channel is started at the same time both *d1* and *d4* can sense each other causing traffic loss. To minimize *nCO* interference channel assignment performs very important role. Various channel assignment schemes are proposed which are discussed in chapter 2 in detail. We discuss channel assignment in the next section.

1.3 Channel assignment in WMNs

There are various issues faced by a MRMC-WMNs i.e. node deployment, channel assignment, link scheduling and routing. Channel performs a vital role in minimizing interference among WMN links. Channel assignment refers to proper mapping between the available channels and the radios at a particular node. The radio technology we are using in our thesis is 802.11b.

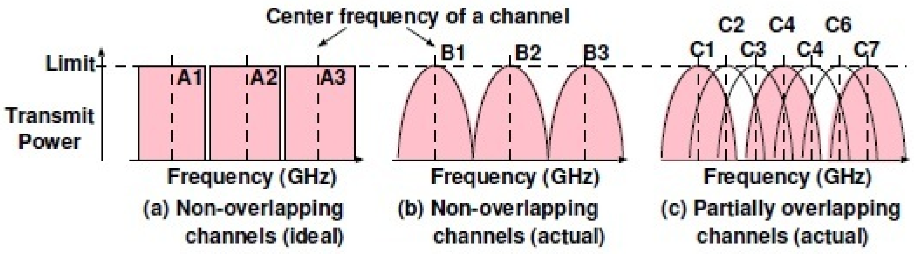


Figure 1.4: IEEE 802.11b/g frequency spectrum[5].

There are 11 frequency channels in IEEE 802.11b frequency band. Two channels separated by at least 25MHz are referred as non-overlapping [3]. In all these available 11 channels only three channels 1, 6 and 11 are non-overlapped [3] and don't interfere with each other. Assigning IEEE 802.11b non-overlapping or orthogonal channels (OCs) minimize channel interference but they constraint network capacity as they are limited in number and lead to co-channel interference. Currently these three traditional orthogonal channels are in use in WMNs.

In IEEE 802.11b frequency spectrum all those channels whose spectrum interferes are known as partially overlapping channels. Figure 1.4 represents IEEE 802.11b frequency spectrum. For any two channels the higher the overlap the more they interfere each other. Till now these partially overlapping channels are not utilized because they are considered harmful [4, 5] and were not used due their interference they have among them. This type of interference is called adjacent-channel interference. Previous results by Mishra et. el. [4] have shown that if the spectral gap among channel is increased they cannot sense each other as much as they sense a fully overlapping channel. That's the reason why channel 1 and 6 in 802.11b do not interfere each other.

Figure 1.5 shows an example on how partially overlapping channels can be used to improve network performance and by using maximum channels. Dotted circles are the various carrier sensing ranges of transmitter T. Here $r|x-y|$ is the carrier sensing range between channel x and y. If x and y are same then $r|x-y|= r|0|$ which represents the carrier sensing range for same channel (maximum carrier sensing range).

In the given Figure 1.4 $r|x-y|$ varies from $r|0|$ to $r|5|$. It should be noted that $r|5|$ is the carrier sensing range between non-overlapping or orthogonal

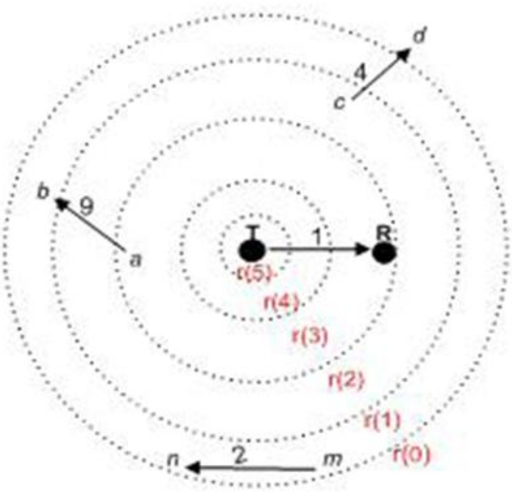


Figure 1.5: Carrier-sensing ranges for frequency channel separation $r|x-y|$

channels and there is almost no interference among channels. In this figure transmitter T and receiver R are communicating on channel 1. In case of channel reuse we can't assign channel 1 to all the remaining links *(c,d)*, *(a,b)* and *(m, n)* because all these links are in the carrier sensing range of link *(T, R)*. Now look at link *(m,n)*, it is outside $r|1|$, so we can assign a channel to this link that has spectral gap of at least 1 with channel 1 e.g. channel 2. Same is the case with link *(c,d)* where channel 2 can't be assigned as link *(c,d)* is inside the carrier sensing range $r|0|$ and $r|1|$ but channel 3 to 11 can be assigned. Link *(a,b)* is assigned channel 9 that has no interference with any of the three remaining links. So from this it is clear that interference between two links depends on physical distance as well as the spectral gap among channels.

Mishra et. el. [5], *POC* has done allocation statically and through experiments they show that the use of *POC* allocation is not always harmful. In case of static allocation once the channels are assigned they can't be modified frequently. So in case of high traffic load on specific link (i.e. gateway link) we can't switch that particular link to new channel. But due to the introduction of software defined radios (SDR) and cognitive radios now it is possible to allocate frequency channels dynamically to a specific link. So in our thesis we are going to propose an optimization model for dynamic *POC* allocation.

Table 1.1 presents the carrier-sensing ranges from $r|0|$ to $r|5|$. These ranges have been tested using OPNET simulator. We have taken two pairs of mesh nodes and the flow demand on both links was saturated. The physical distance among both pairs and spectral gap among channel was varied. The transmission range Tr of each source is kept $30 meters$.

Table 1.1: Carrier-sensing ranges for channel gap $r|x-y|$

Spectral Gap	**Carrier-Sensing Range**
$r\|0\|$	*2.6*Tr*
$r\|1\|$	*2.26*Tr*
$r\|2\|$	*1.86*Tr*
$r\|3\|$	*1.4*Tr*
$r\|4\|$	*1*Tr*
$r\|5\|$	*0*Tr*

1.4 Research Gap

Garetto et al. classified interfering links as coordinated and non-coordinated. Non-coordinated in further categorized as i) *Information asymmetry(IA)*, ii) *Near-hidden terminal(NH)* and iii)*Far-hidden terminal(FH)* depending on the geometric relationship between the interfering links. The authors have shown empirically that non-coordinated interference results in higher transmission losses compared to coordinated interference. Naveed [6], has given the idea of dynamic channel assignment algorithm LYCAS (Load-aware dYnamic Channel Assignment Scheme) and presented an optimization model for maximizing the network throughput by minimizing the non-coordinated interference. The author minimized non-coordinated interference to maximize WMN throughput assigning non-overlapping channels. Mishra et el. [4, 5] introduced the idea of partially overlapping channel(POC) allocation and derived that POC allocation is not harmful and can be used to maximize network throughput. To be the best of our knowledge non-coordinated interference is never minimized using partially overlapping channel assignment. In our thesis we are going to extend the work done by Naveed [6] to minimize nCO interference and maximize WMN capacity using partially overlapping channel POC assignment.

1.5 Problem Statement

*"A channel assignment scheme using partially overlapping channels, in addition to non-overlapping channels can better minimize non-coordinated (*nCO*) interference in multi-radio multi-channel (MRMC) Wireless Mesh Networks that not only leads to higher network capacity but efficient utilization of IEEE 802.11b frequency spectrum"*

1.6 Thesis Contribution

Our thesis contribution is as follow:

- First we propose an algebraic optimization model which assigns both non-overlapping and partially overlapping channels to WMN nodes keeping in view coordinated and non-coordinated interference.
- Second our optimization model compares the performance of both orthogonal and partially overlapping channel assignment in sparse and dense WMN topologies.
- Third we propose an infrastructure based heuristic algorithm *POCA* (Partially Overlapping Channel Assignment) where a central node (head node) assigns channels to links based on channel assignment strategy given by proposed optimization model.
- In the end we verify our optimization model results through simulations. Our simulation results also show that partially overlapping channel *POC* assignment performs better than traditional non-overlapping channels in both sparse and dense WMN topologies.

1.7 Thesis Organization

The remaining thesis plan is as follow:

Chapter 2 presents a detailed related work done on channel assignment regarding interference reduction and partially overlapping channel assignment.

In chapter 3 we propose our algebraic optimization model which gives optimal channel assignment for a WMN topology. In this chapter we also propose our channel assignment algorithm *POCA*.

Chapter 4 consists of the implementation details of our optimization model using MATLAB, AMPL (A Mathematical Programming Language) and OPNET.

In chapter 5 all the simulation results are discussed. Two topologies dense and sparse are simulated and in the end their results have been compared.

Chapter 6 concludes our thesis work and future work.

1.8 Summary

In this chapter we introduced wireless mesh networks and the difference between single radio and multi-radio wireless mesh networks. We briefly described the difference between coordinated (CO) and non-coordinated (nCO) interference in WMNs. The chapter also highlighted the IEEE 802.11b frequency spectrum consisting of 11 channels. In section 1.3 we presented a detailed overview on how partially overlapping channels along with orthogonal channels can be used to minimize non-coordinated interference in MRMC-WMNs. Through table we presented carrier-sensing ranges for various spectral gaps. These ranges vary from $r|0|$ to $r|5|$. In the end we described the problem statement of our research thesis.

Chapter 2

Literature Review

In this chapter we present our literature review which is classified into two broad categories. Section 2.1 consists of detailed related work regarding interference in WMNs. In Section 2.2 we present an overview on how partially overlapping channel assignment is used to minimize interference and maximize WMN performance.

2.1 Interference in Wireless Mesh Networks

Extensive studies have already been done regarding interference and its impact on the performance of WMNs. Garetto et al. [2] divided interfering links into two categories. 1) Coordinated (CO) and 2) Non-coordinated (nCO) links. The author further classified nCO links as a) Information Asymmetric (IA), b) Near-Hidden (NH) and Far-hidden (FH) interfering links. The authors derived conditional packet loss probabilities of links under each category of interference. The author has made a comparison of CO and nCO transmission losses and proved that non-coordinated links result in significantly higher transmission losses as compared to coordinated interference.

Naveed [6], has given the idea of dynamic channel assignment algorithm LYCAS and presents an optimization model for maximizing the network throughput by minimizing the non-coordinated interference. The author has review both coordinated and non-coordinated interference and showed that non-coordinated interference is more harmful than coordinated regarding interference. The author used non-overlapping channel assignment scheme for non-coordinated minimization. In our thesis we are extending the work[6] for partially overlapping channels ($POCs$) to maximize network capacity and minimize non-coordinated interference.

2.2 Partially Overlapping Channels and WMNs

Interference is considered a key issue in wireless mesh networks which decreases the network capacity and throughput. Interference from the same channel is called co-channel interference while from adjacent channels the interference is called adjacent channel interference. Various researches have been conducted on the allocation of partially overlapped channels to adjacent links to monitor the impact of adjacent channel interference. Mishra et el. [4] introduced the idea of partially overlapping channel(POC) allocation. This was the first systematic work to take advantage from *POCs*. Although they did not present a particular algorithm for channel assignment but it was a reasonable step towards the design of new and efficient algorithms for WLANs and wireless mesh networks. They showed how interference can be minimized in WLANs and WMNs by using partially overlapped channels in a single radio environment.

Mishra et el. [5] presented that *POC* channels are not harmful and can be used for improving network capacity. They found inference factor (I-factor) which is the ratio of overlap among various channel. The channels having more I-factor have more SNR. The channel assignment they did was static and was for single radio. Zhirong et el. [19] and Mishra et el. [5] proposed a channel assignment scheme based on traffic load and dynamic *POC* allocation. In their proposed model the sender and receiver are tuned to different channels that are partially overlapped. Based on the traffic load the node switches its radio among various channels. Although in this approach the authors did not mention a proper algorithm for switching among channels but they presented the idea of switching dynamically to the more ideal channel in case of higher traffic demand.

For allocating overlapping channels dynamically in WLAN Robert Akl et el. [7] first developed a mathematical model in which the amount of interference between overlapping channels has been captured. Second they presented a dynamic channel allocation algorithm by minimizing channel interference between access points (APs). Yong et el. [8], did static channel allocation of *POCs* of 802.11b/g to maximize the throughput in WMNs. The authors proposed a weighted conflict graph to model the interference between wireless links. Based on this model a greedy algorithm for partially overlapping channel assignment is presented and then they proposed a novel genetic algorithm. The authors did not work to minimize non-coordinated interference*(nCO)*.

Zhenhu et el. [9] worked on the dynamic channel allocation assignment of partially overlapped channel in one hop wireless transmission scenarios. The authors presented an analytical model to estimate the capacity improvement using *POCs* in wireless networks. They also characterized various effects of node density, node distribution, network topology and traffic pattern on the performance of *POC* based approach[9]. Through simulation results they showed how *POC* based approach works better in denser environment with heavy traffic. There have been several well-known test beds of WMNs. The MIT RoofNet [10] is a popular test bed for wireless mesh networks but it is built on the MIT campus. Microsoft [11] also developed a test bed inside their own office building. In both these test beds they have studied co-channel interference.

For multi-hop wireless mesh networks Haiping Liu et el. [12], propose a channel allocation and link scheduling algorithms in the MAC layer to enhance network performance and present a heuristic algorithm to fulfil end-to-end flow transmission constraints. They consider different link requirements in the network and discuss various factors i.e. such as topology, node density, and node distribution (e.g. in [9]) that affects the performance of partially overlapping channels (*POCs*) in multi-hop wireless mesh networks. Through simulation they show how POC scheme works better in denser node situations while in scarce environment it does not perform well as the nodes are located apart so that they do not interfere. The authors focused in single radio environment and their work is not feasible to take advantage of multi-radio environment.

Mohammad A. Hoque et el. [13] presents a new interference model I-Matrix that selects channels dynamically with less interference and a *POC* based channel assignment algorithm. Their *POC* based algorithm shows capacity improvements over orthogonal channels. They also focus on minimizing the interference in MRMC-WMN but they deal coordinated and non-coordinated interference as the same. Our work is different from then in the sense that we are prioritizing the minimization of non-coordinated interference over coordinated interference. Vibhav et el. [14] mentioned joint channel assignment and flow allocation for Multi Channel Multi Radio WMNs as a Mixed Integer Linear Program (MILP). The channel allocation they have done is static and their objective is to maximize end-to-end throughput by utilizing both orthogonal and non-orthogonal channels.

A. Raniwala et el. [15] presented an iterative approach for solving the joint routing and channel assignment issue. Their proposed scheme calculates both a routing scheme and a channel assignment scheme. Further the problem has been formulated by Alicherry [16] and Kodialam [17] by using linear programming with constraints on interference and fairness, which is NP hard. Our thesis work is different in the sense that we are working on minimizing non-coordinated interference to maximize the wireless mesh network capacity.

2.3 Summary

In this chapter we reviewed the related work regarding interference and partially overlapping channel assignment. Difference between coordinated and non-coordinated interference is highlighted. Further the non-coordinated interference is categorized as Information asymmetry,ii) Near-hidden terminal and iii) Far-hidden terminal. Then we described in detail the work done on the use of *POCs* in wireless mesh networks. IEEE 802.11b frequency spectrum consists of 11 channels in which only three non-overlapping channels are used. The study showed the use of partially overlapping channels along with orthogonal channels to optimize the network performance.

Chapter 3

Proposed Optimization Model and Algorithm

In this chapter the proposed optimization model is presented. The objective of our optimization model is to assign optimal channels to WMN links to maximize the network capacity. The model assigns both orthogonal and POC channels to links based on their carrier sensing ranges. In this way those links which were unable to transmit in case of orthogonal channels and co-channel interference are now able to become active on partially overlapping channels which leads to higher network capacity.

Section 3.1 we formulate our optimization model consisting decision variables, set of constrains and objective function. Our proposed channel assignment algorithm *POCA* is given and explained in section 3.2.

3.1 Problem Formulation

In this section we formulate our proposed non-linear optimization model. The model consists of decision variables, objective function and constraints. Naveed [6] presented a related optimization model but that was for non-overlapping channels. We are extending that previous model to POC channel assignment model.

Let we have directed graph G of V mesh nodes and E links. M is the set of all available frequency channels i.e. M=(1,2,3,...11) and k is number of channels that is 11. C_{c_j} represents the capacity of each frequency channel. $I(v_i)$ is the set of directional links incident on node v_i while $c(e_j)$ shows channel assigned to link e_j. The number of interfaces on each node v_j is $n(v_j)$

which is ≥ 2. $N_{nco(e_j)}$ represents the set of all non-coordinated interfering links of a link e_j. $N_{co(e_j)}$ is set of all coordinated interfering links of e_j. Flow over link is $f(e_j)$. Set of all partially over-lapping channels is $poc(c_j)$. $y(e_i, c_j)$ is representing the binary decision variable which is 1 if link e_i in active on channel c_j otherwise 0. $\lambda(e_i)$ is the fraction of traffic flow on any link. Carrier-sensing or interference range is represented by $r(|c_i - c_j|)$. $N_{nco(e_i, r(|c_i - c_j|))}$ is the set of *nCO* interference links of e_i (active on c_j) in carrier-sensing range $r(|c_i - c_j|)$. The list of all model notations and their description is also given in Table 3.1.

3.1.1 Assumptions

In our proposed model we have considered the following assumptions.

- In our proposed model capacity of all channels used is the same.
- Each node is equipped with more than two radios so as take advantage of multiple channels and multi radio technology.
- All the nodes are static and all the paths in network are single link paths.
- Only single flow at time is passing from one link (a links is not shared by multiple flows).

3.1.2 Decision Variable

Decision variable is an important part of any optimization model. As we are working on channel assignment so our decision variable is based on assigning an IEEE 802.11b channel to a link. Following is our decision variable that will be used in our optimization model. It states that if any link e_i is active on any channel c_j then it is equal to 1 and otherwise 0. This kind of decision variable is also called binary variable.

$$y(e_i, c_j) = \begin{cases} 1 & \textit{if the directed link } e_i \textit{ operates on channel cj} \\ 0 & \textit{otherwise} \end{cases}$$

3.1.3 Constraint Set

Constraints are the limitations on an optimization model and they describe the unacceptable results. Following is the constraint set of our channel assignment model.

Table 3.1: List of Notations

Notation	Definition
V	Set of vertices
E	Set of directed links selected
G	Directed network topology graph
M	Set of all usable channels of 802.11b/g
K	Number of channels in set M
C_{c_j}	Capacity of channel c_j
$I(v_i)$	Set of directional links incident on node v_i
$c(e_j)$	Channel assigned to link e_j
$n(v_j)$	Number of interfaces of node v_j where $n(v_j) \geq 2$
$N_{nco(e_j)}$	The set of all non-coordinated interfering links of e_j
$N_{co(e_j)}$	The set of all coordinated interfering links of e_j
$f(e_j)$	Flow over link e_j in time interval T
$poc(c_j)$	Set of all partially over-lapping channels that have spectral gap between 1 and 4 with channel i.
$y(e_i, c_j)$	Binary variable: set to 1 if link e_i in active on channel c_j
$\lambda(e_i)$	Fraction of traffic flow on any link fulfilled in T
$r(\|c_i - c_j\|)$	carrier-sensing or interference range of channel c_i with its (poc) channel c_j
$N_{nco(e_i, r(\|c_i - c_j\|))}$	Set of nCO interference links of e_i (active on c_j) in carrier-sensing range $r(\|c_i - c_j\|)$

1. *Single Channel per Link Constraints:* First constraint in our optimization model ensures that every link in the set E (edges) must be assigned only one channel. Single Channel per Link Constraints states that if e_i is a link and we sum it over all channels then it evaluates to 1.

$$\sum\nolimits_{cj \in M} y(ei, cj) = 1 \qquad \forall ei \in E \,, cj \in M \tag{3.1}$$

2. *Coordinated Interference Constraints:* Coordinated links do not cause interference. Channel assignment is not affected if multiple coordinated links operate on the same channel. The channel capacity is in fact distributed amongst all the coordinated interfering links. Following constraint shows how a channel capacity is shared when multiple coordinated links are active on same channel.

$$y(ei, cj).\lambda(ei).f(ei) + \sum\nolimits_{ek \in Nco(ei)} y(ek, cj).\lambda(ek).f(ek) \leq Ccj \qquad \forall ei \in E, \forall cj \in M \tag{3.2}$$

3. *Non-coordinated Interference Constraints (Fully over-lapped channels constraint):* The channel assignment should ensure that non-coordinated links do not operate on common or fully over-lapping channel. Here e_i and e_k are different links working on the same channel c_i. So only one of them will be active on channel c_j in interference range $r|c_j - c_j|$.

$$y(ei, cj) + \frac{\sum_{ek \in nco(ei,r|cj-cj|)} y(ek, cj)}{1 + \sum_{ek \in nco(ei,r|cj-cj|)} (1)} \leq 1 \qquad \forall ei \in E, \forall cj \in M, ek \in E \tag{3.3}$$

4. *Partially over-lapping channel constraint:* This constraint states that non-coordinated links can't operate on *POCs* inside their relevant carrier-sensing range(ranges are given in Table 1.1). The purpose of this constraint is to minimize non-coordinated interference when *POC* channels are utilized. In the given constraint if a link e_i is active on channel c_j then non of its non-coordinated links in set $N_{nco(e_i,r|c_j-c_i|)}$ is active on any partially over-lapped channel in carrier-sensing range $r|c_j - c_i|$. $r|c_j - c_i|$ varies from $r|0|$ to $r|4|$.

$$y(ei, cj) + \frac{\sum_{ek \in nco(ei,r|cj-ci|)} y(ek, ci)}{1 + \sum_{ek \in nco(ei,r|cj-ci|)} (1)} \leq 1 \quad \forall ei \in E, \forall cj, ci \in M, \forall ci \in M, ek \in E, cj \neq ci \tag{3.4}$$

5. *Channel per node constraint:* This constraint is related to WMN nodes consist of multi-radios. The constraint insures that total number of channels active on links of a particular node should not be more than the number radios on that node. The equation is given below:

$$\sum_{cj \in M} \sum_{ei \in I(vi)} y(ei, cj) \leq n(vi) \quad \forall ei \in E, \forall cj \in M \, \forall vi \in V, cj \in M, ei \in E \tag{3.5}$$

3.1.4 Objective Function

The objective of our model is to maximize the MRMC-WMN capacity. Getting the objective all the constraints must be considered. So we are adding all the link flows fulfilled over all the links and channels.

$$\max \quad \sum_{ei \in E} \sum_{cj \in M} y(ei, cj).\lambda(ei).f(ei)$$

s.t

$$\sum_{cj \in M} y(ei, cj) = 1 \qquad \forall ei \in E\,, cj \in M$$

$$y(ei, cj).\lambda(ei).f(ei)+\sum\nolimits_{ek\in Nco(ei)} y(ek, cj).\lambda(ek).f(ek) \leq Ccj \qquad \forall ei \in E, \forall cj \in M$$

$$y(ei, cj) + \frac{\sum_{ek\in nco(ei,r|cj-cj|)} y(ek, cj)}{1+\sum_{ek\in nco(ei,r|cj-cj|)} (1)} \leq 1 \qquad \forall ei \in E, \forall cj \in M, ek \in E$$

$$y(ei, cj)+\frac{\sum_{ek\in nco(ei,r|cj-ci|)} y(ek, ci)}{1+\sum_{ek\in nco(ei,r|cj-ci|)} (1)} \leq 1 \quad \forall ei \in E, \forall cj, ci \in M, \forall ci \in M, ek \in E, cj \neq ci$$

$$\sum_{cj\in M} \sum_{ei\in I(vi)} y(ei, cj) \leq n(vi) \quad \forall ei \in E, \forall cj \in M \forall vi \in V, cj \in M, ei \in E$$

3.2 Proposed Channel Assignment Algorithm: POCA(*Partially Overlapping Channel Assignment*)

In this section we propose a heuristic channel assignment algorithm *POCA*. The algorithm assigns and distributes channel assignment strategy given by our proposed optimization model. Both orthogonal and partially overlapping channels are assigned to all the active links of MRMC-WMN. The algorithm is infrastructure based where a central node allocate channels to all the links.

let we have WMN graph $G(V, E)$ which consists of V nodes and E set of links. Set C is the set of all frequency channels. $Eco(e_i)$ is the set of coordinated links of link e_i while $Enco(e_i)$ is the set of non-coordinated links of link e_i $NBR(Vi)$ represents the set of neighbours of node V_i inside the transmission range Tr of v_i. v_i receiving signal power strength is represented by $SGNL - STRNGHT$. CE is the final channel assignment set given by our optimization model. C_{c_j} is the capacity of each frequency channel c_j. $I(v_i)$ is the set of directional links incident on a node v_i. When a channel is assigned to a link it is represented by $c(e_j)$. $n(v_j)$ is the number of interfaces of node v_j where $n(v_j) \geq 2$. V_j is a node belong to set V while c_j is the frequency channel belong to set C and e_i is a link belong to set E. (cj, ei) is the channel c_j

Table 3.2: List of Algorithm Notations

Notation	Definition
V	Set of WMN nodes
E	Set of WMN edges
C	Set of available frequency channels
v_j	A node belong to set V
c_j	A channel belong to set C
e_i	A link belong to set E
$Eco(e_i)$	Set of coordinated links of e_i
$Enco(e_i)$	Set of non-coordinated links of e_i
$NBR(v_i)$	set of neighbours of V_i in transmission range tr
$SGNL-STRNGHT$	receiving signal power strength
C_{c_j}	Capacity of channel c_j
$I(v_i)$	Set of directional links incident on node v_i
$c(e_j)$	Channel assigned to link e_j
$n(v_j)$	Number of interfaces of node v_j where $n(v_j) \geq 2$
(cj, ei)	Channel c_j assigned to link e_i
$CENT-NODE$	Central node which distributes channel assignment information
$CENT-NODE-ID$	Central node Identifier
$JOINING-NODE(V_i)$	A node which joins the WMN first time
$LEAVING-NODE(V_i)$	A node which leaves WMN
$NBR-LIST(v_i)$	Neighbour nodes list
$SGNL-STRNGTH(NBR(V_i))$	Signal strength of all neighbours of node v_i
CE	Set of resulted channel assignment which is distributed

assigned to link e_i. $CENT-NODE$ is the central node that distributes channel assignment information. $CENT-NODE-ID$ is the central node identifier. The node which will join a node is represented by $JOINING-NODE(V_i)$ while the leaving node is represented by $LEAVING-NODE(V_i)$. $NBR-LIST(v_i)$ shows the neighbour list of a node. $SGNL-STRNGTH(NBR(V_i))$ is the signal strength of the neighbour of node v_i. Table 3.2 lists all the notations.

3.2.1 *POCA* Algorithm

- *ALGORITHM NOTATIONS*
  All the notations used in *POCA* algorithm are given in Table 3.2.

- *INPUT*
  Set V, node v_i ($JOINING-NODE(v_i)$ or $LEAVING-NODE(v_i)$), Set

C, Set E

- *OUTPUT:*
  Set of link channel assignment (cj, ei) where (cj, ei) ϵ CE
  ALGORITHM:

```
1.  $V_i$ sends JOIN message to all $NBR(v_i)$ (neighbour nodes of $v_i$)
2.  $NBR(v_i)$ send REPLY with $CENT - NODE - ID$
3.  $v_i$ sends $NBR - LIST(v_i)$ and $SGNL - STRNGTH(NBR(v_i))$
4.  $CENT - NODE$ checks each $NBR(v_i)$'s $SGNL - STRNGTH$ from
.   their respective neighbours
5.  for all $e_i$ belong to $E$ do
6.      Find out the set of $Eco(e_i)$
7.  end for
8.  for all $e_i$ belong to $E$ do
9.      Find out the set of $Enco(e_i)$
10. end for
11. for all $e_i$ belong to E do
12.     Find out the optimal channel assignment set $CE$ of $(c_j, e_i)$
13. end for
14. $CENT - NODE$ broadcasts set CE to all $v_i$ belong to $V$
```

3.2.2 POCA Explanation

In *POCA* algorithm when a new node v_i enters to WMN it first sends a joining message JOIN to all its neighbours $NBR(v_i)$. The neighbours in response sends a REPLY message to v_i along with ID of the central head node $CENT-NODE-ID$. After REPLY v_i sends its neighbour list $NBR-LIST(v_i)$ and signal strengths $SGNL-STRNGTH(NBR(v_i))$ to head node. In this way the central node has signal strength information of all the nodes. Based on this information the central node calculates the information how far a node is from the other node. Now the central node knows about the coordinated and non-coordinated links of a node. From step 5 to step 10 the algorithm finds coordinated and non-coordinated links of each node. From step 11 to 13 the central node runs the optimization model and finds the optimal channel assignment set CE. In the end central node broadcasts the channel assignment information to all the nodes of WMN. In this way all the WMN nodes come to know about their assigned channel.

3.3 Summary

In this chapter we discussed our proposed channel assignment model. The model consists of one binary decision variable and five constraints. The value of our decision variable is 1 if a channel is assigned to a link otherwise 0. The first constraint i.e. single channel per link assignment constraints states that every link in the set E (edges) must be assigned only one channel. The second constraint called coordinated interference constraints ensures that a channel can be shared among coordinated links. Third constraint is fully over-lapped channels constraint stats that non-coordinated links cannot operate on common or fully over-lapping channel as this can cause severe interference. The fourth constraint i.e. partially overlapping channel constraint ensures that non-coordinated links can't operate on *POC* channel inside their respective carrier-sensing range. The fifth constraint is the channel per node constraint which describes the total number of channel active on links of a particular node should not be more than the number radios on that particular node.

The objective of our model is the capacity optimization subject to all the above stated constraints. We also explained our proposed heuristic channel assignment algorithm *POCA*. This heuristic algorithm *POCA* is infrastructure based and assigns both orthogonal and partially overlapping channels to all the active nodes and links of MRMC-WMN. In the end we described some assumption regarding our model.

Chapter 4

Implementation

In this chapter we explain the implementation details of our thesis. The chapter is divided into three sections. In first section a brief introduction to MATLAB is given which describes how we have used MATLAB to generate two WMN topologies consisting of 30 nodes. For implementing our optimization model we have used AMPL language, so the second section gives details about AMPL language. In section third OPNET simulator is explained. We have done all our simulations using OPNET.

4.1 MATLAB WMN Topology

MATLAB stands for Matrix Laboratory is a powerful fourth generation language used for numerical computing, algorithm implementation, plotting graphs etc. In MATLAB it is very easy to create graphs so for our thesis we have used MATLAB for physical topologies generation. We generated two topologies in order to compare. In these network topologies one is sparse while the other is dense. Before implementing our optimization model we needed the set of co-ordinated*(CO)* and non-coordinated*(nCO)* interfering links. All these interfering link sets have been taken from MALAB. Figure 4.1 represents one of the MATLAB generated topology. The given MATLAB topology is dense. It consists of 30 WMN nodes.

For coordinated and non-coordinated interfering links we plot three circles. The circle in solid line represents the transmission range of a node. For example the given transmission range belongs to node 1. So node 1 can transmit to all other nodes that are inside his transmission range (the solid line circle). The second dashed circle represents the sender carrier-sensing range. For example if 1 and 2 forms a links *(1,2)* where node 1 is the sender

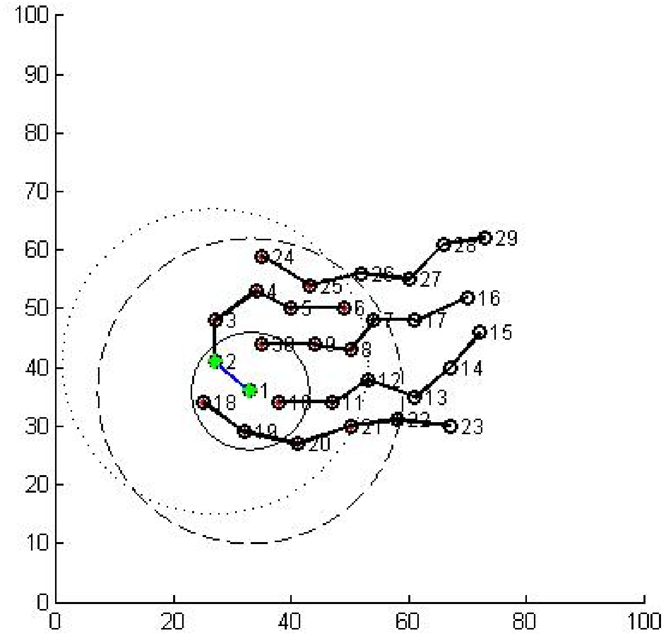
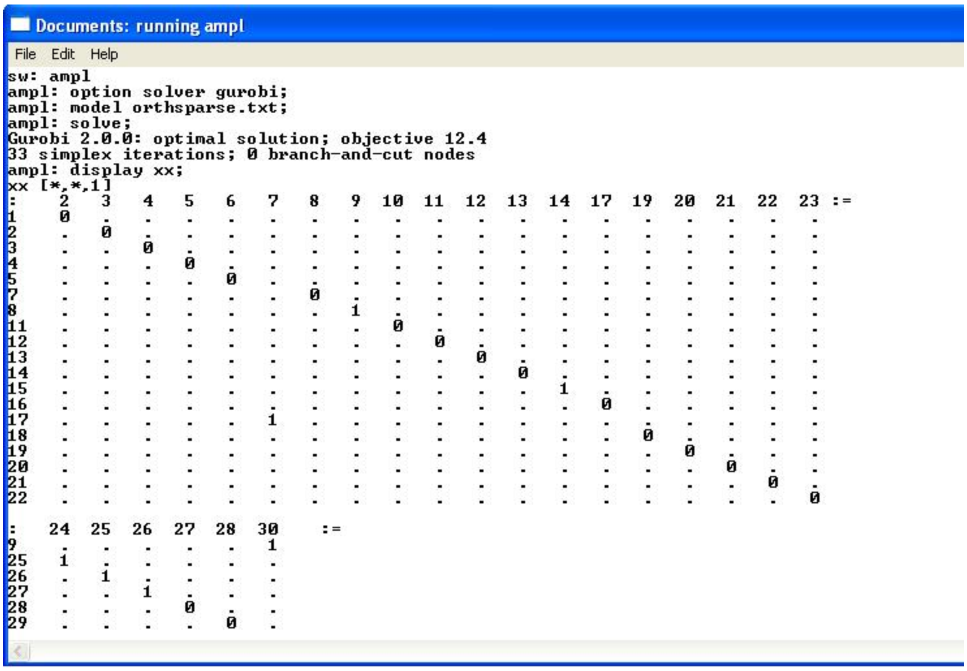


Figure 4.1: MATLAB generated WMN dense topology

and node 2 is the receiver then dashed circle is the carrier-sensing range of node 1. The third circle which is dotted represents the carrier-sensing range of the receiving node 2. Keeping in view all the conditions for information asymmetry *IA*, near-hidden *NH* and far-hidden *FH* interference (explained in chapter 2) we have derived the non-coordinated interference links for each link. After finding the non-coordinated and coordinated links the results have been fed to AMPL model file and data file which will be explained in the coming section.

4.2 AMPL Implementation

For implementing our optimization model we use AMPL(A Mathematical Programming Language). AMPL is powerful language used for solving complex algebraic models [18]. These algebraic optimization problems include linear, nonlinear, mixed-integer linear, mixed integer nonlinear, quadratic problem etc. For solving a particular optimization problem AMPL has optimization solvers. These solvers include IPOPT, GUROBI, MINOS, KNI-



```
sw: ampl
ampl: option solver gurobi;
ampl: model orthsparse.txt;
ampl: solve;
Gurobi 2.0.0: optimal solution; objective 12.4
33 simplex iterations; 0 branch-and-cut nodes
ampl: display xx;
xx [*,*,1]
:      2    3    4    5    6    7    8    9   10   11   12   13   14   17   19   20   21   22   23   :=
1      0    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
2      .    0    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
3      .    .    0    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
4      .    .    .    0    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .
5      .    .    .    .    0    .    .    .    .    .    .    .    .    .    .    .    .    .    .
7      .    .    .    .    .    .    0    .    .    .    .    .    .    .    .    .    .    .    .
8      .    .    .    .    .    .    .    1    .    .    .    .    .    .    .    .    .    .    .
11     .    .    .    .    .    .    .    .    0    .    .    .    .    .    .    .    .    .    .
12     .    .    .    .    .    .    .    .    .    0    .    .    .    .    .    .    .    .    .
13     .    .    .    .    .    .    .    .    .    .    0    .    .    .    .    .    .    .    .
14     .    .    .    .    .    .    .    .    .    .    .    0    .    .    .    .    .    .    .
15     .    .    .    .    .    .    .    .    .    .    .    .    1    .    .    .    .    .    .
16     .    .    .    .    .    .    .    .    .    .    .    .    .    0    .    .    .    .    .
17     .    .    .    .    .    1    .    .    .    .    .    .    .    .    .    .    .    .    .
18     .    .    .    .    .    .    .    .    .    .    .    .    .    .    0    .    .    .    .
19     .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    0    .    .    .
20     .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    0    .    .
21     .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    0    .
22     .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    .    0

:     24   25   26   27   28   30     :=
9      .    .    .    .    .    1
25     1    .    .    .    .    .
26     .    1    .    .    .    .
27     .    .    1    .    .    .
28     .    .    .    0    .    .
29     .    .    .    .    0    .
```

Figure 4.2: AMPL implementation using gurobi solver

TRO, SNOPT etc. AMPL has two types of files in order to solve a particular problem. These files are model file and data files. The model file consists of the actual algebraic model while the data file consists of the data that is needed to a model file during the execution. The AMPL solver gives the objective value and decision variable values. These are the actual values required to users. One can also write both model and data file in one file combined file.

For our thesis implementation we create two AMPL files for each WMN topology. For example for sparse topology the AMPL files are *'orthsparse.txt'* and *'pocsparse.txt'*. For model files the *'.mod'* and for data files *'.dat'* extension can also be used. In our thesis we include both model file and data file in one single file. The *'orthsparse.txt'* does the orthogonal channel assignment while *'pocsparse.txt'* is used for partially overlapping channel assignment. The solver used for implementing these files is GUROBI. In Figure 4.2 we give an implementation example. In this figure 4.2 we execute *'orthsparse.txt'* using AMPL solver. The solver gives the objective value 12.4 which is the optimal network capacity in megabits$Mbps$. The *'display xx'* statement gives the optimal channel assignment. The value is one only if a channel is assigned to a link.

4.3 OPNET Simulator

We use OPNET (Optimized Network Engineering Tools) for analyzing the performance of our MRMC-WMN topologies. OPNET is available free for academic uses. For commercial uses OPNET needs a license. OPNET simulator gives a comprehensive and detailed environment to users for simulation, modelling and analysis for all kind of networks ranging from a small LAN to satellite networks. One of the key properties of OPNET simulator is its hierarchical structure of modelling. The hierarchies are network model, node model and process model. For performance analysis of user created networks one can view the results in both graphical and data formats. For simulation in OPNET we created two topologies sparse and dense. For example the physical topology in Figure 4.1 is transformed in to an OPNET topology. The topology in Figure 4.3 is an OPNET physical topology. Different parameters considered for simulations are given in Table 4.1.

Table 4.1: Simulation parameters

Parameter	**Value**
Radio Technology	IEEE 802.11b
Number of Nodes	30
Radios per Node	3
Transmission Capacity	11Mbps
Transmission Range	30 meter
Carrier-Sensing Range	2.6*30 meter
Number of Channels	1 to 11
Packet size	4096 bits
Terrain Area	270m X 270m
Transmission Power	0.1W
Packet Reception Power:	-50dB
Simulation Time	4 minutes

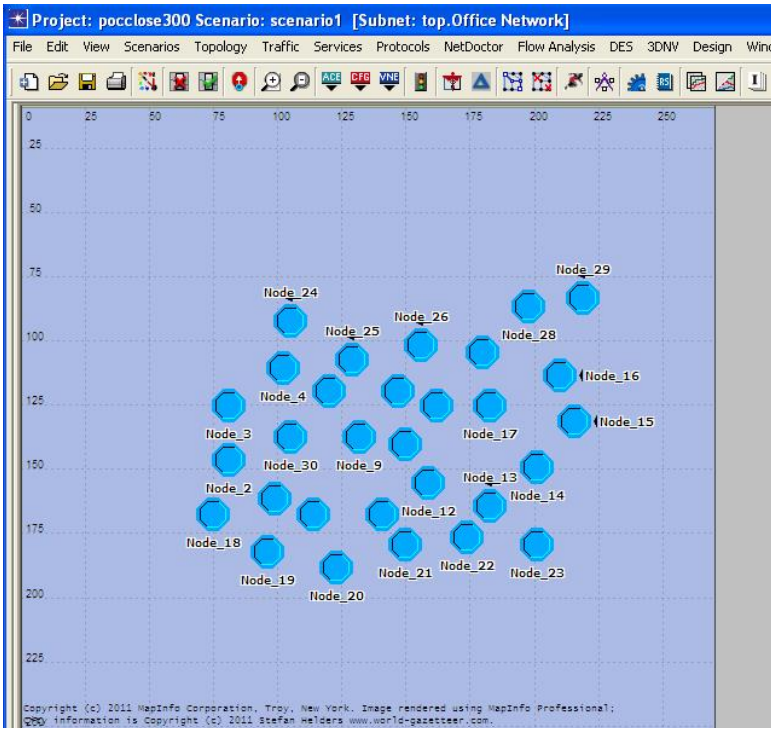


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Figure 4.3: OPNET network topology of 30 nodes

4.3.1 OPNET Network Topology

Keeping in view all the parameters in Table 4.1 we create two the OPNET MRMC-WMN topologies. For example in Figure 4.3 we show such a topology. This topology consists of 30 MRMC-WMN nodes. The transmission range is kept a maximum of $30m$ while the carrier-sensing rage of each node is 2.6 times that of transmission range. During simulation load on every node is varied from $100 packets/sec$ to $500 packets/sec$. The node placement is exactly according to the MATLAB network topology. All the nodes are equipped with 3 radios. Channel assignment during simulation is done according to the channel assignment results given by AMPL optimization model.

4.3.2 Node Model

Each node in this topology looks like the Figure 4.4 from inside. The source generates data and sends it to network process layer. The network process layer further gives data to routing layer and so on to physical layer. On physical layer there are 3 radios. Each radio can transmit and receive. In the

Figure 4.4 the sink process receives the data coming towards it. Two files are also needed for routing packets among WMN nodes. One file includes Source-Destination list while the other file consists of source-destination, Next hop and Radio number information (See Table 4.2 and 4.3).

Table 4.2: Source-Destination file

Source-IP	Dest-IP

Table 4.3: Routing File

Source-IP	Dest-IP	Next-hop	Radio-number

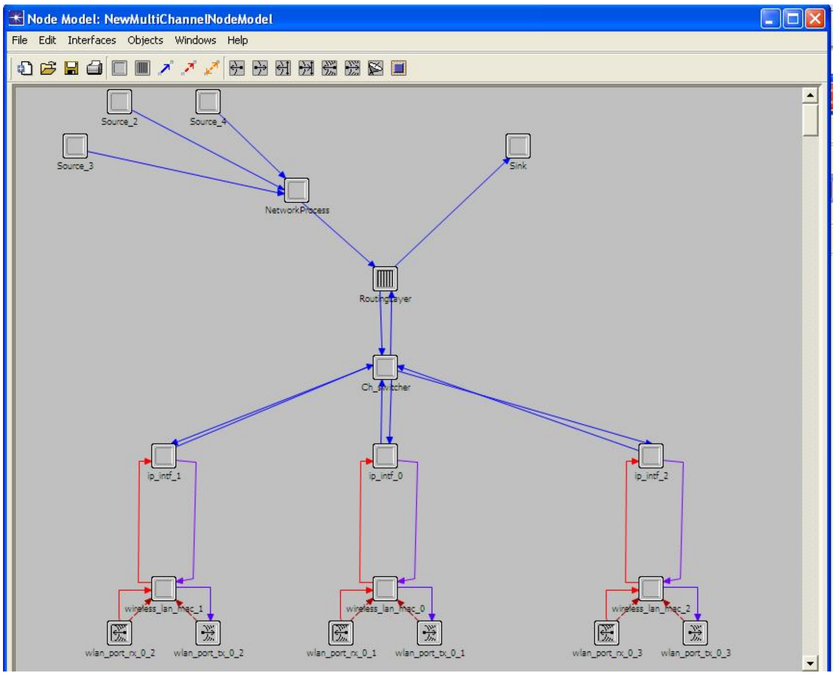

Figure 4.4: Node model

4.3.3 Process Model

Each processor in Figure 4.4 consists of a process model. For example Source-2 from Figure 4.4 looks like the process model in Figure 4.5. The process model consists of various states. The states in the given process are Init

(Start), generate (packet generation) and stop states. When the process starts first it executes init state and then takes transition to generate state. As this is a source process model therefore it must have a packet generation process. For our simulation we have used Poisson packet generation method. After packet generation a transition is made towards the stop state which is the end state in this process model. Inside every state there is a source code. Some source code is predefined while some is user defined. By double clicking one can see the source code inside the process stat.

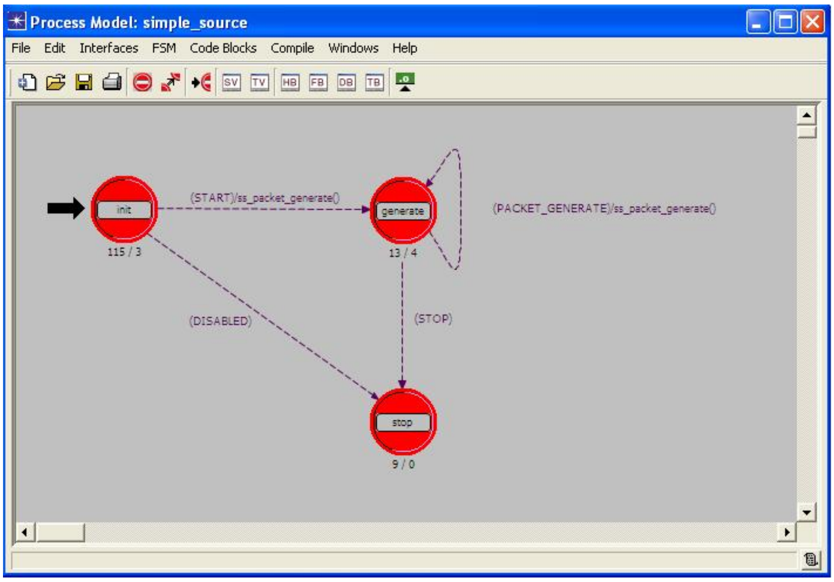

Figure 4.5: OPNET process model of source processor model

4.4 Summary

In this chapter we explained the implementation details of our research work. This implementation is divided into three steps. In first step we created two WMN topologies in MATLAB. One of the topology is sparse while the other is dense. These two topologies are created for comparison purposes as we are analyzing the performance of *POC* assignment in sparse and dense environments. From MATLAB we have derived sets of coordinated and non-coordinated links of each link. These coordinated and non-coordinated sets are further used as input into AMPL model file. In the second step we used AMPL for executing our optimization model. For both sparse and dense WMN topology the model is executed in AMPL. The channel assignment given by AMPL is further used as input into OPNET. For simulation purposes we used OPNET in the third step. Both sparse and dense WMN topologies created in MATLAB are created again in OPNET. We assigned channels to all the links according to the channel assignment set given by AMPL.

Chapter 5

Results and Discussion

In this chapter we present results taken from AMPL and OPNET. Two different topologies of MRMC-WMN are presented in which one topology is sparse and the other is dense. First we take both AMPL optimized results and OPNET results for sparse topology and then same kind of results have been taken for dense topology. Here sparse WMN topology refers to a topology where the number of non-coordinated (nCO) interfering links is higher while in case of dense WMN topology the number of non-coordinated links is not high. In the end both sparse and dense results are compared which shows that partially overlapping channel assignment performs well in sparse environment than dense environment as non-coordinated interference is higher in sparse environment. The results show how the non-coordinated is minimized and the whole MRMC-WMN capacity is maximized.

For OPNET simulation we have used IEEE 802.11b radio technology. Each node is equipped with three radios. For data traffic generation Poisson traffic generator is used. For orthogonal channel assignment three channels 1, 6 and 11 are used and for partially overlapping channel assignment all the channels from 1 to 11 are used.

5.1 MRMC-WMN Sparse Topology

Figure 5.1 shows a MATLAB generated WMN topology consisting of 30 nodes. Maximum Transmission range *Tr* of each node is 30m while carrier sensing range *Cr* is 78m maximum which 2.6 times of *Tr*. All the paths are single link paths. For AMPL model all the coordinated and non-coordinated links have been taken through MATLAB. All the links in this topology are directed links. For example link $(11, 10)$ is directed link where node 11 is the sender while the node 12 is the receiver. The *Tr* of node 11 is represented by solid line circle and carrier-sensing range is represented by dashed line circle. In the same way for receiving node 12 the carrier-sensing rage is represented by dotted line circle.

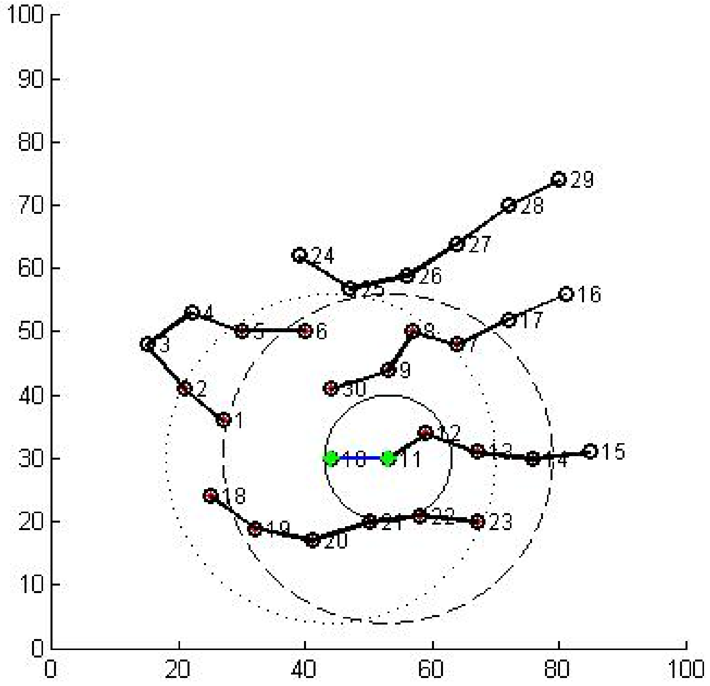

Figure 5.1: MATLAB: MRMC-WMN Sparse Topology:

5.1.1 AMPL Results

In this section AMPL results regarding channel assignment and optimized network capacity are presented. Table 5.1 shows results for sparse WMN topology taken for different flow demands (in packets per second). We generated different uniform random topologies for WMN sparse environments. Table 5.1 presents average results for different flow demands ranging from 100 packets/sec to 500 packets/sec. The load on each source is varied from 100 to 500 *packets/sec*. Table 5.1 is also represented by a line chart in Figure 5.2.

Table 5.1: AMPL: Network capacity for *OC* and *POC* assignment

Packets/sec	*OC* assignment(packets/sec)	*POC* assignment(packets/sec)
100	2330	2500
200	2820	4240
3030	2700	4902.6
400	3116.6	5166.6
500	3205	5366.6

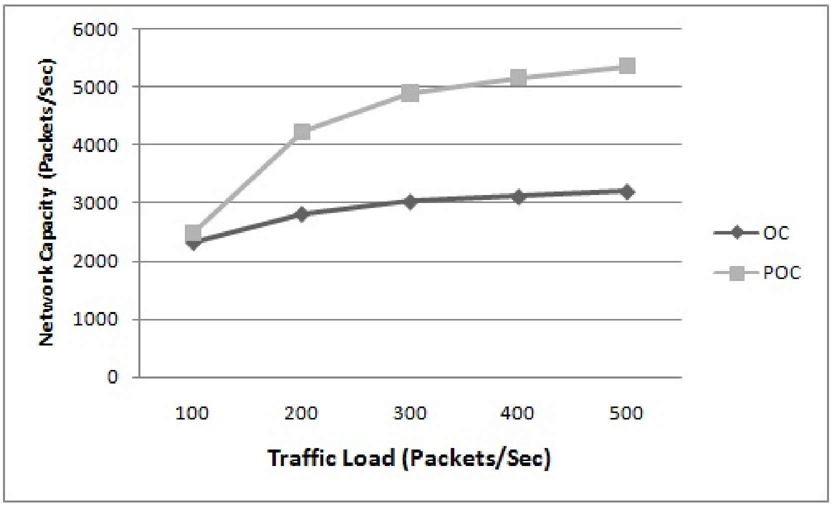

Figure 5.2: AMPL Results: Network Capacity improvement of POC over OC

5.1.2 OPNET Results

For OPNET results we use the channel assignment given by AMPL model. The MATLAB WMN topology presented in Figure 5.1 is transformed into an OPNET MRMC-WMN topology which is given in Figure 5.3. The topology in Figure 5.3 is assigned orthogonal channels and partially overlapping channel for different flow demands varying from 100 to 500*packets/sec*. In Figure 5.4 and Table 5.2 both results have been compared. Graph shows how partially overlapping channel performs better than orthogonal channels.

From Table 5.2 it is clear that *POC* performs better than *OC* for Figure 5.3. For each traffic load varying from 100 to 500 *packets/sec* we calculated percentage improvement of *POC* over *OC* assignment. In the last column of

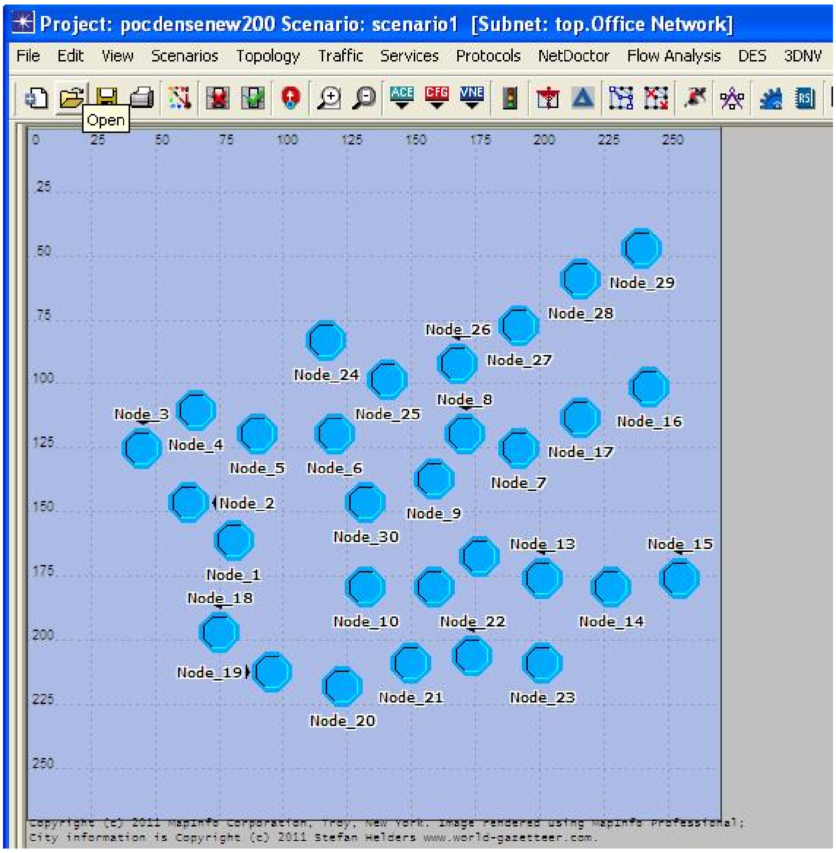

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Figure 5.3: OPNET: MRMC-WMN Sparse Topology

Table 5.2: OPNET: Network capacity for *OC* and *POC* assignment

Packets/sec	OC assignment(packets/sec)	POC assignment(packets/sec)	% increase
100	2242.03	2505.29	11.74
200	3274.77	3871.15	18.21
300	3758.63	4174.23	11.05
400	4006.63	4822.08	20.35
500	4092.45	5079.47	24.11

the Table 5.2 the average percentage increase of *POC* over *OC* assignment is given for all the traffic loads. The results show that for WMN sparse topology *POC* assignment performs 17% better than *OC* assignment. Figure 5.4 gives the OPNET results.

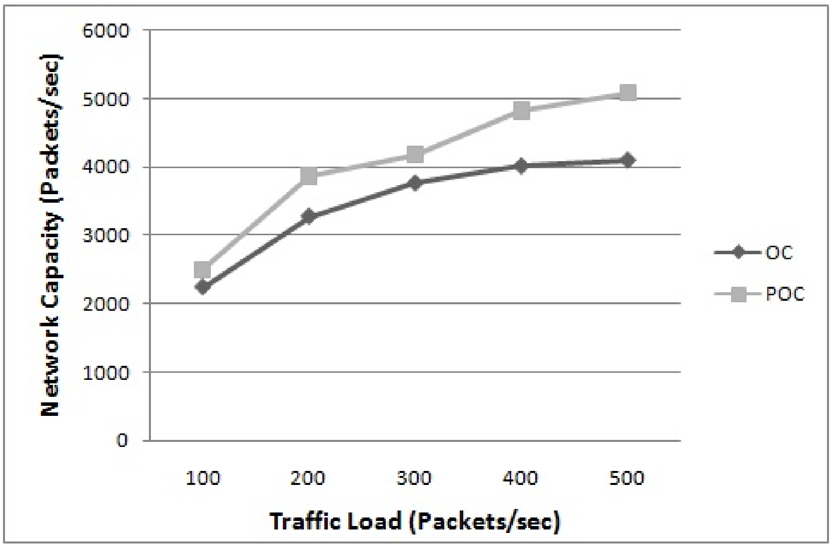

Figure 5.4: OPNET: Network Capacity improvement of POC over OC

5.2 MRMC-WMN Dense Topology

In this section the dense topology is presented. The topology is the same as in Figure 5.1 but the nodes are placed denser. Figure 5.5 shows the dense MATLAB generated topology consisting of 30 WMN nodes.

In Figure 5.5 the transmission range Tr for node 1 is represented from a solid line circle while carrier-sensing range from a dashed circle. As *(1,2)* is a directed link therefore carrier-sensing range Cr for node 2 is denoted from dotted circle. Node 2 is the receiving node in directed link *(1,2)*. Based on these circle information coordinated and non-coordinated links of each link is derived. These CO and nCO links are then used as input to AMPL optimization model. The channel assignment information and the objective of our model for each traffic load are given in Table 5.3.

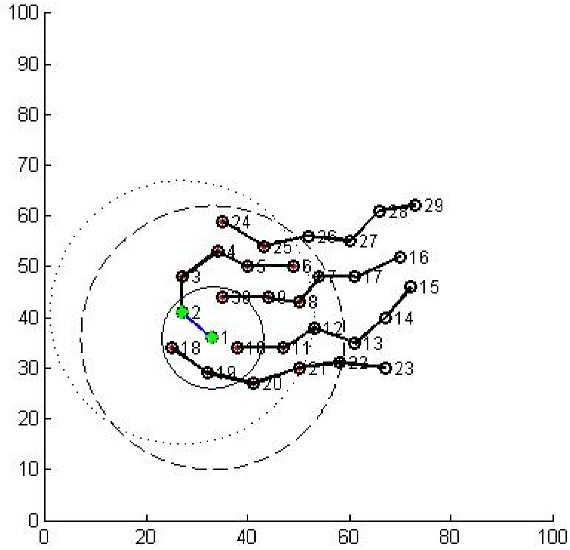

Figure 5.5: MATLAB: MRMC-WMN Dense Network Topology

5.2.1 AMPL Results

Table 5.3 shows AMPL results for dense WMN topology taken for different flow demands. The load one each source is varied from 100 to 500 *packets/sec*. Again *POC* assignment performs better than *OC* assignment. These values are represented through a line graph in Figure 5.6. From graph comparison it is clear that orthogonal channel assignment is outperformed by partially overlapping channel*POC* assignment for dense environment too.

Table 5.3: AMPL:Network Capacity for OC and POC Channel Assignment

Packets/sec	OC assignment(packets/sec)	POC assignment(packets/sec)
100	1810	2210
200	1787.5	2440
300	1777.5	2882.5
400	1750	3050
500	1750	2800

5.2.2 OPNET Results

In Figure 5.7 an OPNET generated MRMC-WMN dense topology is presented. The topology is the same as Figure 5.5 MATLAB generated topol-

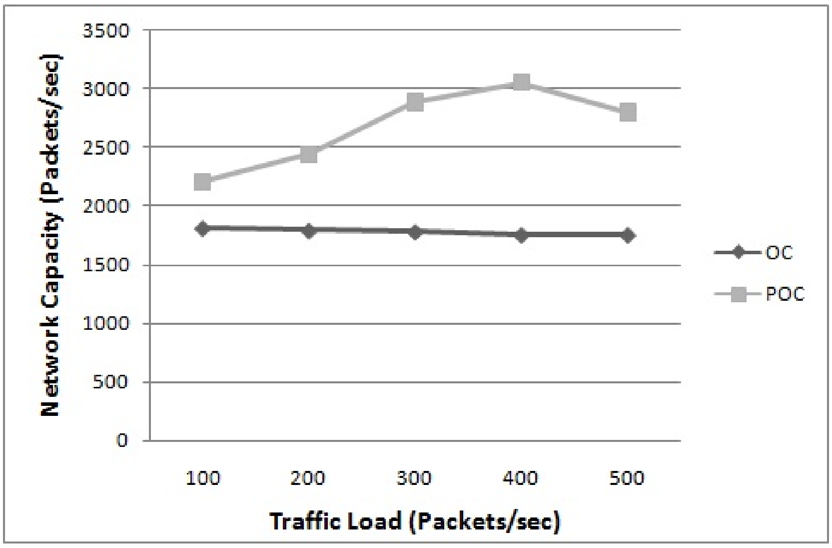

Figure 5.6: AMPL: Network Capacity improvement of POC over OC

ogy. This time the MRMC-WMN nodes are placed closer to each other. The transmission range is kept $30m$(maximum). The terrain area is kept unchanged that is 270m X 270m. The topology is executed for both OC and POC channel assignment under different load demands (from 100 to 500*packets/sec*). Total simulation time was 4 minutes. Channels were assigned according to the channel assignment set given by AMPL optimization model. For both *OC* and *POC* assignment the simulations are executed.

Table 5.4 consists of network capacity taken from both the *OC* and *POC* assignment schemes. For each traffic load from 100*packets/sec* to 500*packets/sec* the network capacity is compared. We also derive the percentage capacity improvement of *POC* over *OC* for each load. In the end column of Table 5.4 the average percentage capacity improvement of *POC* over *OC* is derived. The percentage capacity improvement of *POC* over *OC* assignment for all traffic loads is 9%. These results are also represented through a line graph in Figure 5.8.

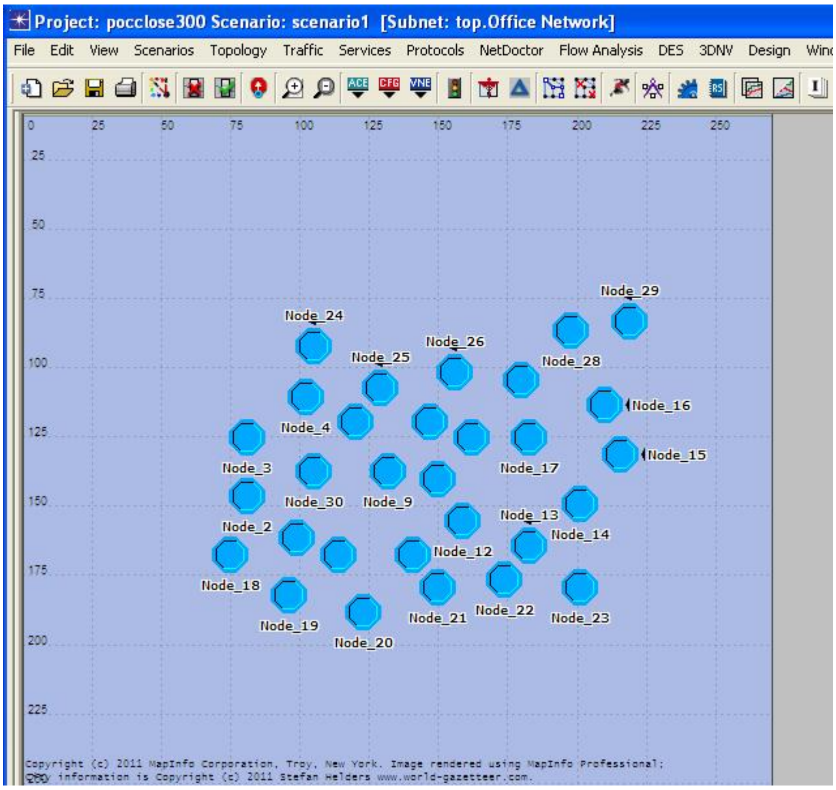

Figure 5.7: OPNET: MRMC-WMN Dense Topology

Table 5.4: OPNET: Network Capacity for OC and POC Channel Assignment

Packets/sec	*OC* assignment(packets/sec)	*POC* assignment(packets/sec)	%age increase
100	2112.53	2263.24	7.13
200	2884.88	2982.36	3.37
300	2752.23	3202.43	16.35
400	2937.27	3278.44	11.61
500	3120.57	3335.52	6.88

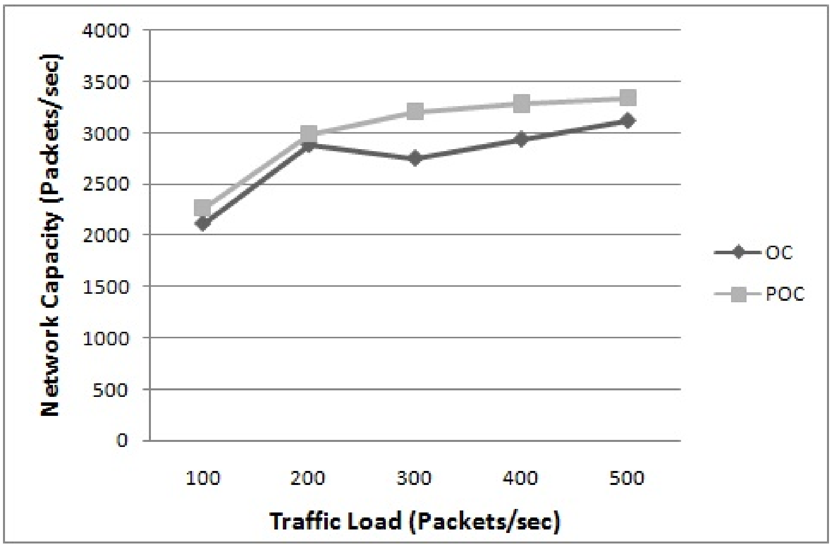

Figure 5.8: OPNET: Network Capacity improvement of POC over OC

5.3 Summary

In this chapter we discussed our thesis results. First we have taken results in AMPL for sparse WMN topology. Load on each link is varied from 100 packets/sec to 500 packets/sec. The channel assignment given by each load in AMPL is fed to OPNET sparse WMN topology. It should be noted that both orthogonal and partially overlapping channel assignment is compared on this sparse WMN topology. The OPNET results showed that *POC* assignment performed 17% better than *OC* assignment. Same kind of procedure is repeated for dense WMN topology. The load is again varied from 100 packets/sec to 500 packets/sec . The results given by OPNET showed that *POC* assignment performed 9% better than *OC* channel assignment. The reason behind *POC* better performance is that the sparse topology had more non-coordinated interference than dense WMN topology. From these results we conclude that our proposed *POC* assignment model performs better where the non-coordinated interference is high.

Chapter 6

Conclusion and Future Work

6.1 Conclusion

Multi-Radio Multi- Channel (MRMC) Wireless mesh networks (WMNs) have already been deployed in some areas but still the capacity of WMNs is limited due to non-coordinated interference among channels. A lot of work was already been done to minimize the interference and optimize the network capacity. Various optimization models are proposed to perform the optimal channel assignment and non-coordinated interference. Most of the models already proposed are based on traditional orthogonal channel assignment. As orthogonal channels are limited which leads to co-channel interference in WMN networks.

In our thesis we propose an optimization model that maximizes network capacity and minimizes non-coordinated interference using partially overlapping channel(POC) assignment in Multi-Radio Multi-Channel (MRMC) WMNs. We also propose a heuristic channel assignment algorithm $POCA$. $POCA$ is an infrastructure algorithm where a central node keeps and distributes all the channel assignment information. Our proposed model assigns both orthogonal and partially overlapping channels that also utilize the IEEE 802.11b spectrum efficiently. The proposed optimization model gives better results for those environments where the non-coordinated interference is higher. Simulation results show that POC assignment performs 17% better than OC assignment in sparse WMN topologies where the non-coordinated interference is high. For dense WMN network environments where the non-coordinated interference is not high, POC performance is 9% better than OC assignment.

6.2 Future Work

Keeping in view the results we obtained from our research work in future we are extending our work to find end-to-end throughput in MRMC-WMNs using our *POC* based optimization model. End-to-end throughput is the realistic objective of MRMC-WMNs where data travels from source to destination nodes through multi-hop delivery fashion. In that case our objective will be to find the end-to-end and aggregate throughput of MRMC-WMN. We hope that partially overlapping channel assignment model for MRMC-WMN throughput optimization will also give significant results.

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