Topology Control in Wireless Mesh Networks

By
Kashif Sattar
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Supervisor
Dr. Anjum Naveed
NUST-SEECS

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Approval

It is certified that the contents and form of the thesis entitled "**Topology Control in Wireless Mesh Networks** " submitted by **Kashif Sattar** have been found satisfactory for the requirement of the degree.

Advisor: **Dr. Anjum Naveed**

Signature: ______________
Date: __________________

Committee Member 1: **Dr. Zawar Hussain**

Signature: ________________
Date: ________________

Committee Member 2: **Dr. Adnan Khalid**

Signature: ________________
Date: ________________

Committee Member 3: **Dr. Shahzad Younus**

Signature: ________________
Date: ________________

Abstract

Wireless Mesh Network (WMN) is an emerging technology for providing wireless broadband access due to its capability of self-organization and self-configuration. These kinds of networks are very helpful for various applications where the wired backbone is not available or expensive and also these are reliable due to availability of redundant paths between the sender and receiver. The main disadvantage of WMN is the highly connected network topology, which results in high interference, thus affecting the aggregate end to end throughput. The capacity of WMNs can be improved significantly by equipping each node with multiple interfaces and by using multiple channels (MR-MC) but the limitation of channels in the radio spectrum restricts the network to a certain bandwidth limit. Thus an effective MR-MC topology control strategy is required to overcome this problem. In this paper, first we propose an optimization model on the basis of interference and link capacities that find out the aggregate end to end throughput for a given network topology having static traffic on all the possible disjoint multiple paths. Then we propose new optimized Interference Aware Pruned Two Path (IA-P2P) topology control scheme which uses our network optimization model and prunes some links in the physical topology to select best two among multiple completely disjoint paths for each flow. This pruning process minimizes the interference which results in higher throughput as compare to actual physical multipath topology. The mathematical results of the model show that this reduction in interference provides more chances of transmission for nodes and hence enhances aggregate end to end throughput by 21.3%. Extensive simulation based experiments in OPNET simulator have also been conducted to test the effectiveness of the proposed scheme. Simulation results also demonstrate that our IA-P2P topology control scheme can increase throughput by 16.8% than the existing physical multipath topology control scheme.

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.

Author Name: **Kashif Sattar**

Signature: ________________

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Kashif Sattar

Contents

List of Abbreviations

Abbreviations	**Descriptions**
AMPL	A Mathematical Programming Language
AOMDV	Ad-hoc On-demand Multipath Distance Vector
CLICA	Connected Low Interference Channel Assignment
CSMA/CA	Carrier Sense Multiple Access / Collision Avoidance
DSR	Dynamic Source Routing
IA-P2P	Interference Aware Pruned Two Path
I-ART	Interference-Aware Robust Topology
MAC	Medium Access Control
Mbps	Mega bits per second
MR-MC	Multi Radio Multi Channel
TORA	Temporally Ordered Routing Algorithm
WMN	Wireless Mesh Networks
WLAN	Wireless Local Area Network

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Chapter 1

INTRODUCTION

A wireless mesh network (WMN) consists of a group of radio nodes/router (fixed/mobile) organized in a mesh topology, which provide internet connectivity to fixed/mobile clients as shown in Figure-1.1. Radio nodes act as access points for the clients as well as extend the connectivity over the wireless links to other radio nodes in a multi-hop fashion. These kinds of networks are very helpful where the wired backbone is not available or expensive and also these are decentralized, resilient and reliable due to availability of redundant paths between the sender and receiver.

Generally, mesh routers do dedicated routing and traffic aggregation, which have limited mobility but it can be mobile. Some of the routers have some additional functionality and work as a gateway to extend the network services. WMNs are similar to an ad hoc network but the topology composed to backhaul routers is static and we can say that WMN is a subclass of ad hoc networks. The multi-hop transmission is the main difference between wireless mesh networks and the infrastructure mode of WLAN. A detail survey of WMNs can be found in [10].

Wireless Mesh Networks (WMNs) are very useful for various applications like broadband home networking, enterprise networking, neighborhood gaming, battlefield surveillance, hot spot areas in cities and many other applications due to its self-organization and self-configuration nature. In WMNs multipath exists between each pair of nodes which offer multiple advantages like alternate route in case of node failure or weak link.

As compared to wired links, WMNs have limited throughput of links. Network capacity have become a critical requirement in these kind of networks due to the limited channel capacity, the affect of interference, the emergence of real time multimedia applications and large number of users. The major factor is the wireless interference which affecting the throughput of wireless links. Only one link among all the links present in the carrier sens-

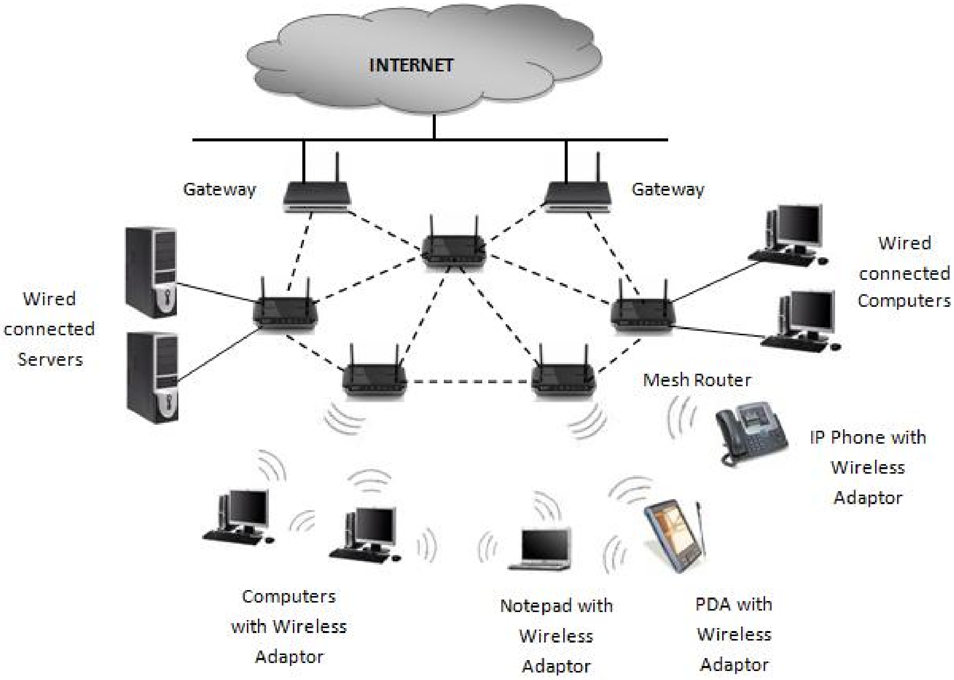


Figure 1.1: Wireless Mesh Network

ing range of the transmitting node can transmit the data at a time due to interference. So how we reduce the interference of flows is a major challenge in WMNs.

The rest of the chapter is organized as follows. In Section 1.1, we introduce MR-MC WMNs and explain their affect on interference and its limitations. Routing in WMN is explained in Section 1.2. Some of the existing on demand routing protocols which find multiple path between each source destination pair to distribute the traffic with reliability are also listed in this section. In Section 1.3, we introduce topology in WMN and explain that how it differs than a wired network topology which forms the basis of research in this thesis. The problem statement and thesis contributions are stated in Section 1.4 and Section 1.5 respectively. In Section 1.6 we conclude the chapter with an outline for the rest of the thesis.

1.1 Multi-Radio Multi-Channel WMN

To reduce the effect of interference researchers have proposed the use of multiple radios on WMN nodes, which can communicate on multiple channels.

These kinds of networks are called Multi-Radio Multi-Channel (MR-MC) WMNs. Multiple frequency channels can be achieved by splitting the radio spectrum and multiple radios can transmit data on multiple channels at the same time to get more bandwidth. For example if we have 3 radios then one is dedicated to the front side clients and two radios are used for the backhaul and can transmit and receive simultaneously over different channels as shown in Figure-1.2.

IEEE 802.11b/g has 11 frequency channels in the 2.4 GHz band and among them only 3 are orthogonal (non-overlapping) channels whereas in IEEE 802.11a there are at most 24 channels in the 5 GHz and only 12 are orthogonal channels. Simultaneous data transmissions on multiple interfering links, each operating on a different orthogonal channel does not result in any interference. But the limitation of channels in the radio spectrum restricts the network to a certain bandwidth limit and also there are a limited number of radios on physical devices and we cannot use all the available limited orthogonal channels simultaneously. Thus an effective strategy is required to increase the throughput in WMNs.

1.2 Routing in WMN

Selection of efficient routing protocol is also very important in such dynamic wireless networks. As in on demand routing protocols, only the actively used routes are maintained therefore these are much popular due to their less routing overhead and lot of work has been done in this area. Some on demand routing protocols find multiple path between each source destination pair which not only provides an easy mechanism to distribute the traffic but also provides reliability. This helps the network to balance the load with fault tolerance ability.

In dynamic adhoc wireless networks the Dynamic Source Routing (DSR) protocol [1] maintains multiple routes and the quality of routes can be easily evaluated on hop count basis and the best (i.e., least number of hops to the destination) one can be used. But DSR protocol maintains too many routes in an inconsequential way, without considering their ultimate usefulness. The Temporally Ordered Routing Algorithm (TORA) [2] also provides multiple alternate paths but the mechanism to evaluate the quality of the routes is not easy and it is very difficult to find that which path is the shortest.

Ad-hoc On-Demand Multipath Distance Vector AOMDV [3] is another multipath routing protocol. This is a multipath extension for the DSR protocol and explores multiple disjoint routes between each source destination pair. There are two variations of AOMDV protocol; in the first variation

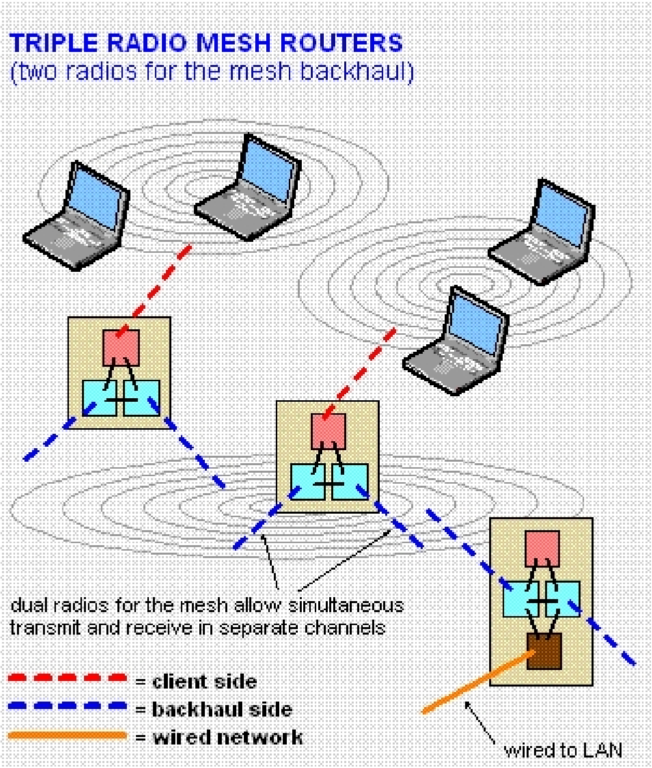


Figure 1.2: Multi Radio Multi Channel WMN (Src: Computer Desktop Encyclopedia)

only the source gets multiple alternate routes while in the second each intermediate node on the primary route gets an alternate route. This protocol reduces the frequency of route discovery flood and hence reduces the network overhead.

As we increase multiple paths between each source destination pair, interference also increases and instead of getting more advantage of load sharing we are reducing the aggregate end to end throughput of the network. Alternate routes are always longer than the primary routes, especially when we focus only on completely disjoint routes. This will make the end-to-end delay of data packets longer, but in case of one link failure we have an alternate disjoint path between source and destination. Hence to achieve a fault tolerance network we need to trade-off between all the available multiple paths and network throughput.

1.3 Topology of WMN

In this section, we explain how topology adversely affects the throughput of the links in WMN. This will enable us to explain interference in WMN, which aims at maximizing the aggregate end to end throughput.

WMN physical topology contains multiple paths between each pair of nodes which provides a reliable network but on the other hand the disadvantage is that the network topology is highly connected, which results in high interference, thus affecting the aggregate end to end throughput. Unlike wired networks, in WMN each link amongst a set of interfering wireless links can only attain a fraction of the capacity of the wireless channel. Because when one link is activate on some channel then no other link in the interference range can activate on the same channel at the same time.

MR-MC can significantly reduce the effect of interference but we cannot eliminate the entire interference due to limited number (3 channels are commonly used) of available orthogonal channels. Topology control in WMN is currently the key area which can significantly reduce the interference and results higher throughput.

1.4 Research Gap and Problem Statement

Multiple paths in a MR-MC network can increase the network capacity by load sharing and also provides reliability with alternate path but as we increase number of alternate paths the effect of interference greatly reduces the aggregate end to end throughput. Mostly routing protocols selects the shortest path as a primary path between each source destination pair even though the shortest path may have more interference and/or bottleneck links. Some routing protocols have not completely disjointed multiple paths and failure of one common link breaks the entire connection. Most of the existing topology control schemes do not consider the tradeoff between network connectivity and throughput of the network. Consequently, the achievable throughput is indirectly affected. So there is a gap between the actual results which we are getting currently and the optimal results in a multipath environment. In our study we focus on the capacity enhancement of the network with reliability and we have proposed a new Interference Aware Pruned Two Path (IA-P2P) topology control scheme which consists of a linear optimization model. This model first find out the optimized throughput for a given multipath topology having static traffic by considering interfering links, bottleneck links, link capacity and flow demand as constraints and then we use this model for our proposed topology control scheme to get comparatively higher throughput.

A formal problem statement is given as:

"Given a network topology, in MR-MC multipath WMN by pruning links for all the nodes in such a way that each pair of nodes has two completely disjoint paths, in order to reduce the interference of the network with reliability"

1.5 Thesis Contribution

Our research work contributes in two ways, first we propose an optimization model and then we propose new optimized Interference Aware Pruned Two Path (IA-P2P) topology control scheme. Both contributions are summarizing as follows:

- We formulate the optimization model on the basis of interference and link capacities constraints. This model gives us the optimal values of the flows on each path that can be achieved in order to maximize the aggregate end to end throughput for the given topology.
- We propose new optimized Interference Aware Pruned Two Path (IA-P2P) topology control scheme which uses our network optimization model and select best two among multiple completely disjoint paths for each flow. We prune the remaining links to reduce interference. The mathematical results of the model show that this reduction in interference provides more chances of transmission for nodes and enhances aggregate end to end throughput.

1.6 Thesis Organization

The rest of the thesis is organized as follows:

Chapter 2 reviews the relevant literature aimed at minimizing the interference in WMN using topology control schemes. Existing body of work is broadly categorized and deficiencies are highlighted.

In Chapter 3, we formulate the problem in the form of mathematical model. Then explains that how we can get the optimal results for a given topology. Also how the model is helpful for our proposed scheme to get higher throughput.

In Chapter 4, we implement our model and prove that compared to existing physical network topology, our new Interference Aware Pruned Two Path (IA-P2P) topology control scheme severely impact the aggregate end to end throughput of WMN.

In Chapter 5, we discuss the mathematical and simulation results and conclude the thesis with a summary of the research findings and a note on the future work.

Chapter 2

LITERATURE REVIEW

We divide the literature into two broad categories. Section 2.1 presents an overview of the interference analysis conducted for multi-hop wireless networks. In Section 2.2, we present a detail overview of to date topology control schemes. We also highlight how these schemes are not providing us the optimal results.

2.1 Interference in WMN

Interference has severe influence on the throughput of the links in WMN. Commonly two protocols are being used to check the impact of interference, one is protocol model [4] and other is physical model [5]. In the protocol model there are two types of wireless node ranges one is the transmission range (R_{TX}) and the other one is carrier sensing range (R_{CS}) from the node 'i' as shown in Figure-2.1. A node 'i' can transmit data to all the nodes in the range of R_{TX} due to good signal strength where as a node 'i' cannot transmit within the range greater than R_{TX} and $\leq$ than R_{CS} because signal strength is weak but all the nodes in this region may affect the transmission on a common channel and the links between all these nodes are called interfering links. The interference between two interfering links occurs when the two links simultaneously transmit the data. For a group of 'n' interfering links, the transmission of a one link is successful only, if the remaining 'n-1' links are silent for the entire duration of that transmission.

This interference reduces the overall throughput of the network and further decreases when we use random access MAC protocols like CSMA [6], where multiple nodes within the interference range simultaneously start transmission. In a result transmitted data collides and affect the throughput. Wireless mesh networks have the characteristics of multi-hop transmission.

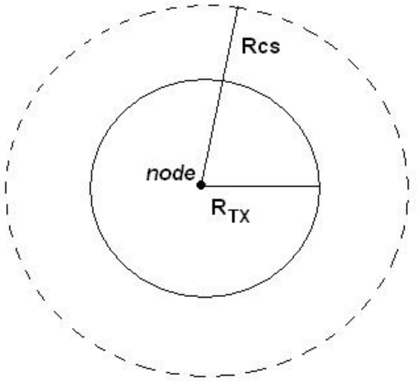


Figure 2.1: Transmission and Carrier sensing Ranges in wireless nodes

The medium sharing and the single hop transmission are the weakness of CSMA/CA IEEE 802.11 MAC standard which make it not fit for the requirements of backhaul networking in wireless mesh networks.

In the physical model if node 'i' wants to transmit data to node 'j' then a transmission will be successful only if SNR at 'j' with respect to 'i' i.e. SNR_{ij} exceeds a threshold SNR_{TH}. Also some other interference models have been proposed to measure the impact of interference on throughput of the network [7, 11, 12, 18, 19]. In our work we are only considering the protocol model to measure the interference.

2.2 Topology Control Schemes

The main purpose of the topology control is to minimize the interference by identifying a subset of wireless links which still provides connectivity for wireless nodes. And to reduce interference a certain design criteria has been considered, including power consumption, broadcast, quality-of-service (QoS), directional antennas and reliability.

Topology control problem has been studied comprehensively in the past twenty years, for the emerging wireless ad hoc and wireless sensor networks (WSNs) [8, 15, 16, 20]. However, in a typical ad-hoc network all nodes are equipped with single radio and are operating on the same single channel. Also these schemes involves careful tuning of the node transmit power to construct interference optimal topologies. Whereas, in MR-MC WMN, topology control is in many ways inter linked with channel assignment. Furthermore, mesh nodes are usually assumed to be transmitting using fixed transmission power. For example, tree topology is constructed by the schemes proposed by Raniwala et al. [9, 17]. However, the resulting topologies in these schemes do not take advantage of the multiple paths that may exist in the WMNs.

We also reviewed some channel assignment schemes which explicitly focus on constructing the low interference network topology. These schemes are generally static and the channel assignment only takes place at the time of network initialization. Tang et al. [13] have proposed the static channel assignment scheme with the primary objective of constructing the low interference K-connected network topology. Many interfering radios have been used as a metric to measure the interference and a heuristic based algorithm have been proposed which selects the low interference topology of all possible K-connected topologies. A static channel assignment scheme has also been proposed by Marina et al. [14]. This scheme models the channel assignment as a topology control problem and aims at providing the basic connectivity in the WMN by utilizing the minimum number of radios and channels. This scheme also uses the number of interfering radios as an indicative of the level of interference and constructs the low interference topology in WMN. Both these schemes are static and do not support the changes in traffic conditions. Using the number of interfering links to measure the level of interference has two drawbacks. Firstly, a potential interfering link may never interfere if that link is not a part of any flow. Therefore, considering such links to measure interference is just wastage of resources. Secondly, the above mentioned schemes assume that impact of interference of all interfering links on the throughput is same; this assumption also effects the resource allocation.

Kejie Lu et al.[21] proposed a topology control scheme and tried to maximize the overall throughput in the network for random unicast traffic demands. Basically he established multiple horizontal and vertical wireless highways, each of which can convey the traffic for nodes along the highway.

This scheme is not addressing the internal interference of the cell and also as any two nodes within two adjacent cells can communicate directly as shown in Figure-2.2, therefore interference may increase and affect multiple cells nodes that are in the carrier sensing range of the transmitting node.

The work which is quite similar to our proposed algorithm is by A. Naveed [22]. But the author uses heuristic approach for deducing results and uses only clustering techniques for a network which may creates overhead in some cases e.g. if node 'I' want to communicate with its immediate neighbor node 'L' in another cluster, it transmit data through 3 hops. Also all pairs have not complete disjoint multiple paths e.g. node 'C' and 'E' pair have not 2 complete disjoint paths with maximum hop limit of 3 and node C and G pair have not two paths at all with 3 hops as shown in Figure-2.3.

Mahesh et al. [23] assigning channels to radio interfaces for achieving

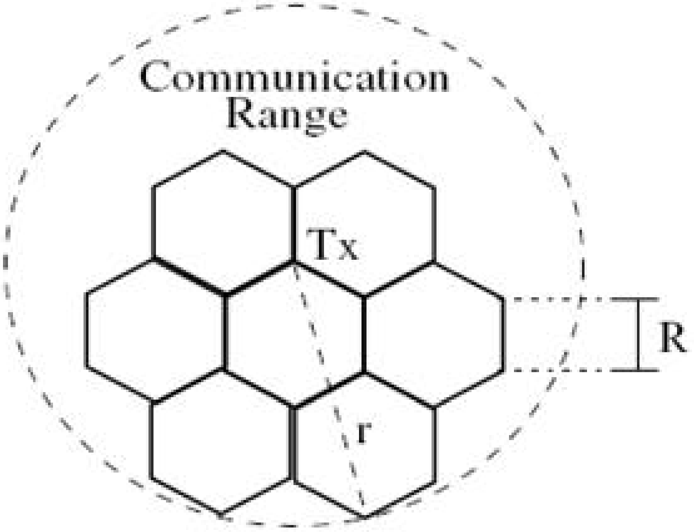


Figure 2.2: Communication Model[21]

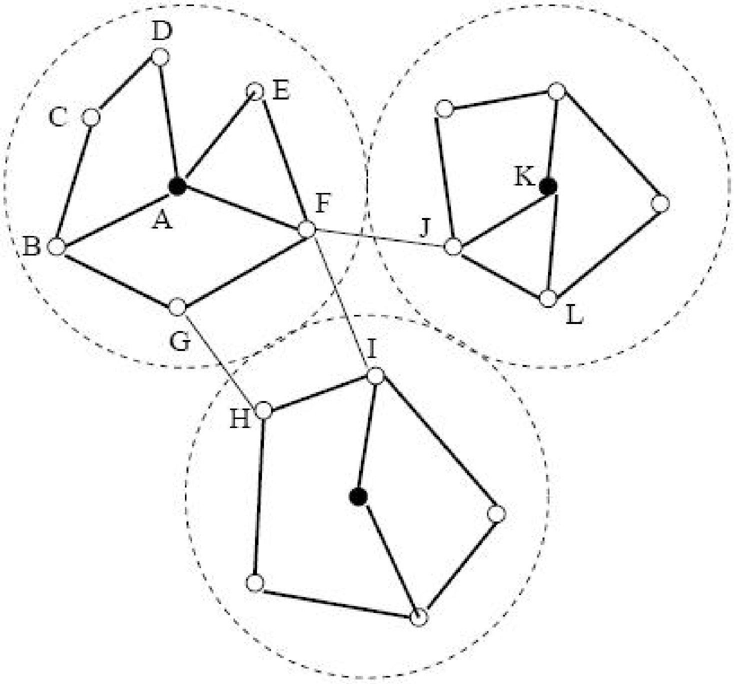


Figure 2.3: Clustering Based Topology [22]

efficient channel utilization by graph theoretic formulation of the channel assignment. Then they developed a new greedy heuristic channel assignment algorithm (named CLICA) for finding connected, low interference topologies by utilizing multiple channels.

Also, instead of rate-based channel assignment scheme, Theodoros et al. [24] formulated a new utility based framework for joint channel assignment and topology control and presented a greedy procedure for solving the corresponding throughput optimization problem. In both papers [23][24] channel assignment is controlling the topology of the network and the authors try to minimize the interference by channel assignment without removing the mesh links. But the mesh links are still there in the carrier sensing range of the transmitting node, which may interfere the transmission and we need to reduce those interfering links with a little or no affect on the throughput of the network.

W. Zhang et al. [26] define the Interference-Aware Robust Topology (I-ART) problem, which seeks network topology design and a channel assignment for the network topology such that the induced network topology has the small network interference. This is heuristic approach and 2-connected network topology is based on minimum number of edges even though those edges may face strong interference and/or bottle neck edges.

Q. Liu et al. [27] propose a topology control method for multi-channel multi-radio wireless mesh networks that use directional antennas. They first formulate the problem to an equivalent optimization problem with a clearer measurable metric, which is to minimize the largest interfering traffic of links in the network. Then they do a fine-grained adjustment of antenna orientations and assign channels to them, such that the transmission area of each antenna covers all the links it serves and the largest interfering traffic of links is minimized. Again it is problem of optimizing antenna orientations and channel assignment. Directional antennas require adjustments and have problem of localization and positioning specially in case of mobility and multichannel environment.

Chapter 3

OPTIMIZATION MODEL AND PROPOSED SCHEME

We divide this chapter into four parts. In Section 3.1, we formulate the mathematical model. This model considers interfering links, bottleneck links, link capacity and flow demand as constraints to maximize the objective function. Section 3.2 explains the working of the proposed model and in Section 3.3 we propose new Interference Aware Pruned Two Path (IA-P2P) topology control scheme which is based upon our linear optimization model.

3.1 Problem Formulation

Linear programming is the problem of optimizing a linear function (objective function) subject to linear inequality constraints. We formulated a linear mathematical constraint model to optimize the flows/sub flows on each path for MR-MC fixed wireless mesh networks. Let directed graph G(V,E) represent the WMN, V being the set of nodes and E being the set of directed links (edges). There are Q orthogonal channels and R radios on each node such that R≤Q. All nodes are using the same transmission range R_{TX} and interference range R_{CS} and the ratio is "R_{CS}=1.5 R_{TX} ".

The description of the model and other notation used are as follows:

Given:

V =Set of n Nodes
v_i=Where each Node $v_i \epsilon V$ is a network node, $1 \leq i \leq n$
E =Set of m Links
e_h =Where each link $e_h(v_i, v_j) \epsilon E$ is a link between nodes $v_i, v_j \epsilon V$, $1 \leq h \leq m$

$C(e_h)$ =For all $e_h \epsilon E$ the capacity of link e_h is $C(e_h)$

P_{sdl}=Known set of links on path l between source destination pair $(v_s, v_d), where\ v_s, v_d \epsilon V\ and P_{sdl} \leq E$

F =Set of q flows

f_k =Where each flow $f_k \epsilon F$ traverse the network between $v_s, v_d \epsilon V$ $1 \leq k \leq q$

d_k =Demand of flow f_k

E_{kl} =Set of all the links in flow f_k on path l since each f_k has l paths, where $E_{kl} = P_{sdl}$

e_u =Where each link $e_u \epsilon E_{kl}$ and $1 \leq u \leq t$

E_k =Set of all the links in flow f_k on all possible paths, where $E_{kl} \leq E_k \leq E$

e_v =Where each link $e_v \leq E_k$ and $1 \leq v \leq r$

f_{kl} =Where each sub flow f_{kl} is the %age of f_k passing through E_{kl}

d_{kl} =Portion of Demand d_k fulfilled through E_{kl}

$B(e_{kl})$ =Capacity of the bottleneck link on sub flow f_{kl} on path l where $e_{kl} \epsilon E_{kl}$

Q =Set of orthogonal Channels

c_a =Where each Channel $c_a \epsilon Q$

Cc_a =Capacity of channel c_a

Iv_{ia} =Set of interfering links of node v_i at channel c_a

Decision Variable:

Which path will carry how much %age of data (sub flow) for a given flow such that over all demand of flows is maximized?

Where $0 \leq d_{kl} \leq d_k$

Constraints:

Flowdemand Constraint:

All the sub flows for flow f_k must be no more than demand of f_k.

$$\sum_{l} d_{kl} \leq d_k \qquad \forall f_k \tag{3.1}$$

BLCapacity Constraint:

Portion of Demand d_k fulfilled on path l for flow f_k must be no more than the Capacity of the bottleneck link on sub flow f_{kl}.

$$d_{kl} \leq B(e_{kl}) \tag{3.2}$$

LinkCapacity Constraint:

Total demand of all the sub-flows on link e_h must be no more than the total Capacity of the link.

$$\sum_{k=1}^{q}\sum_{l} d_{kl}.e_h \leq C(e_h) \quad where\ e_h = \begin{cases} 1 & if\ e_h \in E_{kl} \\ 0 & otherwise \end{cases} \qquad (3.3)$$
$$\forall\, e_h \in\ E$$

Interference Constraint:

Sum of all Sub flows at the interference links of each node v_i on each channel c_a must be no more than the channel capacity Cc_a.

$$\sum_{e_h \in I v_{ia}}\sum_{k=1}^{q}\sum_{l} d_{kl}.e_h \leq Cc_a \quad where\ e_h = \begin{cases} 1 & if\ e_h \in E_{kl} \\ 0 & otherwise \end{cases} \qquad (3.4)$$
$$\forall\, v_i \in\ V\ and\ \forall\, c_a \in\ Q$$

Objective Function:

$$\max.\ \sum_{k=1}^{q}\sum_{l} d_{kl} \qquad (3.5)$$

3.2 Throughput Maximization for given topology

In our proposed model we consider multi flow WMNs having completely disjoint multiple paths, in which communication between sources and destinations occurs through multiple hops. The model also considers some links common to multiple flows and some bottleneck links in sub flows. In the optimization model discussed in section 3.1, we consider sub flow as an objective function. In a multipath environment if we get the optimum value of sub flow for each flow then we can get the optimum aggregate end to end throughput for the given topology.

The first constraint ”Flowdemand Constraint” restricts the solver to allocate value to sub flow in such a way that the sum of all the sub flows for a given flow must be no more than the demand of the flow. The second constraint ”BLCapacity Constraint” checks all the links in a sub flow and find out the bottle neck link (minimum capacity link). Due to this constraint the solver allocates the value to sub flow which is less or equal to the bottleneck link. All the links in the network have limitation of link capacity and it depends upon the SNR value of the node receiver. As we discussed above that some links are common in different flows and also some links may be bidirectional therefore we need to check the overall allocation of sub flows on each link in the network. The third constraint "LinkCapacity Constraint" restricts the solver to allocate the value to the sub flows such that the sum of all the allocations must be less or equal to the link capacity. The last but most important constraint is the "Interference Constraint" which restricts the solver to assign values to a link such that all the interfering links on a particular channel share the total transmitting capacity of the radio or in other words the sum of all sub flows at the interference links of each node on a particular channel must be no more than the channel capacity.

With all the necessary constraints used in the model the objective achieved is the optimal aggregate end to end throughput for a given network topology. With the help of this model we can get optimal results for a single path, two path and multipath between each source destination pair. To keep this model simple we have a limitation of fixed nodes but it can be dynamic by adding some more constraints.

3.3 Proposed IA-P2P Topology

In WMN the multipath environment provides reliability and also to some extent more chances of transmission through the use of second alternate path. But as we increase alternate path the links creates lot of interference and instead of getting some good results we are decreasing the throughput of the network. The reason is that the alternate path usually have longer path and can introduce many interfering links which severely affects the throughput. On the other hand the alternate path provides reliability so we need to tradeoff between these two.

We propose a new optimized IA-P2P topology control scheme which consists of two alternate paths between each source destination pair. Mainly the second path is for the sake of reliability but in some cases where we have many bottle neck links or common links between multiple flows, this can be helpful to increase throughput. The selection of two paths is based on our proposed model which helps us to select best two paths from the set of alternatives. This reduction of paths prunes the interfering links and the remaining links gets more chance of transmission. After selection of two paths we again run the model to get the optimized results. With the help of this scheme we can increase the throughput by a considerable factor as compare to the multipath given topology as discussed in section 3.2.

Chapter 4

IMPLEMENTATION

In this chapter Section 4.1 explains the AOMDV routing algorithm and the data file for solver. In Section 4.2 we discuss AMPL language and the model file used for optimization. Section 4.3 shows the flow chart diagram of our proposed scheme and Section 4.4 shows the physical network topology which we have considered for the comparison purpose. Then in Section 4.5 we develop the OPNET module for MR-MC WMN for multipath flows. This section also explains the node model and process model which we have developed and implemented. This module helps us for getting simulation results.

4.1 AOMDV Routing Algorithm

In the first phase we implemented the existing AOMDV [3] completely disjoint multipath routing algorithm on the multipath physical network topology and generated the data file as shown in Appendix-A. This data file is required by AMPL solver to solve the problem and consists of all the possible complete disjoint multiple paths for all the flows e.g. for first flow of the topology shown in Figure-4.2, the possible shortest disjoint paths between node 1 and 13 are:

1. (1,2)(2,13)
2. (1,3)(3,4)(4,13)
3. (1,5)(5,3)(3,7)(7,11)(11,13)

4.2 AMPL Language

In the second phase we implemented the model in the AMPL syntax. AMPL is a comprehensive and powerful algebraic modeling language used for linear and nonlinear optimization problems (production, distribution, blending, scheduling and many other kinds of problems), in integer or continuous variables. It can communicate with a wide variety of solvers. Its flexibility and convenience make it ideal for rapid prototyping and development of models. That's why we implemented our optimization model in this language. The complete model file with all the required information is shown in Appendix-B.

4.3 Flow Diagram of IA-P2P scheme

The flow chart diagram of our proposed IA-P2P scheme is shown in Figure-4.1. Solver takes both files (i.e. the data file and model file) and solves it to get optimized results and calculate the aggregate end to end throughput of the network. From those optimized results we selected best two sub flows (path) for each flow and pruned the original physical network topology. The exception is the source destination pair that have only single path in the physical topology. This process creates a pruned two path network topology file as an input to the routing algorithm and generates again data file for the AMPL solver. Solver takes both files again and further optimizes the flows. The remaining links in the pruned network topology experienced reduced level of interference and showed significant gain in the overall network throughput.

In the third phase we developed and implemented MR-MC Multipath WMN module for the OPNET network simulator and compared our mathematical results with simulation results.

4.4 Network Topology

For the implementation purpose we considered static nodes with three IEEE 802.11b radios on each node. Each radio can communicate with other radios on 3 channels which are orthogonal to each other. One node can communicate simultaneously with more than one neighbor at the same time using different channels. Also full duplex operation is possible at each node, i.e., a node can be receiving from or transmitting to a neighbor i on channel 1, while transmitting to or receiving from neighbor j on channel 6. Due to limited number of orthogonal wireless channels, more than one node in a given region could contend for the same channel at the same time, thereby resulting in interference and collisions. Channels are assigned for communication between neighbors in a static fashion and every link between a pair of neighboring nodes is bound to a particular channel and this binding does vary over time.

We constructed the network topology at the time of network initialization

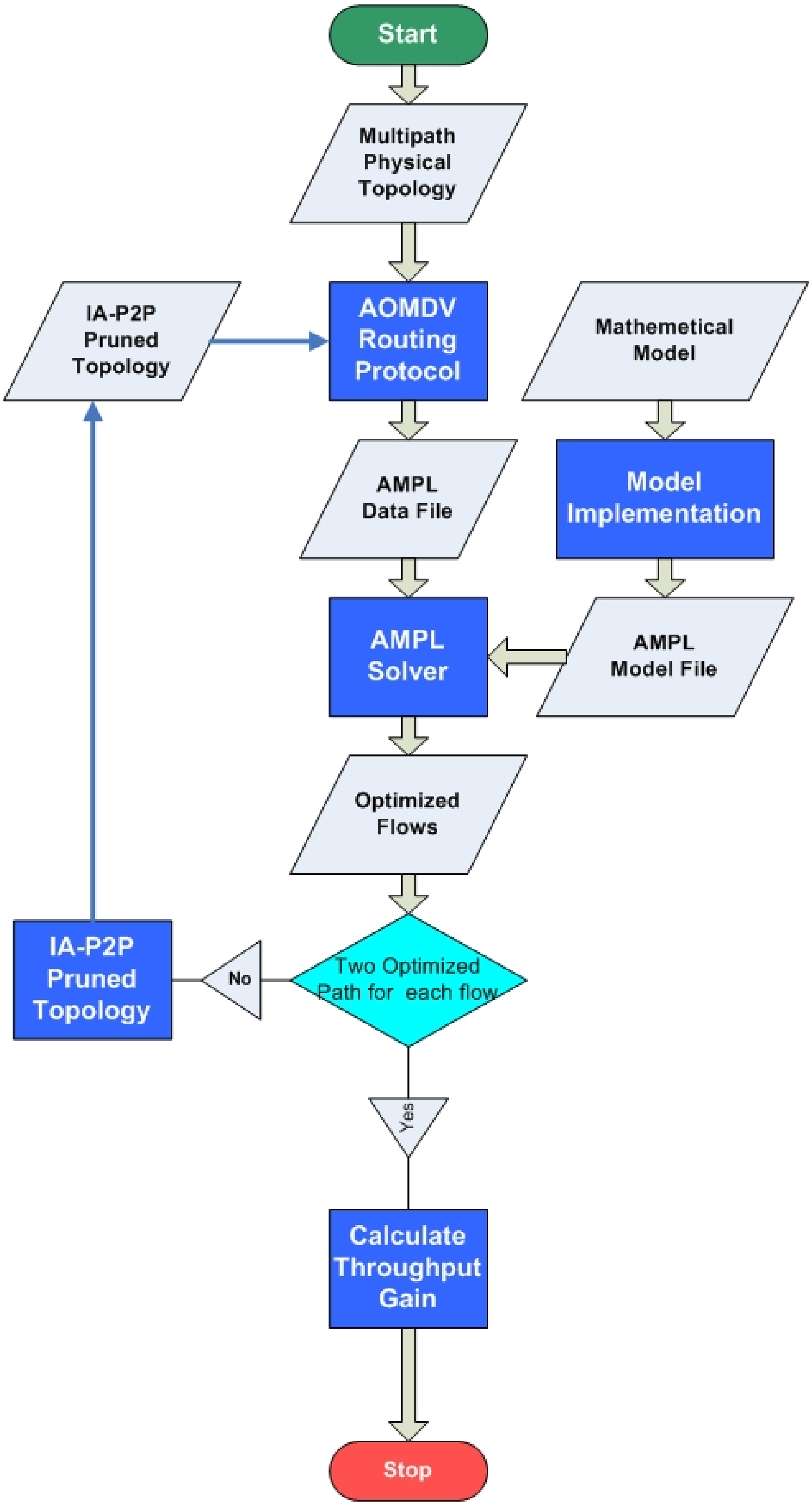


Figure 4.1: Flow Chart Diagram of Proposed IA-P2P Scheme

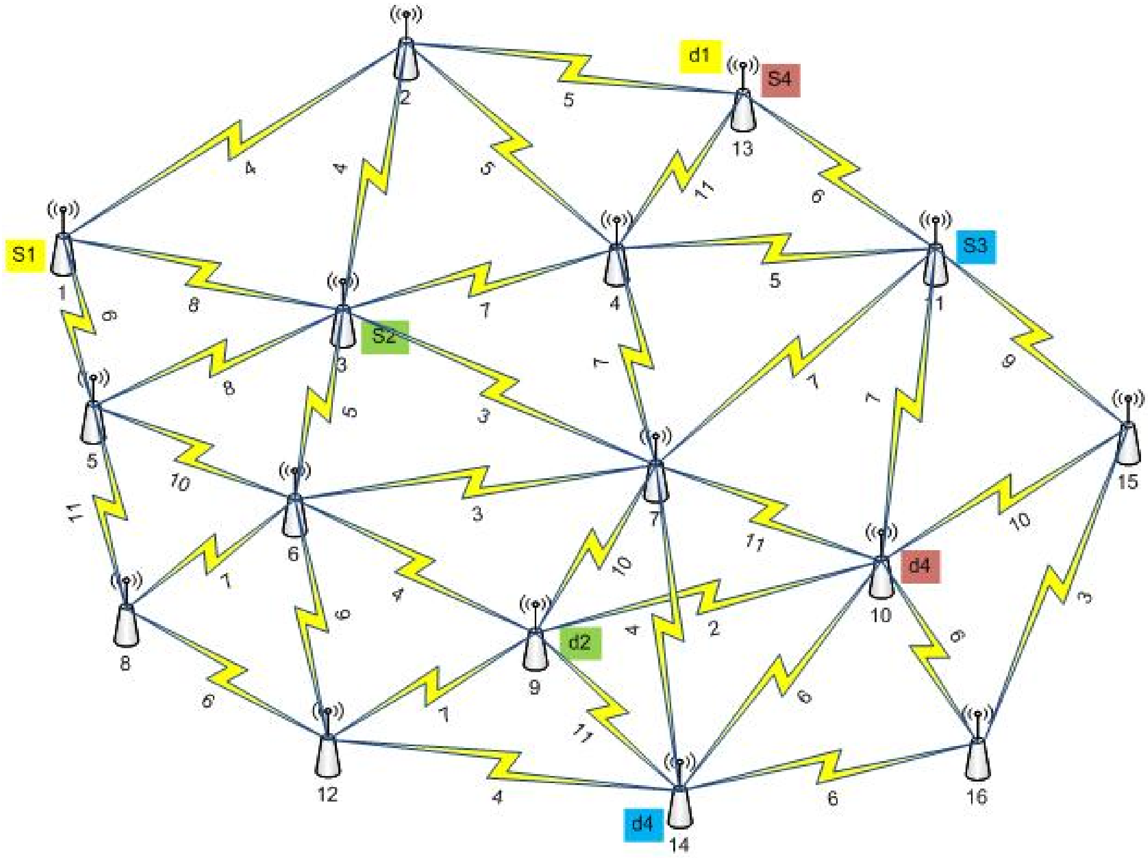


Figure 4.2: Actual Physical Network Topology with 4 Flows

and this topology does not change except when a node is leaving or new node is joining the network. We considered 4 flows e.g., S1 and d1 are the source node and destination node respectively for the flow1 as shown in Figure-4.2. Links between each pair of nodes is highlighted having some value which shows the link capacity and it varies between 2Mbps to 11Mbps. This variation creates some bottleneck links in the flows or sub flows which helps the solver to select the optimized paths even though the paths are longer. Each node has three radios and each radio can communicate on 3 orthogonal channels i.e. 1, 6, and 11. Each source have 3-4 completely disjoint multiple paths to reach its destination.

4.5 OPNET Simulator

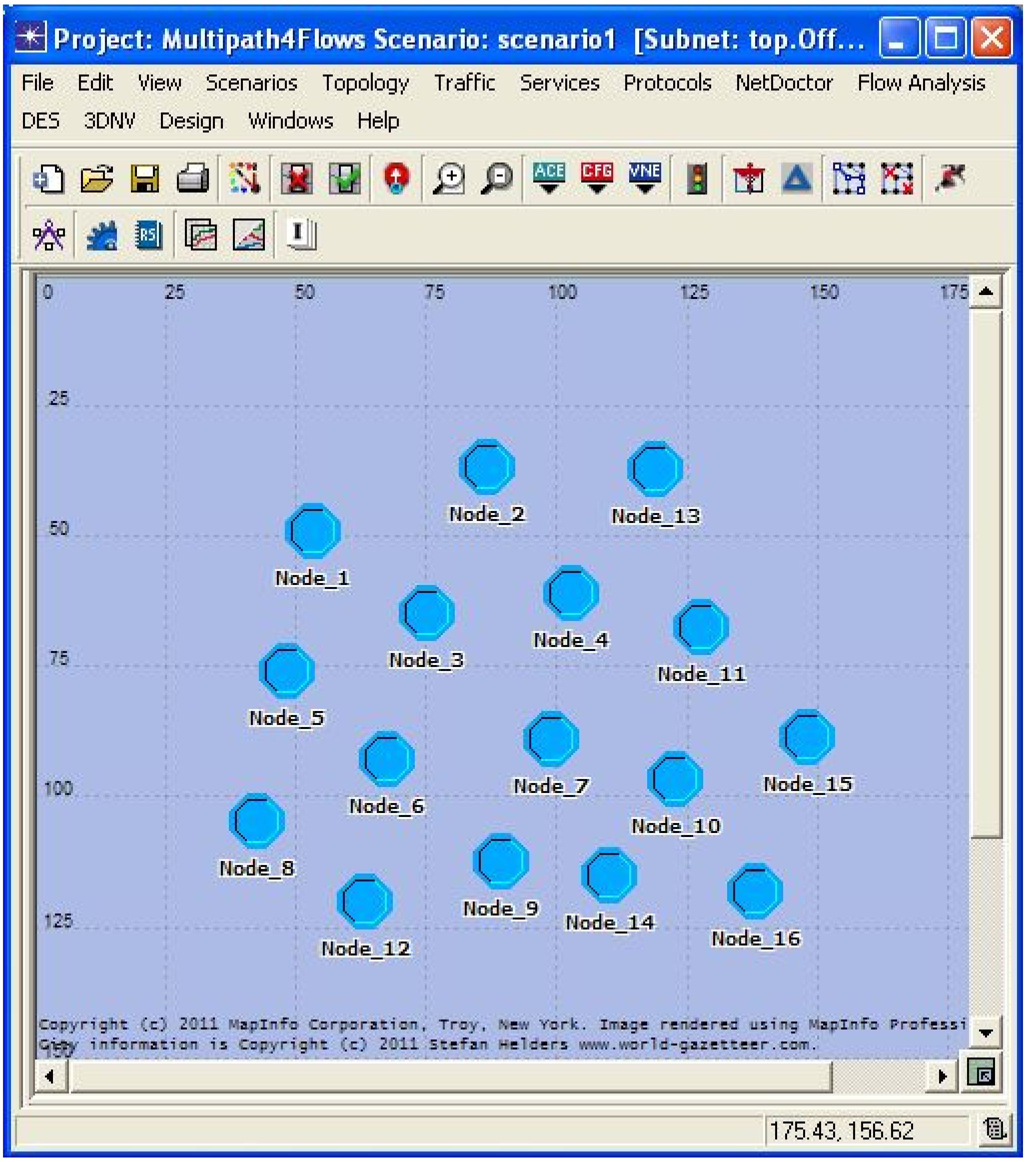
Simulation on computer is becoming more popular among computer network students and researchers for performance modeling and evaluation of computer and telecommunication networks. Many sophisticated and powerful simulators are available now a day which also provides development facility in a flexible way for the communication networks to validate the results. Some simulators are open source and some are commercial. OPNET is becoming popular network simulator as the package is available to academic institutions at no cost, especially OPNET IT Guru. Results obtained by different experiments show that OPNET provides credible simulation results close to a real system [25]. We simulated both multipath physical topology and proposed IA-P2P topology in OPNET simulator. The parameters we considered for simulation are shown in the Table 4.1 and the network which we constructed in OPNET simulator by randomly placing the nodes is shown in the Figure 4.3:

Table 4.1: Simulation Parameters for performance evaluation

Radio Type:	IEEE 802.11b
Data Rate:	11 Mbps
Terrain Area:	175m x 150m
Source Pkt Interarrival Time:	Poisson with 0.005Sec
No. of Nodes:	16
Node Placement:	Random
No. of Radios:	3/Node
No. of Channels:	3[1 6 11]
Transmit Power:	7E-006W [for around 30m]
Packet Reception Power:	-95dB
Packet Size:	4096 bits
Simulation Time:	10 minutes

4.5.1 Node Model

We developed a node model for MR-MC WMN by equipping each node with 3 radios as shown in Figure 4.4. Each radio can transmit as well as receive



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City information is Copyright (c) 2011 Stefan Helders www.world-gazetteer.com.

Figure 4.3: Opnet Network

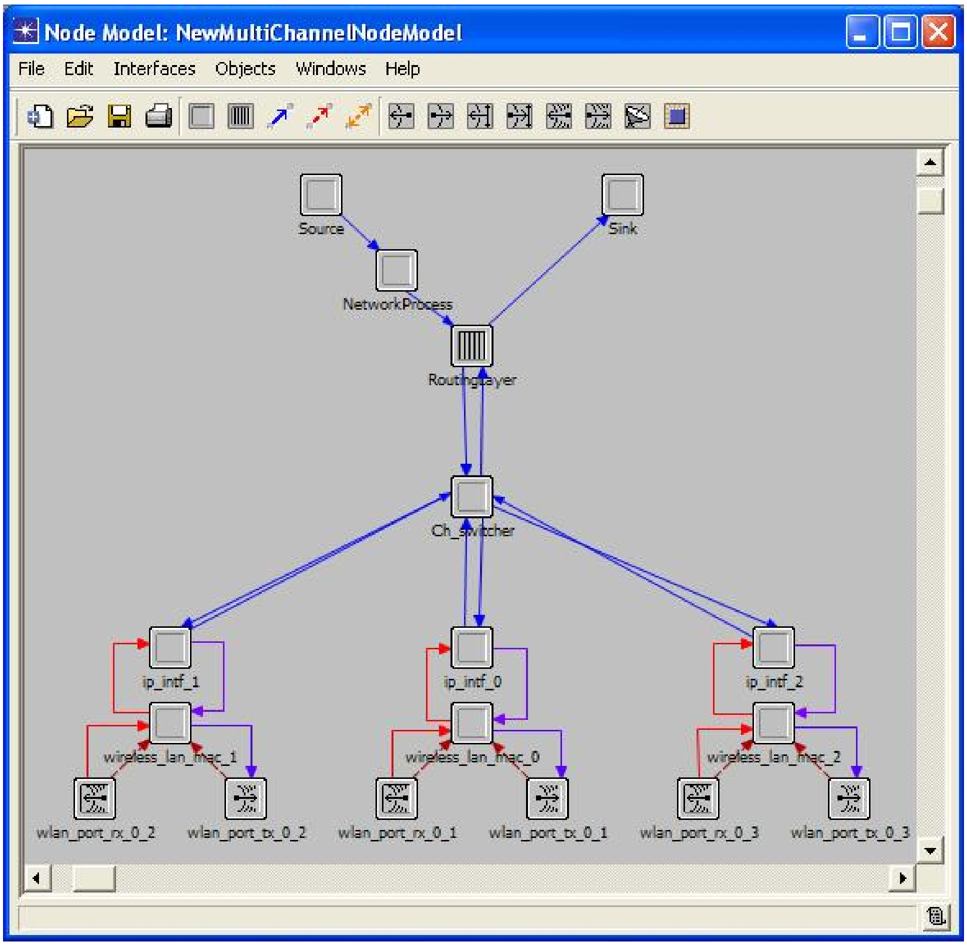


Figure 4.4: OPNET Nodel Model

data. Source process is generating data packets for the source nodes and sink process is receiving data packets if it is the destination node. There are two input files for this node model one file consists of source destination pair nodes and the other file consists of routing table having four fields (Source, Destination, NextHopRadio and Channel). The Network process reads the destination of the source and fills the packet fields with the required information. The most important process is the Routing process at routing layer which we have discussed separately in the next subsection.

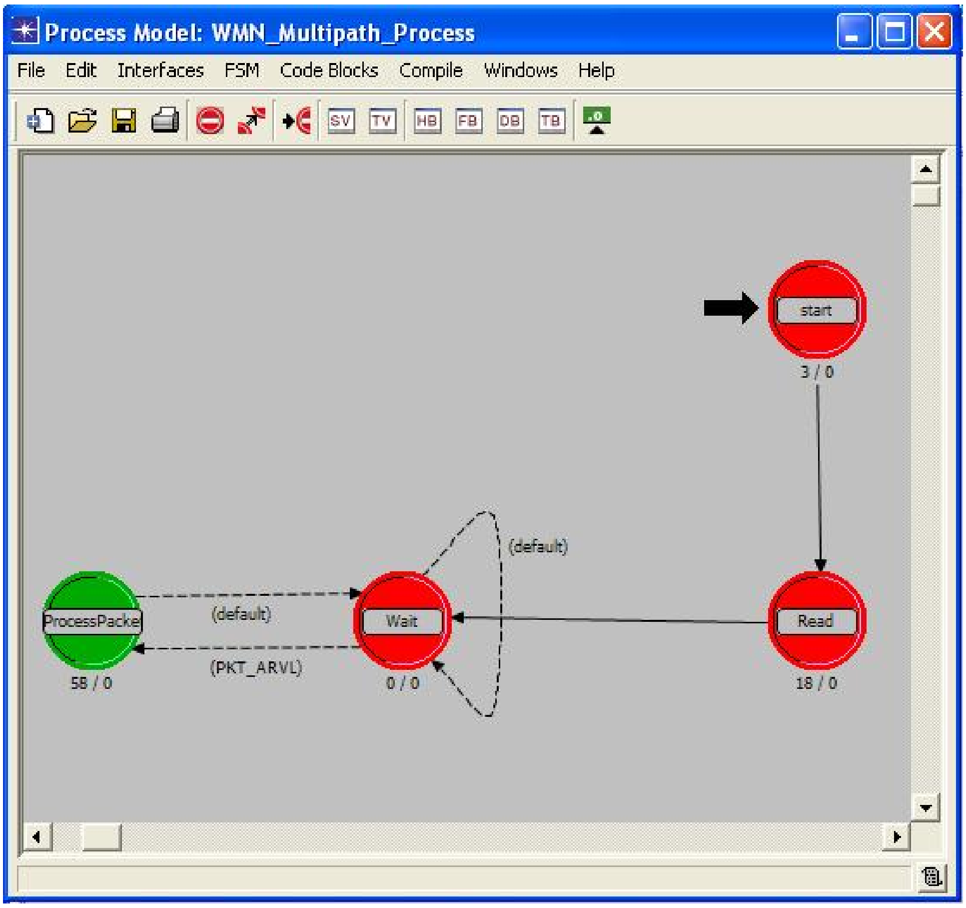


Figure 4.5: Routing Process Model

4.5.2 Routing Process Model

This process model consists of four states as shown in Figure 4.5. The ”start” state is just taking the id of the node on which this process is running at the moment. Then the ”Read” state reads the routing file as an input and stores all the routing entries in the static variables of the process model which are related to the current node. The ”Wait” state just wait for the next packet arrival and finally the ”ProcessPacket” state reads the packet information and if this packet is for him then it sends to the sink process of node model otherwise compare it with the routing entries. This state also decides which packet has to go on which path to reach a particular destination. If the node has multiple paths then this state sends the packets on multiple paths.

Chapter 5

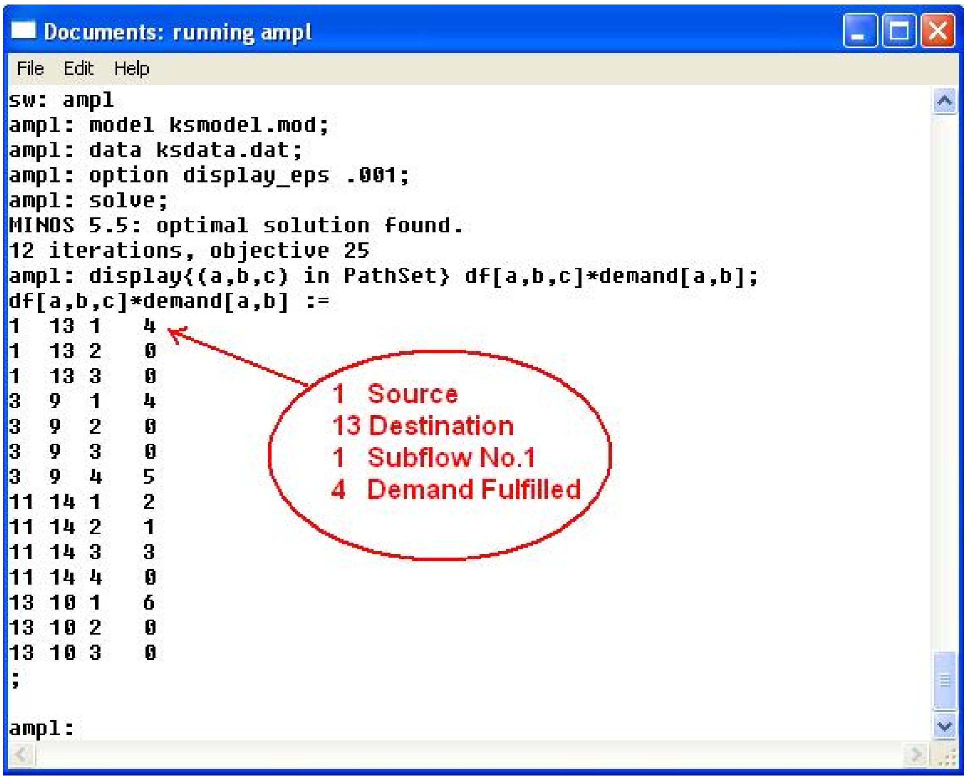
RESULTS AND DISCUSSION

We evaluated the effectiveness of our scheme in improving the overall network throughput of multi-hop multipath flows. We considered four flows having 3-4 multiple paths to see the effectiveness of interference in the network. We evaluated two experiments first we considered all multiple paths in the physical topology and applied the optimization model on it and get the results then secondly we considered pruned topology having only two optimized path between each source destination pair by reducing the number of links and compare the results.

Then we simulated both scenarios in the OPNET simulator for our evaluations. In both simulation experiments, we use IEEE 802.11b radio interfaces with data transmission rate of 11Mbps. Each MR-MC WMN node is equipped with 3 wireless interfaces/radios. Data traffic is generated by using a Poisson traffic generator at the application layer with mean inter-arrival duration of 0.005Sec at each source. This results in saturated traffic load on a wireless link with transmission capacity of 11Mbps. In both scenarios, the source generated packets of fixed size (i.e., 4096 bits) on all the four sources.

5.1 Optimization Model Results by Solver

We used MINOS 5.5 solver to get the optimization result. With the first scenario of multipath physical topology we got objective of 25 as shown in the Figure-5.1. This value is in Mbps and is the sum of all the flows which can be possible through different paths from sources to destinations. The solver assigns different allowable values to each sub flow which is also highlighted in the Figure-5.1.



```
sw: ampl
ampl: model ksmodel.mod;
ampl: data ksdata.dat;
ampl: option display_eps .001;
ampl: solve;
MINOS 5.5: optimal solution found.
12 iterations, objective 25
ampl: display{(a,b,c) in PathSet} df[a,b,c]*demand[a,b];
df[a,b,c]*demand[a,b] :=
1   13 1    4
1   13 2    0
1   13 3    0
3   9  1    4
3   9  2    0
3   9  3    0
3   9  4    5
11  14 1    2
11  14 2    1
11  14 3    3
11  14 4    0
13  10 1    6
13  10 2    0
13  10 3    0
;

ampl:
```

1 Source
13 Destination
1 Subflow No.1
4 Demand Fulfilled

Figure 5.1: Solver Results for Multipath Physical Topology

5.2 Given Topology with Optimized Results

The Figure-5.2 below shows that how much flow can be possible on each path for a given topology. These are the results we have achieved from the AMPL solver. These results will help us to remove those links which have zero or very less flow and they are just creating interference. After pruning the links we have IA-P2P topology as shown in Figure-5.3.

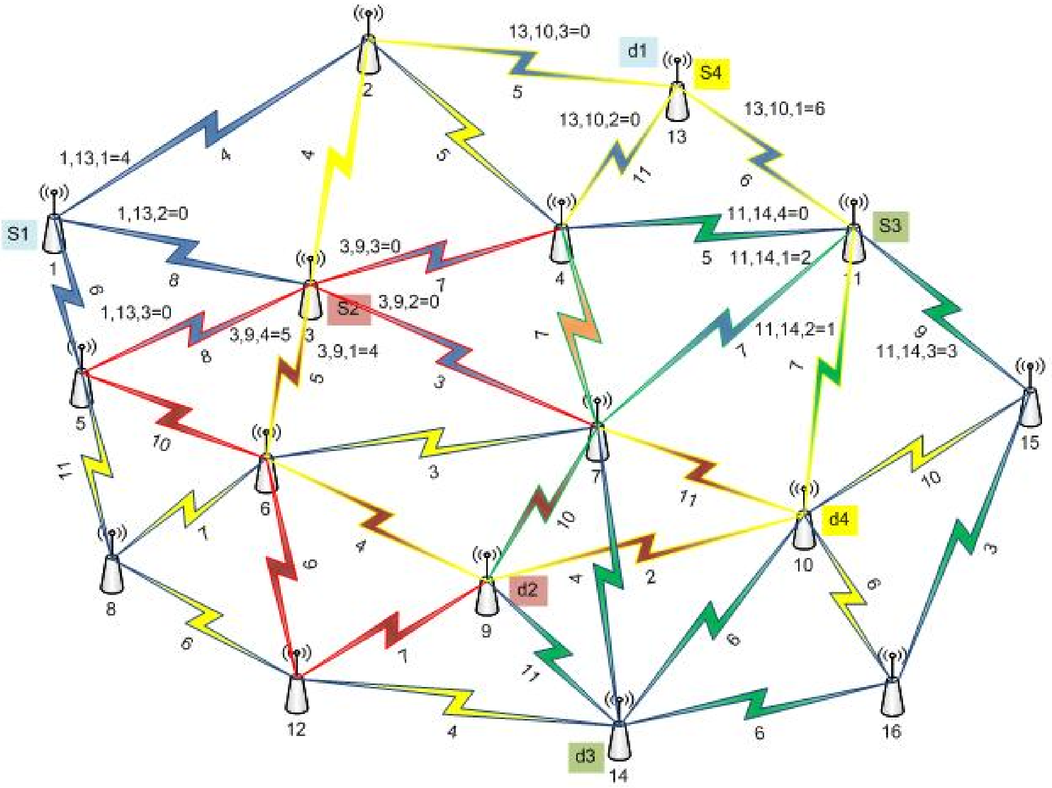


Figure 5.2: Multipath Physical Topology

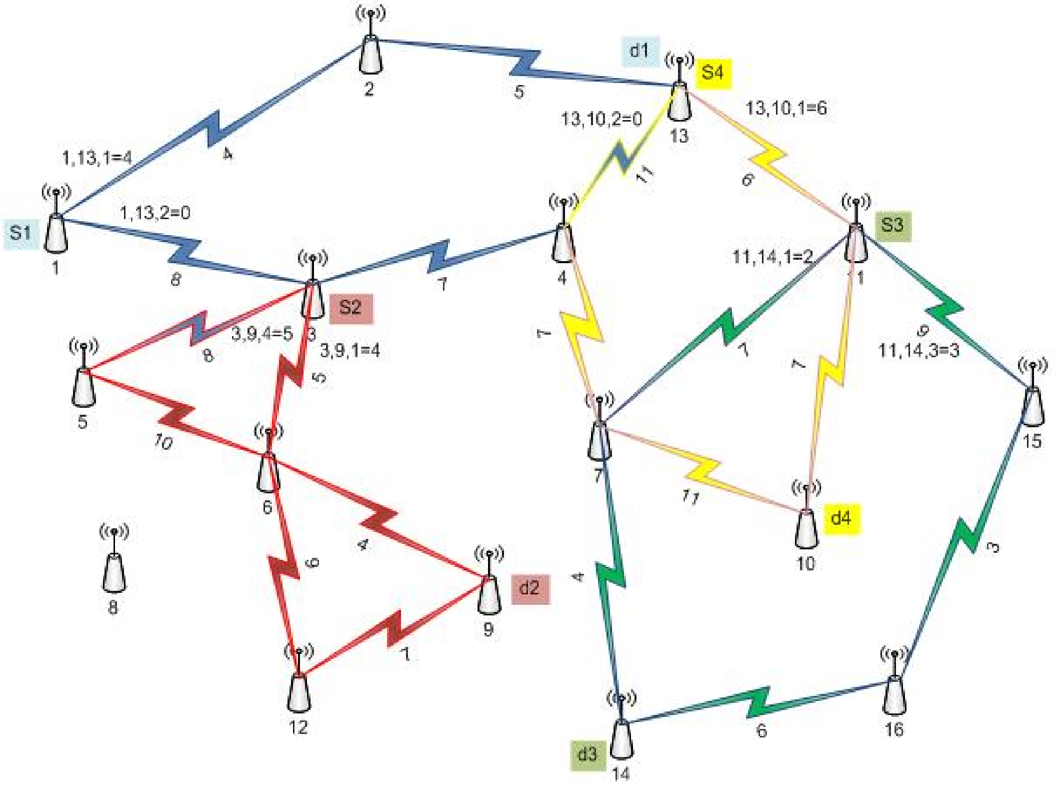
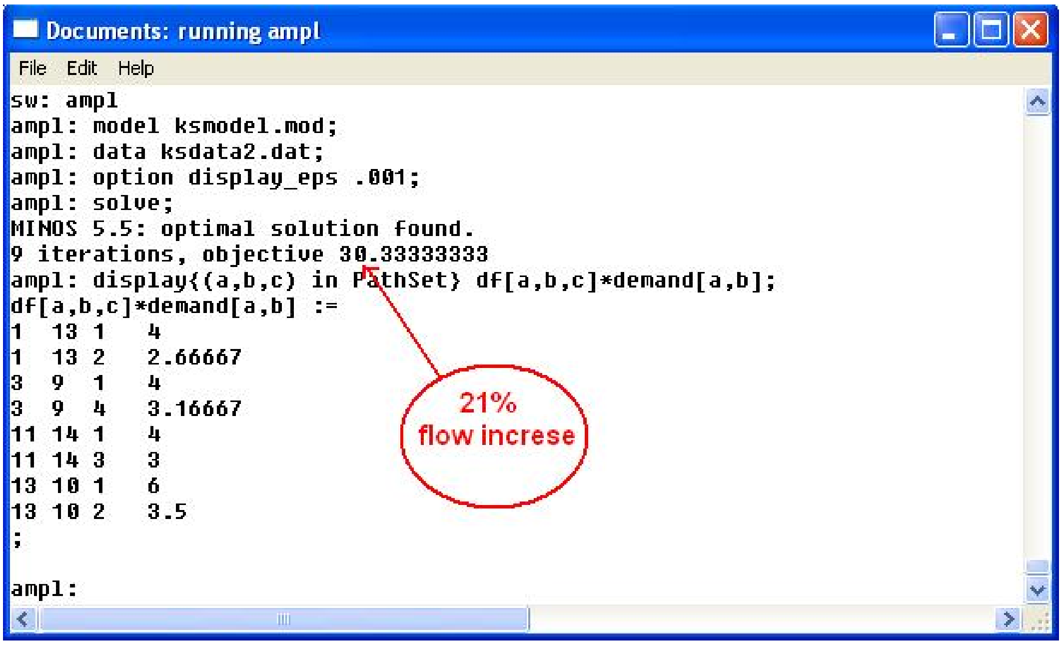


Figure 5.3: Pruned Two Path Topology

5.3 Optimization Model Results for Pruned Topology

With the second scenario of pruned two path topology we got objective of 30.33Mbps. The solver assigns new optimized values to each sub flow of each source destination pair. The new values and the objective are shown in the Figure 5.4 . The results shows that we have 21.3% increase in the aggregate end to end throughput of the network.



```
sw: ampl
ampl: model ksmodel.mod;
ampl: data ksdata2.dat;
ampl: option display_eps .001;
ampl: solve;
MINOS 5.5: optimal solution found.
9 iterations, objective 30.33333333
ampl: display{(a,b,c) in PathSet} df[a,b,c]*demand[a,b];
df[a,b,c]*demand[a,b] :=
1   13 1    4
1   13 2    2.66667
3   9  1    4
3   9  4    3.16667
11  14 1    4
11  14 3    3
13  10 1    6
13  10 2    3.5
;

ampl:
```

21%
flow increse

Figure 5.4: Solver Results for Pruned Two Path Topology

5.4 Pruned Topology with optimized flows

After getting the results from solver we finalized our optimized IA-P2P topology as shown in Figure 5.5. Each source has now two completely disjoint paths and each sub flow has some value which shows the maximum amount of flow that can be passed on that path with all the constraints. In the figure the label e.g. ”1,13,1=4” shows that Source node is 1, Destination node is 13, Path number is 1 and 4Mbps demand can be fulfilled along that path.

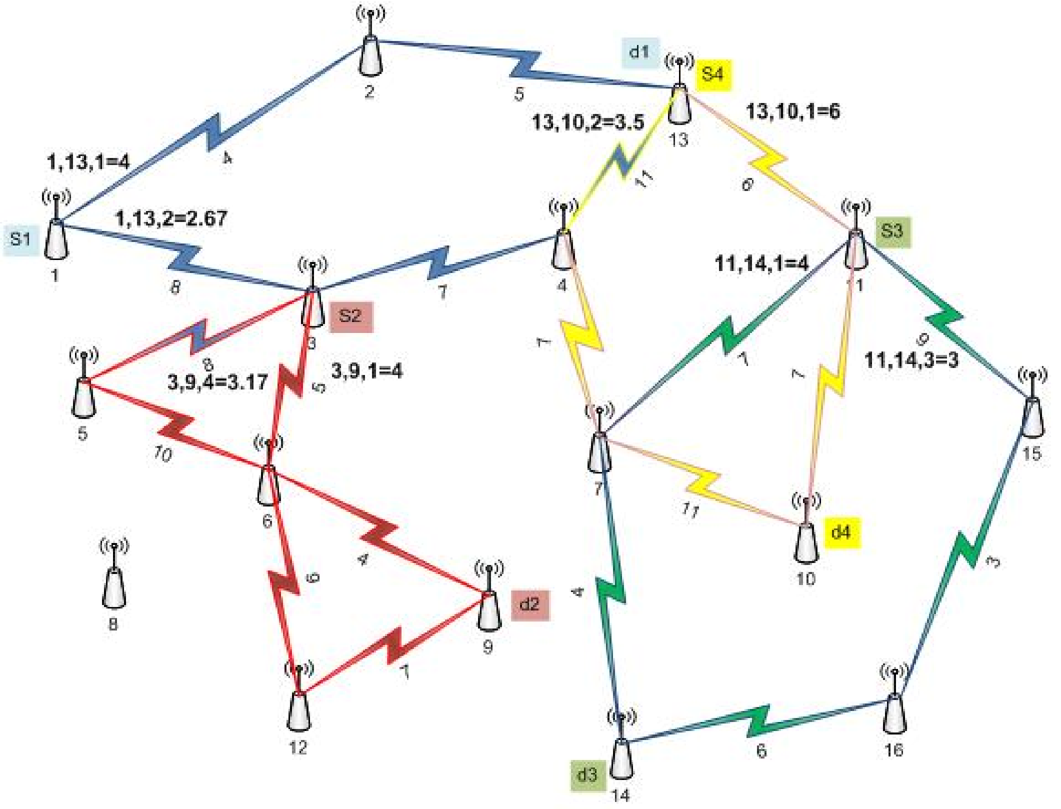


Figure 5.5: Optimized Pruned Two Path Topology

5.5 Mulipath Topology Results in Simulator

We used OPNET simulator to get the simulation results. We have four source nodes i.e. 1, 3, 11, 13 and four destination/sink nodes i.e. 9, 10, 13, 14. Each source destination pair have three to four completely disjoint paths. For the analysis purpose we have used poisson traffic distribution for traffic generation which is commonly followed by network traffic. A poisson random variable is the number of successes that result from a Poisson experiment. The probability distribution of a Poisson random variable is called a Poisson distribution. For stable results we simulate the network for 10 minutes. With the first scenario of multipath topology we have the following results as shown in Figure-5.6 below.

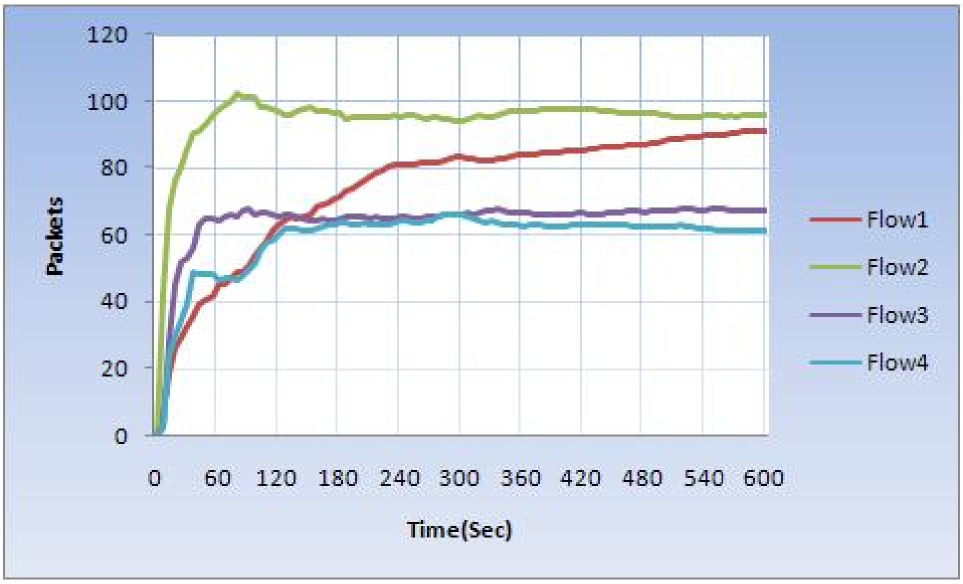


Figure 5.6: Flows Progress with MR-MC MultiPath Physical Topology

In the graph on the x-axis we have a time bar and on the y-axis we have number of packets per second. Each graph curve represents number of packets received at destinations for that flow. The low throughput of the graphs shows that all the flows and even all the sub flows for each flow creates interference and due to this reason their entire demand cannot be fulfilled in the current scenario. The aggregate end to end throughput for all the flows is calculated in Table-5.1:

Table 5.1: Multipath Physical Topology Flow Rates per Second

Flow No.	Source Node	Destination Node	No. of Packets/Sec	Throughput(Mbps)
1	1	13	91	0.372
2	3	9	96	0.393
3	11	14	66	0.270
4	13	10	61	0.249
Total:	4	4	**314**	**1.284**

Table 5.2: IA-P2P Topology Flow Rates per Second

Flow No.	Source Node	Destination Node	No. of Packets/Sec	Throughput(Mbps)
1	1	13	122	0.499
2	3	9	105	0.430
3	11	14	59	0.242
4	13	10	81	0.332
Total:	4	4	**367**	**1.503**

5.6 Proposed Topology Results in OPNET

As in the previous scenario we used the same parameters with the second scenario of pruned two path topology and got the graph shown in Figure-5.7. The entire demand of all the flows cannot be fulfilled in the current scenario too because the flows are still facing some interference due to multiple flows and most importantly due to of alternate path for each flow. But for reliability we have to add that alternate paths. However as compare to previous scenario the throughput is better in our proposed scheme.

The curves for each flow show that due to pruning of links we have reduced level of interference. And this reduction of interference increases end to end throughput. The aggregate end to end throughput for all the flows for our proposed scheme is calculated in Table-5.2:

We also compares the aggregate end to end throughput for the both schemes in Figure-5.8 which shows that our proposed IA-P2P topology control scheme increases throughput of network by 16.8% than given topology.

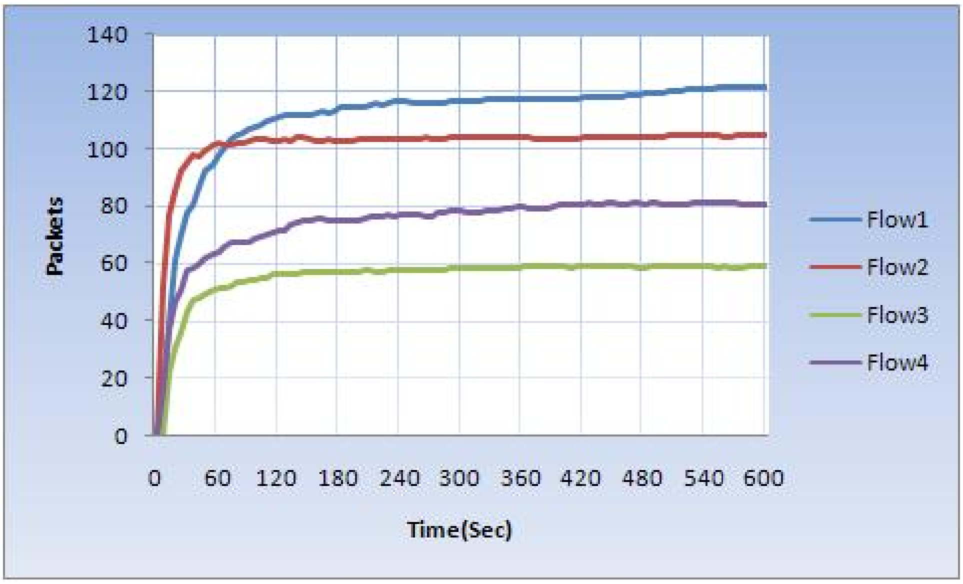


Figure 5.7: Flows Progress with MR-MC Pruned Two Path Topology

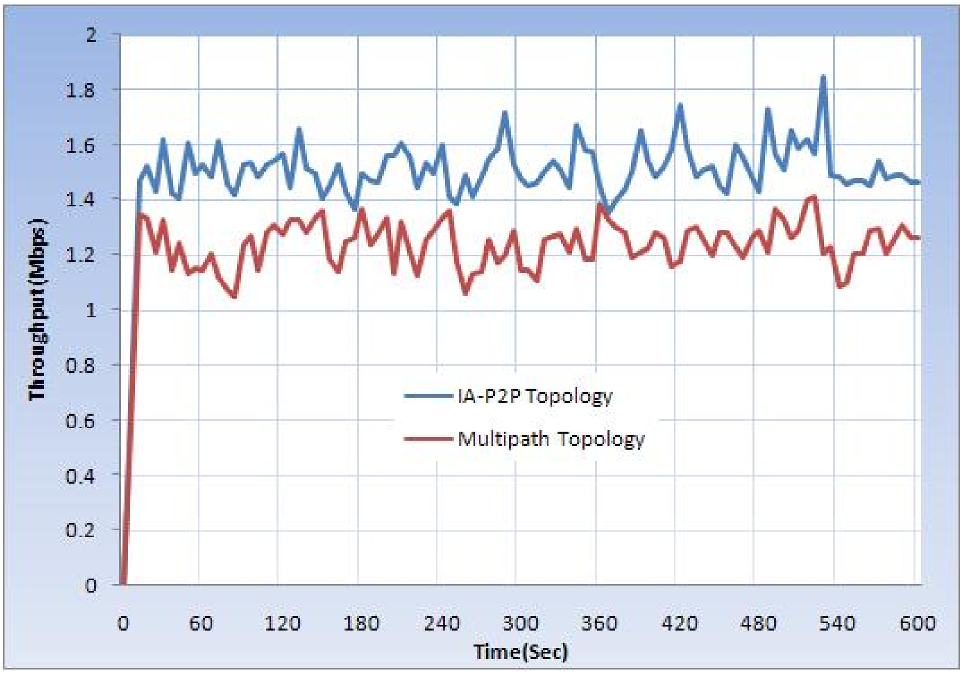


Figure 5.8: Comparison of Aggregate end to end Throughput

5.7 CONCLUSION

Wireless Mesh Networks (WMNs) are a self organized low cost alternative for extending wireless network connectivity where fixed infrastructure is not present. Various efforts have been made to develop the necessary protocols for mesh deployments such that these deployments can fulfill the traffic demand of end users. But due to the affect of interference in a multipath environment they are not getting the optimal throughput particularly in saturated conditions.

We proposed an optimization model on the basis of interference and link capacities constraints for static nodes and static traffic based WMN. This model find out the aggregate end to end throughput for all the flows using all possible disjoint multiple paths for the given topology. Optimization model results shows that the multipath network topology introduces lot of interference due to multiple paths, multiple flows and multiple hops between source and destination. This interference can be reduced by pruning of some links in the physical topology.

In this research work we also propose new optimized Interference Aware Pruned Two Path (IA-P2P) topology control scheme which uses our network optimization model and select best two among multiple completely disjoint paths for each flow. We prune the remaining links to reduce interference. The pruned topology experienced reduced level of interference while still providing alternate path connectivity between the nodes for reliability. We evaluated multipath physical topology and our pruned two path topology and compared the performance of both schemes. The mathematical results of the optimization model showed that our IA-P2P topology control scheme can improve the network throughput by an additional 21.3%, compared to existing multipath physical topology scheme. While the simulator results showed 16.8% improvement which is lesser than the mathematical but stills sufficient gain in the aggregate end to end throughput of the network.

In future the proposed model may be used to find more optimal results by relaxing the condition of mandatory alternate path. Because some times the second path of a flow is creating lot of interference and reduces the throughput but we are bound to add those links for reliability. Similarly sometimes the third path of a flow has no or little affect of interference and can increase throughput but we are not considering it. Also our proposed model may be used in future for dynamic nodes and dynamic traffic by adding some more constraints.

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Appendix A

Data File for AMPL Solver

```
set NODES:=1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 ;
set Source:=1 3 11 13 ;
set Dest:=13 9 14 10 ;
set Length:=1 2 3 4 ; #No. of possible paths for each flow
set EDGES:= (1,2)(1,3)(1,5)
    (2,1)(2,3)(2,4)(2,13)
    (3,1)(3,2)(3,4)(3,5)(3,6)(3,7)
    (4,2)(4,3)(4,7)(4,11)(4,13)
    (5,1)(5,3)(5,6)(5,8)
    (6,3)(6,5)(6,7)(6,8)(6,9)(6,12)
    (7,3)(7,4)(7,6)(7,9)(7,10)(7,11)(7,14)
    (8,5)(8,6)(8,12)
    (9,6)(9,7)(9,10)(9,12)(9,14)
    (10,7)(10,9)(10,11)(10,14)(10,15)(10,16)
    (11,4)(11,7)(11,10)(11,13)(11,15)
    (12,6)(12,8)(12,9)(12,14)
    (13,2)(13,4)(13,11)
    (14,7)(14,9)(14,10)(14,12)(14,16)
    (15,10)(15,11)(15,16)
    (16,10)(16,14)(16,15);
set SrcDest:=(1,13)(3,9)(11,14)(13,10);
set Path[1,13,1]:=(1,2)(2,13);
set Path[1,13,2]:=(1,3)(3,4)(4,13);
set Path[1,13,3]:=(1,5)(5,3)(3,7)(7,11)(11,13);
set Path[3,9,1]:=(3,6)(6,9);
set Path[3,9,2]:=(3,7)(7,9);
set Path[3,9,3]:=(3,4)(4,7)(7,10)(10,9);
set Path[3,9,4]:=(3,5)(5,6)(6,12)(12,9);
```

```
set Path[11,14,1]:=(11,7)(7,14);
set Path[11,14,2]:=(11,10)(10,14);
set Path[11,14,3]:=(11,15)(15,16)(16,14);
set Path[11,14,4]:=(11,4)(4,7)(7,9)(9,14);
set Path[13,10,1]:=(13,11)(11,10);
set Path[13,10,2]:=(13,4)(4,7)(7,10);
set Path[13,10,3]:=(13,2)(2,3)(3,6)(6,9)(9,10);
set PathSet:=(1,13,1)(1,13,2)(1,13,3)(3,9,1)(3,9,2)(3,9,3)(3,9,4)(11,14,1)
    (11,14,2)(11,14,3)(11,14,4)(13,10,1)(13,10,2)(13,10,3);
param: demand:=
1 13 19,
3 9 16,
11 14 20,
13 10 11;
param: cap:=
1 2 4,
1 3 8,
1 5 9,
2 1 4,
2 3 4,
2 4 5,
2 13 5,
3 1 8,
3 2 4,
3 4 7,
3 5 8,
3 6 5,
3 7 3,
4 2 5,
4 3 7,
4 7 7,
4 11 5,
4 13 11,
5 1 9,
5 3 8,
5 6 10,
5 8 11,
6 3 5,
6 5 10,
6 7 3,
6 8 7,
```

```
6 9 4,
6 12 6,
7 3 3,
7 4 7,
7 6 3,
7 9 10,
7 10 11,
7 11 7,
7 14 4,
8 5 11,
8 6 7,
8 12 6,
9 6 4,
9 7 10,
9 10 2,
9 12 7,
9 14 11,
10 7 11,
10 9 2,
10 11 7,
10 14 6,
10 15 10,
10 16 9,
11 4 5,
11 7 7,
11 10 7,
11 13 6,
11 15 9,
12 6 6,
12 8 6,
12 9 7,
12 14 4,
13 2 5,
13 4 11,
13 11 6,
14 7 4,
14 9 11,
14 10 6,
14 12 4,
14 16 6,
15 10 10,
```

```
15 11 9,
15 16 3,
16 10 9,
16 14 6,
16 15 3;
param: BLinkCap:=
1 13 1 4,
1 13 2 7,
1 13 3 3,
3 9 1 4,
3 9 2 3,
3 9 3 2,
3 9 4 6,
11 14 1 4,
11 14 2 6,
11 14 3 3,
11 14 4 5,
13 10 1 6,
13 10 2 7,
13 10 3 2;
set iNodes[1]:=1 2 3 5;
set iNodes[2]:=1 2 3 4 13;
set iNodes[3]:=1 2 3 4 5 6 7;
set iNodes[4]:=2 3 4 7 11 13;
set iNodes[5]:=1 3 5 6 8;
set iNodes[6]:=3 5 6 7 8 9 12;
set iNodes[7]:=3 4 6 7 9 10 11 14;
set iNodes[8]:=5 6 8 12;
set iNodes[9]:=6 7 9 10 12 14;
set iNodes[10]:=7 9 10 11 14 15 16;
set iNodes[11]:=4 7 10 11 13 15;
set iNodes[12]:=6 8 9 12;
set iNodes[13]:=2 4 11 13;
set iNodes[14]:=7 9 10 14 16;
set iNodes[15]:=10 11 15 16;
set iNodes[16]:=10 14 15 16;
```

Appendix B

Model File for AMPL Solver

```
    set NODES; #set of nodes
    set Source; #set of source nodes
    set Dest; #set of Destination nodes
    set Length; #set of possible alternate paths
    set EDGES within NODES cross NODES;
    set SrcDest within Source cross Dest;
    set PathSet within SrcDest cross Length;
    set PathPathSet within EDGES;
    set iNodesNODES within NODES;

param cap{EDGES}≥0,≤11; #capacity of each link

param demand{SrcDest}≥0; #Demand of each flow

param BLinkCapPathSet≥0, ≤11; #BNeck Link Cap. on each sub flow

param radioCapacity=11;

param channels=3;

var df{PathSet} ≥0, ≤1;

maximize Demand: sum{(a,b,c) in PathSet}demand[a,b]*df[a,b,c];

subject to Flowdemand {(x,y) in SrcDest}:
    sum {(a,b,c) in PathSet} if x=a and y=b then demand[a,b]*df[a,b,c]≤demand[x,y];
```

```
subject to BLCapacity {(a,b,c) in PathSet}:
    demand[a,b]*df[a,b,c]≤BLinkCap[a,b,c];

subject to LinkCapacity {(i,j) in EDGES}:
    sum{(a,b,c) in PathSet} if(i,j) in Path[a,b,c] or (j,i) in Path[a,b,c] then
    demand[a,b]*df[a,b,c]≤cap[i,j];

subject to Interference {n in NODES}:
    sum{m in iNodes[n]}(sum{(m,j) in EDGES}(sum{(a,b,c) in PathSet}
    if(m,j) in Path[a,b,c]
       then demand[a,b]*df[a,b,c])) ≤ radioCapacity *channels;
```