Radio Placement Algorithm and Dynamic Channel Allocation for Large Area Community Networks

A Thesis Submitted
in Partial Fulfillment of the Requirements
for the Degree of
Master of Technology

by
Prashant Sharma

to the
Department of Computer Science & Engineering
Indian Institute of Technology, Kanpur

August, 2005

Certificate

This is to certify that the work contained in the thesis entitled " *Radio Placement Algorithm and Dynamic Channel Allocation for Large Area Community Networks* ", by *Prashant Sharma*, has been carried out under my supervision and that this work has not been submitted elsewhere for a degree.

August, 2005

(Dr. Bhaskaran Raman)
Department of Computer Science & Engineering,
Indian Institute of Technology,
Kanpur.

Abstract

Community networks are being deployed today over large geographical regions (few tens of kilometres) to provide various services like VOIP (Voice over Internet protocol), web access, information sharing etc. to people in cities as well as villages. We will call these community networks covering large geographical regions as *Large Area Community Networks*. In this thesis, we consider the large area community networks in which nodes are mounted at pre-existing towers or on the tall buildings and most of the nodes use only a single radio for all of its directional antennas to begin with. More radios are later added to this network to increase its capacity and throughput. In this thesis, we consider the problem of adding new radios to the given network to increase its capacity.

We are proposing a *Radio Placement Algorithm* for the selection of nodes to which new radios could be connected in order to maximize the throughput of the network. The algorithm does node selection, and also allocates an appropriate channel to the newly formed link. This algorithm uses a heuristic to determine position of new radios in the network. This heuristic determines the amount of contention present in the network. So using this heuristic, we determines the position for a new radio, where amount of contention in the network is minimum, this indicates that improvement in the capacity of the network will be maximum. This algorithm determines the node position in linear time as compared to a naive exhaustive search method which is combinatorial. We have evaluated this algorithm through simulation on various kinds of topologies. We also describe *Dynamic Channel Allocation* for large area community networks which uses more than one radio per node. This scheme uses the available channels in the best possible way to minimize the contention in the network.

Acknowledgements

I want to thank and express my gratitude to my supervisor Dr. Bhaskaran Raman for his support, guidance and feedbacks from time to time. He was always approachable no matter how much busy he was. He was always ready to help in any possible way. He gave me lot of ideas from time to time which made possible the work in this thesis. Working with him was an enjoyable and educational experience which I will cherish for long time. I also want to thank people of Media Lab Asia, IIT kanpur for providing all the equipments needed for the experiments.

I would also like to thank my colleague Mohit Choudhary for his support at various stages of this work. My thanks are also for Venkat Chimata who helped me in performing some experiments.

I also want to thank all the faculty members and technical staff of the department. Every one was very helpful and it made my two years stay in iitk a wonderful experience.

Contents

List of Tables

List of Figures

Chapter 1

Introduction

IEEE 802.11-based community networks [1] are being widely deployed today. They are not only deployed by commercial and semi-commercial [2] network service providers, but also by various research organizations [3] as well as non-profit organizations [4] [5]. Community networks [6] are deployed to provide various services to villages and cities. People with Internet connectivity [7] can let other people use the Internet through a community network. Community networks allow people to share information [7][8][9][10] with each other. These community networks also have a profound effect on social interaction in the community [2][4].

1.1 Background and Motivation

In this thesis, we consider community networks which cover large geographical regions having a total span of upto few tens of kilometers. We call such community networks as *Large Area Community Networks*. Directional antennas are used to establish long distance links, because high quality links can be established as energy is concentrated over a small beam-width [2][6]. Further, we consider the case where most of the nodes are using only a single radio for all of its directional antennas. Such a consideration is based on the following:

- *Cost of radio*: At a given network location, there are three main components: the 802.11 radio, the antennae and the antenna tower. Although 802.11 radios are relatively cheap, the cost of the radio could become an issue in community networks. Nodes could be deployed on pre-existing towers, tall buildings or chimneys etc and thus we can ignore the antenna tower cost in these cases. Further, cheap directional antennas like cantennas [2] (available at less then US $5) could be used. Even highly directional antennas cost only about US $20-$50 [12]. Further, the cost of some of the brand 802.11 radios remains very high (like Cisco radios, iBridge and SmartBridge could cost as high as about $1000 per radio). So in such cases, the cost of a radio constitutes a significant part of the total cost of the deployment of a node. Therefore, to reduce the cost, a single radio may be used by the node for all of its directional antennas.

- *Channel Allocation Algorithm*: If multiple radios were to be used at a node, then to take advantage of this, we would require a channel allocation algorithm. Channel allocation algorithms are not widely available and those which are available [13][14] are not likely mature enough for implementation. To avoid the complexity involved in channel allocation, many community networks [3][8] explicitly use single radio at each node.

Another property of large area community networks we consider is the following. Some nodes in the network have wired Internet connection and these nodes can be used to provide Internet connectivity to the other nodes [2][6]. The nodes with wired Internet connection are called *landline* nodes. A node connects to the landline node either directly or through other intermediate nodes. Even with one node having Internet connection, connectivity can be provided to various villages and cities by setting up network nodes there.

The topology of the large area community networks we consider is a tree. This is for the following reason. The landline node is taken as the root of the tree. Each node has a single active path to the landline node, we thus get a tree topology. A node's parent in the tree topology is either landline node itself or the node which is next hop on its path to landline node. Given in Figure 1.1 is a network deployed by IIT-Kanpur and it covers various villages.

The nodes in Figure 1.1 represents various villages. The landline node is the one present at IITK. The arrows show bidirectional links established between the

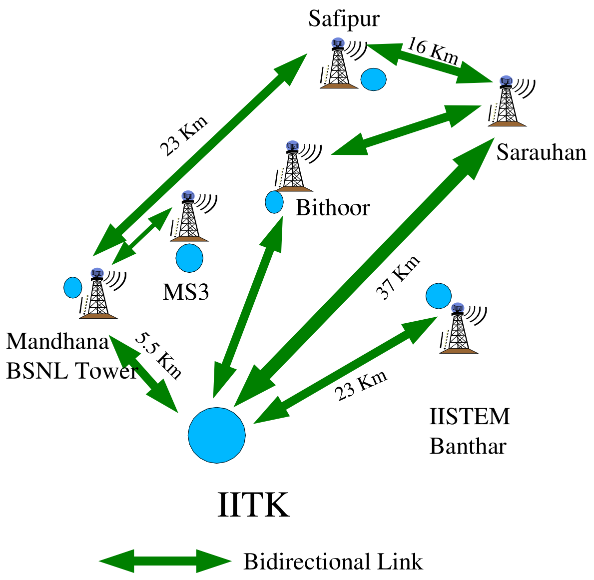


Figure 1.1: DGP Network (Taken from [6])

nodes using directional antennae. All the nodes can get services (Internet connectivity, VOIP (Voice over Internet protocol) etc.) from the landline node. Figure 1.1 shows that some nodes are connected directly to the landline node, some are connected indirectly through other nodes. Topology of network in Figure 1.1 is not tree topology. However, at any point of time only a tree is active, because active node connects to landline node through one particular path.

Any further reference we make in this thesis to community networks is about large area community networks. To summarize, the main characteristics of the network scenario considered in this thesis are:

- Directional antennas are used to establish long distance links.
- Most of the nodes in the network are using a single radio for all of its directional antennas.

- Each node in the network has a single path to the landline node. Thus the topology of the large area community network considered is a tree topology.

We have mentioned above that more than one directional antennas could be connected to a single radio. This is possible through the use of a splitter. A splitter divides the incoming power and distributes it to all of its output ports equally. Depending on the number of links required to be connected, a splitter with appropriate number of output ports (n-way) may be used. Shown below in Figure 1.2 is a two way splitter. Similarly there can be 3 or 4 way splitters. A two way splitter would typically cost around US$50 [15].

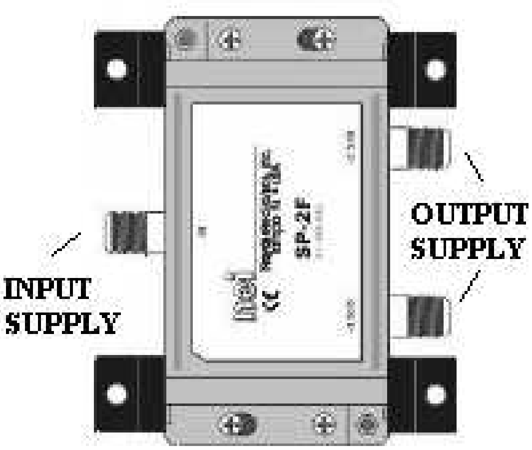


Figure 1.2: Two-way Splitter

We have also made an assumption in the representation of the network by tree topology. Suppose in the network, a node has established links with more than one node using a single directional antenna. In this case, the tree topology will show separate links at the given node for each node connected to it through that directional antenna.

1.2 Problem Statement

This thesis addresses two related problems in large area community networks. First, we consider the problem of "radio addition" to the given network. As described earlier, we have assumed that all, or most of the nodes in the network have a single radio. In such a setting, the throughput as seen by individual users of the community network could be very small. In a multi-hop network, the throughput decreases because of increase in interference among the links in the network. We term the interference among the links present in the network as *contention*. Contention becomes high as more links are active at each node. Since most of the nodes are using a single radio for their links, these links will be working on same channel and hence will cause interference to each other.

So with time, there comes a need of increasing the throughput of nodes by decreasing contention in the network. This is done by adding radios to the network, so that links can be made to work on different channels and interference between the links is decreased. However, addition of a new radio to the network is not trivial as the example below shows. In this thesis, we address the problem of radio addition to the given network. We select a node in the network to which a new radio could be added in order to maximize the throughput of network.

Selection of a node for connecting the new radio is not trivial. A locally optimal solution would connect the new radio at a node having many links working on same channel through a splitter. However, this may not be the best solution and may not lead to the maximum increase in throughput of the network. Throughput of network can be increased to large extent by taking the overall topology of network into account. We will show this through an example. Consider the community network given in the Figure 1.3.

In the Figure 1.3, we have a network with 10 nodes. Node 0 is the landline node. Nodes 4, 5, 6 and 7 are using splitter. Nodes 5, 6 and 7 are using 2-way splitters. Node 4 is using 3-way splitter to connect links 4-1, 4-2 and 4-3 to a single radio. Now suppose that a new radio is to be connected. On first glance, it seems best to connect it to node 4. This is because node 4 has the maximum number of links working through a single splitter. However, if the topology of network and global

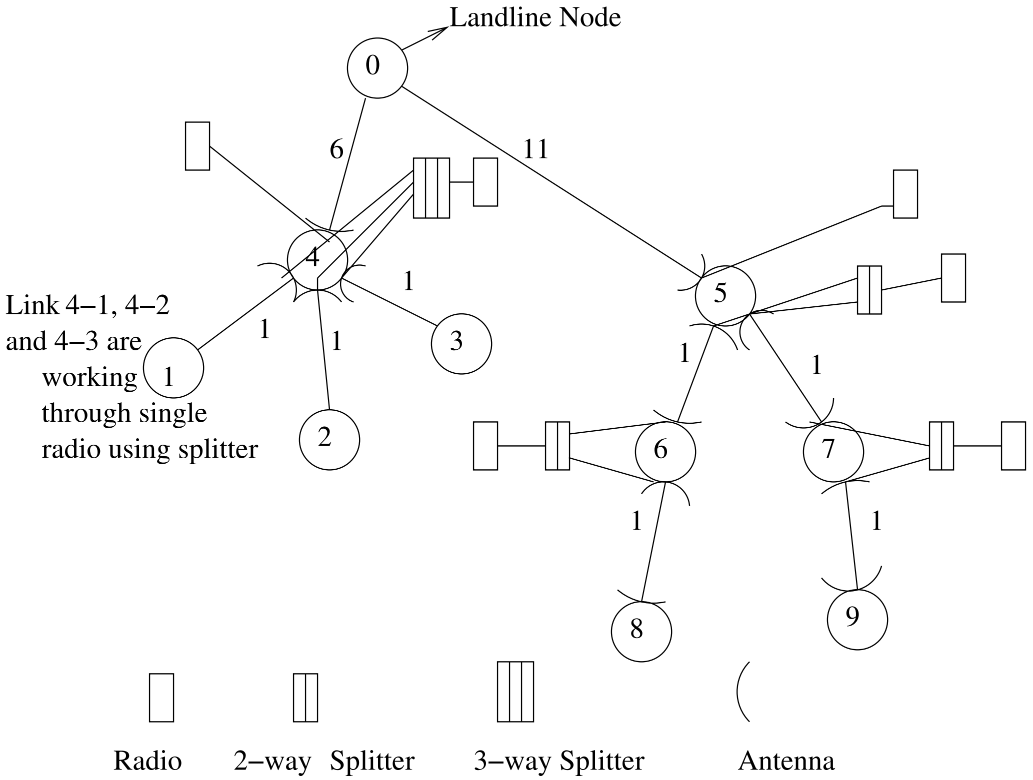


Figure 1.3: Large area community network

effect of the link provided with new radio is taken into account, then a better node can be selected. In this case connecting a radio to any of the links at 4 will produce the same global result and will affect only nodes 1, 2, 3 and 4. However, if the radio is connected at node 5, then it not only affects nodes 5, 6 and 7, but also the nodes 8 and 9. The links at 6 and 7 are working through splitters, thus connecting a radio at node 5 will not only lead to change in its channel, but also the channel of node 8 or node 9. The path of nodes 6, 7, 8 and 9 to the landline node is from node 5. The overall contention at node 5 is reduced, if a new radio is added there. It decreases the contention to the traffic of nodes 6, 7, 8 and 9 at node 5. Thus connecting a radio at node 5 will have a better global effect, improving the throughput of more number of nodes. In more complex topologies, there may be many nodes using splitters, and the effect of connecting a new radio to any link has to be seen globally using the topology of network. In general, we may need to add more than one radio to the network, so the problem becomes more complicated. In this thesis, we describe the design of "*Radio Placement Algorithm*" (RPA) which chooses the nodes in the network, to which a given number of new radios (more than one radio can be added to the network) could be connected in order to maximize the overall throughput of the network.

The Radio Placement Algorithm uses a heuristic to determine the global effect of connecting a new radio to particular link of the node. This heuristic calculates the amount of contention present in the network. By using this heuristic, the value of contention present in the network can be calculated for different possible positions of the new radios. The position where the contention value is minimum indicates the point where the amount of contention in the network will decrease by the maximum amount, when the given new radio is added to this position. Thus the improvement in the capacity of network will be maximum. In this way, using this heuristic, position of new radios in a network can be found. The Radio Placement Algorithm can be used by large area community networks (like Netherlands network [4]) to find the nodes, where new radios could be added.

The second problem addressed in this thesis is termed "*Dynamic Channel Allocation*" problem. Here we consider the scenario, where many of the nodes in the network have more than one radio. We are considering large area community networks that use 802.11b[1] protocol which works between 2.4Ghz-2.4835Ghz ISM band. There are only 3 non-overlapping channels available in this band. Due to 3 available channels, a community network in which a node has 4 or more links will have contention even if each link has its own radio.

If channels are assigned statically, this leads to contention in some cases even when free channel is available. Consider Figure 1.4 in which node 1 is the landline node. Node 2 has four links. Each link in the network has its own radio. Since only three channels are available, links 2-3 and 2-5 use the same channel i.e 6. In this topology, if nodes 3 and 5 are active, then the same channel will be used by links 2-3 and 2-5 in-spite of the fact that channel 11 is free. In all the community

---

[1] Community networks may also use 802.11a which operates in the 5Ghz band

networks, static channel allocation scheme is used. The drawback of the static channel allocation scheme is the main motivation behind Dynamic Channel Allocation scheme, proposed in this thesis. Here, we use a free channel whenever it is possible, we also change the channel of the appropriate links when the nodes become active or inactive in the network.

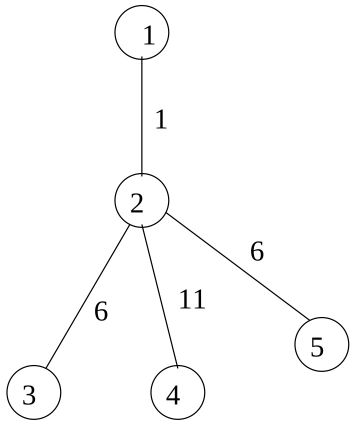


Figure 1.4: Large area community network or Mesh Network

To summarize, the two problems addressed in this thesis are:

- Radio Addition Problem: We address the problem of addition of one or more new radios in the network. To solve this problem, we proposes the Radio Placement Algorithm. The Radio Placement Algorithm determines the nodes to which new radios could be added in order to maximize the throughput of network.

- Dynamic Channel Allocation: This is a scheme for community networks which use multiple radios per node. It allocates channels dynamically in the given network as compared to static channel allocation used by currently deployed community networks. It uses the available channels in the best possible way to minimize the contention in the network.

1.3 Thesis Contributions

This thesis makes the following contributions:

- We design the Radio Placement Algorithm (RPA) which determines the position of new radios in a network in order to maximize the throughput of network. The RPA works in linear time. In comparison, a naive but optimal exhaustive search scheme is combinatorial. We evaluate the RPA by comparing it with the naive exhaustive search method. The position of the given new radios are found using the RPA in linear time. The exhaustive search method is then used to find out position of the given new radios through simulations. We show that the throughput improvement achieved by Radio Placement Algorithm compares well with the throughput improvement achieved by exhaustive search method.

- The Radio Placement Algorithm not only determines the node for connecting the radio, but also gives the channel to be used. Connecting a radio to any link of node leads to change in its channel. This scheme also determines what should be the channel for the link.

- We also present in this thesis a new scheme, 'Dynamic Channel Allocation' for the working of community network which proposes a new concept of dynamically selecting the channel for the active links present in the network. We show that using this scheme the throughput of the network can be further maximized.

1.4 State-of-the-Art

The present community networks use single channel throughout the network. In the present community networks which uses multiple radios per node, static channel allocation scheme is used. The paper [17] 'Centralized Channel Assignment and Routing Algorithms for Multi-Channel Wireless Mesh Networks' presents latest work done in this direction. They have given channel allocation algorithm for the mesh network in which all the nodes are equipped with equal k (k can be 2 or more than 2) number of radios. In comparison to the work presented in [17], in this thesis, we have taken a general scenario of network in which nodes can have any number of radios. With our Radio Placement Algorithm, we not only the finds the position of new radios for maximum increase in capacity of network but also determines channel allocation in the network, when new radios are added. In comparison to the present state of the art static channel allocation scheme, we have proposed a Dynamic Channel Allocation scheme that uses the available channels in the best possible way to minimize the contention in the network.

1.5 Organization of the Report

The rest of the report is organized as follows. Chapter II presents our design and evaluation methodology. Chapter III gives the assumptions underlying the Radio Placement Algorithm. Chapter IV describes how the heuristic used by the Radio Placement Algorithm is obtained. Chapter V describes the Radio Placement Algorithm and its evaluation through simulation. Chapter VI describes the Dynamic Channel Allocation scheme. Chapter VII presents our conclusions and describes future work.

Chapter 2

Design and Evaluation Methodology

In this Chapter, we will describe the design and evaluation methodology of the two problems addressed in this thesis.

First, we consider the radio placement problem. The design of the Radio Placement Algorithm (RPA) is done through simulations. Design of the Radio Placement Algorithm revolves around a heuristic, which selects the node to which a new radio could be connected. This heuristic estimates the contention in the network. The heuristic is obtained from the analysis of the simulations carried out on various topologies. Evaluation of the RPA is done by comparing it with the naive exhaustive search method. The position of the given new radios are found using the RPA in linear time. The exhaustive search method is then used to find out position of the given new radios through simulations. We show that the throughput improvement achieved by RPA compares well with the throughput improvement achieved by exhaustive search method.

The design of the Dynamic Channel Allocation (DCA) scheme is done using the same contention-estimation heuristic as in RPA. The DCA scheme obtains the network of minimum contention. Evaluation of the DCA scheme is based on an intuitive proof. We show that no possible channel allocation can further increase the throughput of the network.

All our simulations are carried out using 'The Enhanced Network Simulator' [20] (TeNs). This Chapter is further divided in to various Sections describing the metric on the basis of which the evaluation of RPA is done, the traffic pattern used for simulation, properties of TeNs and the relevant modifications we have done to TeNs.

2.1 Target Metric

The target metric of the RPA and DCA scheme is the *throughput* of network which is sum of throughput of all the active nodes in the network.

The position of radio by RPA is found, such that throughput of network is maximized. The heuristic for the RPA is obtained from simulations carried out on various topologies. The metric considered in the simulation results is the '*increase in the throughput of the nodes*'. We do not consider any other metric (delay, jitter, packet loss etc.). The traffic pattern used to measure the throughput is explained below.

2.2 Traffic Pattern

Before we explain the traffic pattern, we make the following observation. Inherently there is going to be congestion at the root of the tree topology (landline node is the root), as all the nodes obtain services (web access, VOIP etc.) from the root. The nodes which are near to the landline node will get an unfair share of the available bandwidth, thus limiting the amount of bandwidth that can be used by the far end nodes. Thus we advocate that the traffic from nodes near the landline node should be rate limited, or a fair queuing mechanism used.

The TeNs simulator does not currently have any mechanism to apply rate limiting for TCP traffic. So, if all the nodes are sending TCP traffic, then share of bandwidth for a node decreases as its distance from the root increases. However in TeNs, a node can be set to transfer CBR (constant bit rate) UDP traffic at any given rate. So rate limiting can be applied with UDP traffic by appropriate setting of the period of the CBR packet flow. We thus use UDP based CBR traffic for our simulations.

To apply rate limiting and to give fair share of available bandwidth to all of the nodes, we used an *equal rate traffic pattern*. We set all the nodes of the network to transfer an equal amount of traffic, so that each node gets a fair share of the available bandwidth. Maximum available bandwidth per channel at the root is taken as T (T=6) Mbps. This is maximum rate attainable at the application level, when the 11Mbps data rate is used, after discounting the PHY/MAC/IP overheads [19]. Total available bandwidth at the root is T * (number of channels) Mbps. In equal rate traffic pattern, for a network of 4 nodes (3 nodes excluding the landline node) with single channel at the landline node, we send the traffic at the rate of ($T/3$)Mbps from each of the three nodes to the landline node. So, in a network of n+1 nodes, with single channel at the landline node, each of the n nodes (except the landline node) will send (T/n)Mbps amount of traffic to landline node. Direction of traffic flow is always to the landline node, for all our simulations.

The main aim of carrying out the simulations is to know the global effect of adding radios to the network. The idea is to determine the reduction in contention which is obtained through change in the throughput attained. So we expect the results to be independent of any particular kind of traffic, and to depend only on the relative change in the attained throughput.

2.3 The Enhanced Network Simulator

The Enhanced network simulator is a modification of the network simulator (ns-2) [20]. The ns-2 was modified to add support for various functionalities [22] and is termed as "The Enhanced Network Simulator". The various functionalities added to ns-2 in TeNs are:

- *Support of directional antennas was added*: Previously ns-2 had the support of omni-directional antenna. The ns-2 was modified to provide support for some directional antennas (Parabolic dish antenna or grid antenna). Directional antenna support is provided through antenna radiation pattern in an input file. The antenna radiation pattern used by TeNs is shown in the Figure 2.1. This pattern gives a good approximation of the radiation pattern of a parabolic dish antenna [21].

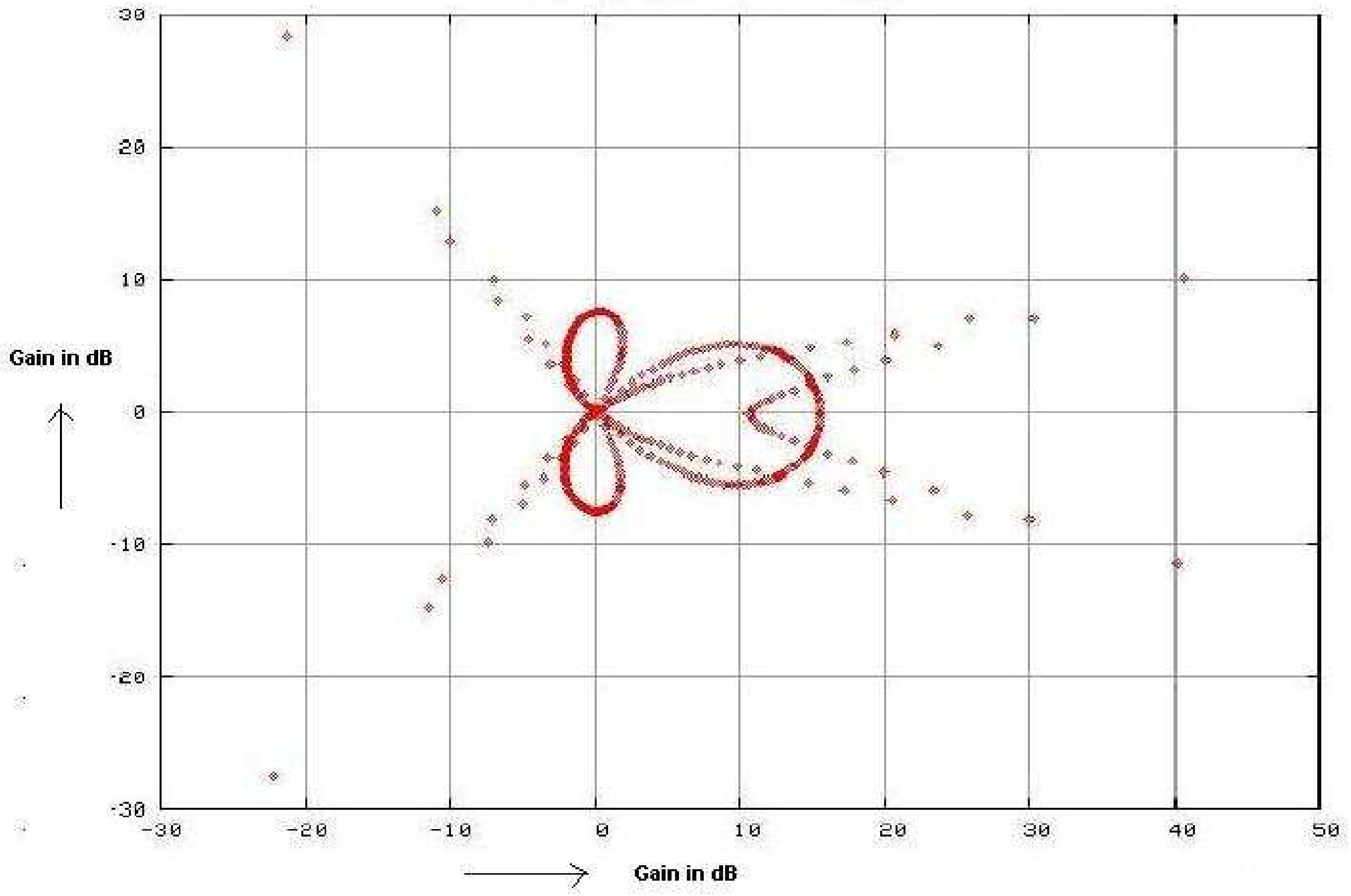


Figure 2.1: Radiation pattern supported by TeNs (Taken from [22])

- *Support of 11 channels was added*: This support was added as per specification of the 2.4Ghz band in IEEE 802.11b protocol, was added in TeNs. Support of random bit error rate and errors due to channel interference was also added.
- *Support for multiple antennas at a node was added*: This support was provided in the TeNs through the way of multiple interfaces at a node, where an interface corresponds to a radio. In TeNs, an interface of a node is associated with a single directional antenna. Thus different directional antennas can be added to a node by adding corresponding number of interfaces and associating each

with the directional antenna.

- Support for gray regions and random temporal variations in signal strength was added. This models real life RF propagation scenarios.

2.4 Modifications to TeNs

We modified TeNs to provide support for power-splitters. TeNs had the support of multiple interfaces at a single node. Each interface represents one radio. However only one antenna can be connected to a single radio in TeNs. Support for connecting multiple antennas to single radio through a splitter is not present. In TeNs, an interface is associated with a single radio and single radiation pattern (corresponding to single directional antenna at the interface). To provide the support of multiple directional antennas, the radiation pattern for the interface is modified such that it represents the combination of the radiation patterns of the multiple antennas. The transmit power at the interface is also decreased by a factor equal to the number of directional antennas. This approximates the behavior of multiple directional antennas at the single interface.

We did modifications in the following files to provide support for power-splitters:

- dir-antenna.c: This is the file in which the main modifications are done. Initially every interface can have single antenna. With each antenna its radiation pattern is associated. The radiation pattern for an antenna is the set of gain values in all directions. Support of multiple antennas at the same interface is provided by modifying the radiation pattern associated with the interface. The radiation pattern of each antenna mounted at the same interface is taken. The final radiation pattern of the interface is obtained by taking the maximum of the gain values from the radiation patterns of different antennas in each direction.

  Simulating multiple antennas at the same interface through single radiation pattern, provides a good approximation for multiple antennas at the same interface. This is based on our assumption that, if we use separate radiation pattern for each antenna at the interface, then the signal received in any direction will be from the antenna which has maximum gain in that direction. So when we represent this case by taking single radiation pattern, we take the maximum gain value in each direction, thus we are saying that in each direction, signal with maximum strength is sent. The same is the case with reception.

This approximation works well in the case of parabolic dish antennas which are considered in all of our simulations. Parabolic dish antennas have energy concentrated over a small beam-width (basically energy of signal is concentrated over half beam-width, after that power drops by 50% or 3dB). When we use multiple parabolic dish antennas through a single radio at a node to connect to different nodes, then signal received by any node from the given node will be from the antenna by which link is established between them. In other words, signal will be received from the antenna having the maximum gain in that direction. So using single radiation pattern for multiple antennas at the same interface, approximates the behaviour of using multiple parabolic dish antennas at the same interface.

- antenna.h: This file was modified to add a new field called as NoOfAntenna. This fields gives the number of antennas present at the given interface.
- wireless-phy.c: A splitter divides the input power equally to all its output ports. For simulating this behavior of splitter, power present at the interface is divided by the amount equal to number of antennas. The code in this file was modified to divide the power by the appropriate value.

Chapter 3

Preliminaries

This Chapter explains the basic assumptions and conditions behind the Radio Placement Algorithm (RPA). The Chapter is divided in to various sections explaining the change of the channel of a link after addition of a new radio, limitations imposed on the use of a new radio at a node, configuration of the splitter after addition of a new radio at a node and a necessary condition for the addition of a new radio at a node.

3.1 Radio addition leads to change in channel

We know that an 802.11b network uses free channels available in the 2.4GHz band. There are 11 channels available in this band. However there is overlapping between the channels which leads to interference between them. So generally 802.11b network uses three channels 1, 6 and 11 which have no overlap among them. We have considered only these three channels in our simulations.

When a new radio is added to any node, the channel of the link corresponding to this new radio is changed. This is a reasonable assumption, since if the channel of the link is not changed, then the increase in throughput of the network due to radio addition is expected to be very less. We illustrate this through a simple example.

Figure 3.1 given below shows the case when a new radio is added, and the channel of the link corresponding to this new radio is not changed. The new radio in this

udp traffic pattern for simulation	
Node 2 to Node 1	1500 bytes packet every 2ms for 1 min.
Node 0 to Node 1	1500 bytes packet every 2ms for 1 min.
tcp traffic pattern for simulation	
Node 2 to Node 1	1500 bytes packet send for 1 min.
Node 0 to Node 1	1500 bytes packet send for 1 min.

Table 3.1: Traffic pattern for UDP and TCP traffic

Figure is connected to node 1. Initially both the links at node 1 were working with the same radio through a 2-way splitter. After adding a new radio, both links at the node have their own radios. So link 1-0 can be tuned to some different frequency. However, link 1-0 is made to work on same channel i.e channel 1.

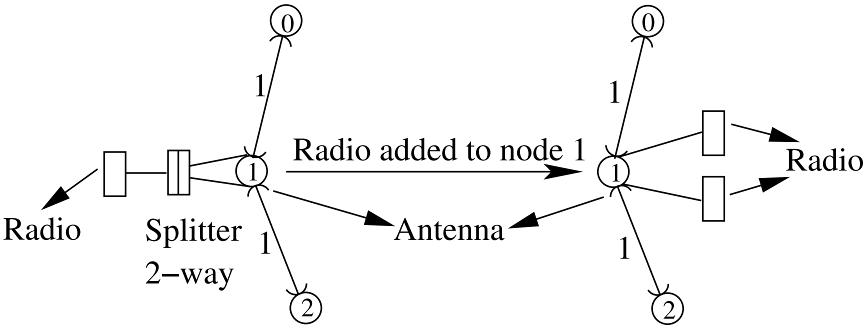


Figure 3.1: Channel of link 1-0 is not changed

We did the simulation on both topologies shown in the Figure 3.1. Node 1 is assumed as the landline node. Simulation was carried out by sending traffic from node 2 and node 0 to node 1 simultaneously. Simulation was carried out for both UDP and TCP traffic. TCP traffic was also used for simulation as there are only two nodes i.e node 2 and 0 and both are one hop distance from landline node, so no traffic limiting mechanism is required in this simple topology. The traffic pattern of UDP and TCP traffic used for simulation is shown in Table 3.1. Tables 3.2 and 3.3 show the results of simulation on both topologies with UDP and TCP traffic respectively.

Before adding Radio		After adding Radio	
Node	Throughput (Mbps)	Node	Throughput (Mbps)
2	3.336	2	3.336
0	2.752	0	2.88

Table 3.2: Results with UDP traffic

Before adding Radio		After adding Radio	
Node	Throughput (Mbps)	Node	Throughput (Mbps)
2	2.312	2	2.18
0	2.064	0	2.24

Table 3.3: Results with TCP traffic

The result of Tables 3.2 and 3.3 show that throughput value is almost same for both the topologies. This comparison of both topologies clearly says that, increase in throughput of network is very less, if channel of the link to which new radio is added is not changed. This is because even after adding a radio, there is no decrease in contention of network. This is because even though the antennas are directional, there is significant side-lobe and back-lobe radiations. These radiations prevent the simultaneous operation of the two links [23]. The contention is decreased only if number of links working on the same channel at a node are decreased.

Now we will see the case when the channel of the link is changed after adding a new radio. Figure 3.2 shows the case in which the channel of link 1-0 is changed after adding a new radio at node 1. Tables 3.4 and 3.5 show the results of the simulation carried out on the two topologies given in Figure 3.2 for UDP and TCP traffic respectively. The same traffic pattern as given in Table 3.1 was used for the simulation.

Tables 3.4 and 3.5 show that the throughput for the nodes 2 and 0 almost get doubled, after addition of a new radio at node 1. This happens because channel of link 1-0 is changed from 1 to 6, so contention at node 1 is eliminated[1].

---

[1] Contention becomes almost zero as the channels 1 and 6 don't have any overlapping between them. The signal of channel 1 doesn't interfere with the signal of channel 6.

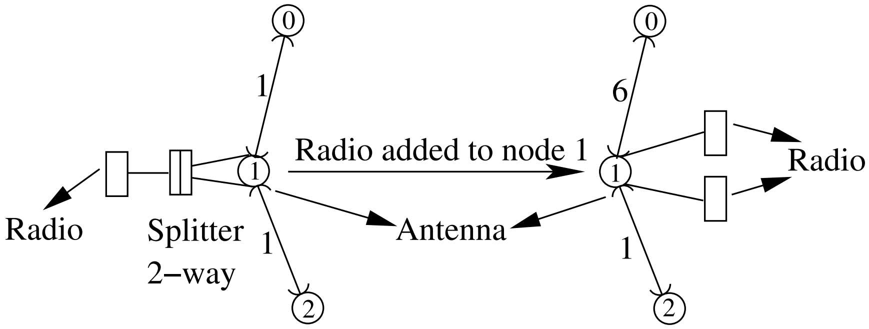


Figure 3.2: Channel of link 1-0 is changed

Before adding Radio		After adding Radio	
Node	Throughput (Mbps)	Node	Throughput (Mbps)
2	3.336	2	5.978
0	2.752	0	6.002

Table 3.4: Results with UDP traffic

Above results clearly show that, adding a radio can increase the throughput of the network, if the channel of the corresponding link is changed. To summarize, RPA makes an assumption that when a radio is added to a node of the network, the channel of the corresponding link is changed.

Before adding Radio		After adding Radio	
Node	Throughput (Mbps)	Node	Throughput (Mbps)
2	2.312	2	4.32
0	2.064	0	4.32

Table 3.5: Results with TCP traffic

3.2 Usage of Newly Added Radio

Our second assumption is with respect to the usage of a newly added radio. We explain this with an example. Consider Figure 3.3 in which node 1 has 4 links working through a 4-way splitter. If we add another radio at node 1, then we have various possibilities of adding this new radio at node 1. The first set of possibilities is where one link is made to work through this new radio which can be either of 1-2, 1-3, 1-4, 1-5. In the second set of possibilities, two links can be made to work through this new radio. This would require an additional 2-way splitter. Out of the 4 links present, there are many possibilities of selecting 2 links.

However, if two or more links are made to work on a new radio then a new splitter is also required. RPA considers only the case of adding a new radio to change the channel of a single link. We have not considered the case, when after adding a new radio to a node, more than one link is made to work through it. That is, in the above example, we do not consider the second set of possibilities in radio addition. Such a restriction is placed for simplicity.

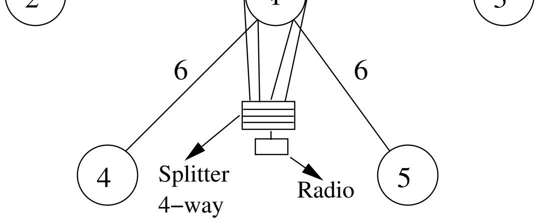


Figure 3.3: Node having 4 links working through single radio

3.3 Splitter Configuration

As explained above, when a new radio is added at a node, only one link is made to work through it. However, there are other possible changes. We can change the configuration of the existing splitters, after adding a new radio at a node. This is explained below with simple example.

Consider again the topology shown in the Figure 3.3. Node 1 has 4 links (1-2, 1-3, 1-4, 1-5) working through a 4-way splitter. Let us say, a new radio is added to node 1. Suppose, link 1-3 is made to work on this new radio [2]. Now at node 4, there are other possible changes also. One of the links 1-2, 1-4 and 1-5 can be exchanged with link 1-0. Suppose, link 1-5 is shifted with link 1-0. The resulting configuration (after shifting of link 1-5 with link 1-0) is shown in Figure 3.4. In this case, link 1-0 will work with links 1-2 and 1-4 through a splitter and link 1-5 has its own radio (radio which was used by link 1-0).

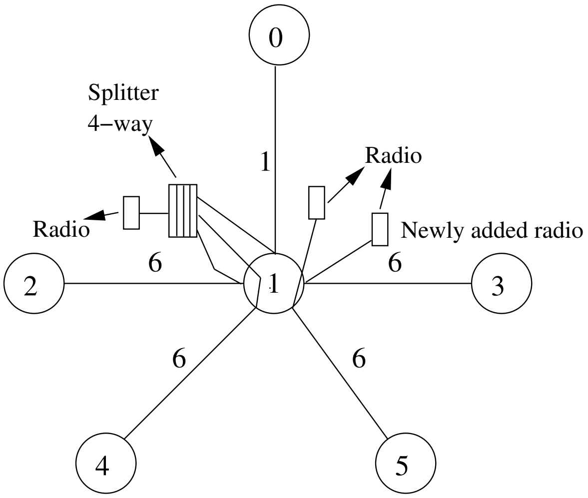


Figure 3.4: Node having 4 links working through single radio

So, there are other possible changes at node, after addition of a new radio. RPA only consider the case, when after adding a radio, one link is made to work through it and there is no other change at the node. This restriction is kept to simplify the

---

[2] If old 4-way splitter is still used for links 1-2, 1-4 and 1-5, there will be loss of power.

design of RPA.

3.4 Free Channels Available

We know that a new radio is added to make one link work on a different channel. Consider the case, when all the three available channels (i.e 1, 6 and 11) are being used at a node. Suppose, a new radio is added, then channel of the corresponding link is to be changed. In this case, no free channel is available at the node, so link is made to work on a channel which is already being used by some link at the node. In this case, the configuration of the network, after addition of a new radio to a node, can also be obtained by the use of a splitter. The link can be made to work on any channel, by combining it with the radio of link working on that channel, through the additional splitter. So, same configuration can be achieved through a splitter, if no free channel is available at a node.

RPA makes an assumption, that the advantage of adding a new radio to a node can only be obtained, if there is a free channel available at the node. If no free channel is available, then a splitter can be used instead of a new radio. This assumption is based on the fact that some of the community networks uses branded radios (like Cisco, iBridge, SmartBridge etc.). Cost of branded radios can exceed US $1000. In this scenario, splitter would be a cost effective solution, if no free channel is available at a node. However, if radios in the cost range of US $50-$100 are used, then the merit of this assumption weakens.

Chapter 4

Design of the Contention based Heuristic

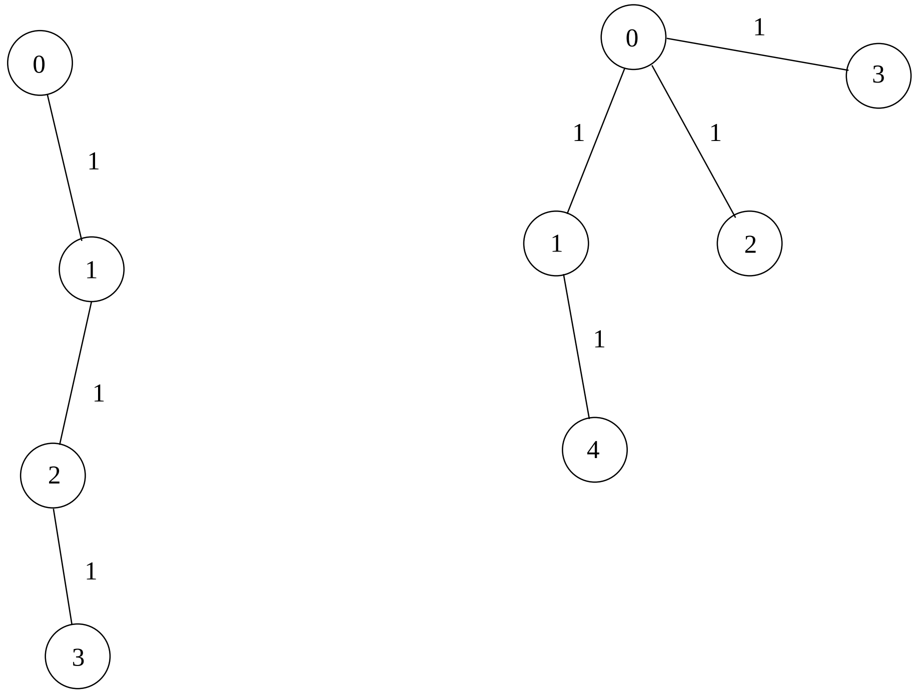
The Radio Placement Algorithm (RPA) uses a heuristic to measure amount of contention present in the network. We call the contention present in the network as "*Total Contention Value of Network*". In this chapter, we will describe how this contention based heuristic is obtained. This chapter is divided in to various sections. Section 4.1 describes how the *contention value* of a single node in the network is determined, Section 4.2 describes the calculation of the *total contention value of the network.*

4.1 Contention Value of a Node in the Network

This section describes how contention value (CV) of a single node in the network is determined. We define *contention value of node* as the amount of contention faced by the traffic from this node to the landline node. This section is further divided in to two subsections. In the first subsection (4.1.1), we describes the calculation of CV of a node for simple topologies (topologies in which nodes have atmost two links); Then using the results of this subsection, the subsection (4.1.2) will describe the calculation of CV of a node in any topology. Our overall approach in both the subsections is to derive contention based heuristic from the simulation results of an example topology. Then we generalize it and substantiate it using other topologies.

4.1.1 Topology having nodes with atmost 2 links

This subsection describes the calculation of CV of a node for topologies with nodes having atmost 2 links. We consider such topology first, because in such cases, the contention faced by traffic from a node X is only due to the links present in the path of node X to the landline node. We illustrate this through two simple topologies shown in Figure 4.1. Node 0 is the landline node in both the topologies. All the nodes are using a single radio (It is already explained, that we consider large area community network in which most of the nodes are using a single radio).



Topology (i)

Topology (ii)

Figure 4.1: Two simple topologies

Topology (i) in the Figure 4.1 presents the case when nodes have atmost two links, in this case contention faced by traffic from node 3 is due to the links 3-2, 2-1 and 1-0 (links in the path of node 3 to the landline node). Topology (ii) in the Figure 4.1 presents the case in which node has more than 2 links. In this case, contention faced by traffic from node 4 is not only due to the links 4-1 and 1-0 but also because of links 3-0 and 2-0. So links which are not present in the path to landline node are also responsible for causing contention.

In topologies with nodes having atmost 2 links, CV calculation of a node becomes a lot simpler, as only the links present in the path of a given node to the landline node are considered.

Now we will show how to calculate contention value of a node. The heuristic for determining contention value of a node is obtained from the analysis of various simulation results. We will describe the heuristic through an example. A typical example of topology with nodes having atmost two links is staircase topology. Consider the staircase topology shown in the Figure 4.2. In this topology, we will determine the position of a new radio through simulation and then describe our heuristic from the analysis of the simulation result. Node 0 is the landline node (in all our topologies, we have followed the convention of taking node 0 as the landline node). All the nodes are using a single radio and directional antennas are used to establish links (antenna radiation pattern considered in all our simulations is already shown in Chapter 2). Link distances are in the range of 1Km to $8\sqrt{2}$Km (in all our topologies, we have generated the network in an area of size 8 square Kilometers). All the links are working on channel 1.

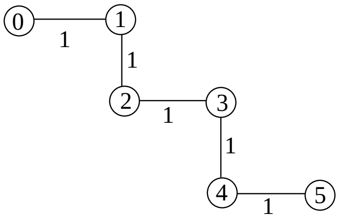
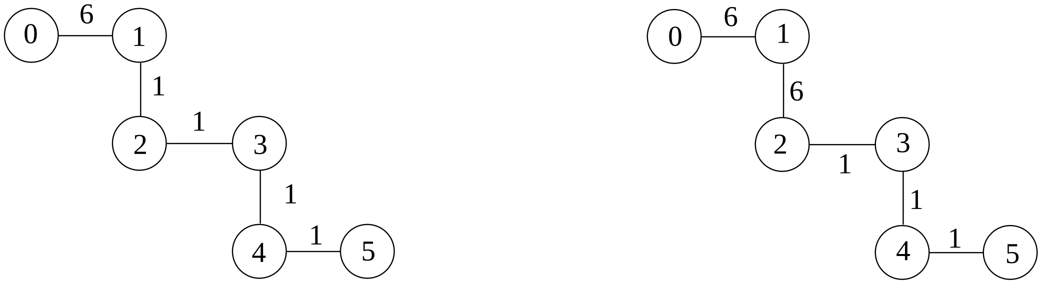


Figure 4.2: Staircase Topology

We did the simulation on this topology to determine position of a new radio, in order to maximize throughput of node 5. To carry out the simulation, traffic source was connected at node 5. Traffic source is connected only at node 5, because we want to find out position of new radio in order to maximize its throughput, so only node 5 is taken as active node. Traffic source was set to send UDP traffic at a rate of 6Mbps (maximum throughput possible per channel at the landline node). We find the position of a new radio by connecting it to all possible positions and measuring the throughput of node 5 in all cases. Figure 4.3 shows topologies for all possible four cases of connecting new radio to topology in Figure 4.2. Connecting a new radio at any node may leads to change in channel of more than one link. As seen in the Figure 4.3, connecting a new radio at node 2 leads to change in channel of the links 0-1 and 1-2. This happens because links are working through a single radio using a splitter, thus a change in the channel of one link at a node will force the change in the channel of some links at other nodes.



(i) Radio added at node 1

(ii) Radio added at node 2

(iii) Radio added at node 3

(iv) Radio added at node 4

Figure 4.3: All possible cases of new radio addition to topology in Figure 4.2

Position of new radio	No additional radio	Radio added at node 1	Radio added at node 2	Radio added at node 3	Radio added at node 4
Throughput (Mbps)	1.488	1.86	2.4	2.36	1.8

Table 4.1: Throughput value of Node 5 for different cases

Simulation results are shown in Table 4.1. Each column represents a different position of a new radio except the first column which shows the initial case of Figure 4.2, when the new radio was not connected.

These results show that the throughput value of node 5 is maximum, when a new radio is added to node 2, the throughput value when a new radio is added at node 3 is also comparable to maximum throughput value. From the Figure 4.3, it is clear that adding a new radio at node 2 or node 3 results in same kind of topology from the perspective of node 5. This is because, in both topologies, path of node 5 to the landline node has one set of 3 links working on same channel and one set of two links working on same channel. That is, the bottleneck to the traffic from node 5 to the landline node is the same in both cases.

The throughput value for node 5 is very less when radio is connected at node 1, compared to when it is connected at node 2. So topology (i) in Figure 4.3 is having more contention than topology (ii). As seen in Figure 4.3, topology (i) has four links working on same channel as compared to topology (ii) in which there is one set of three links working on same channel and one set of two links working on same channel. Link 0-1 of topology (i) in Figure 4.3 is not causing any contention, as it is working on different channel. It means four links working on same channel (as in topology (i)) is causing more contention then set of three links working on same channel in tandem with set of two links working on same channel (as in topology(ii)) to traffic of node 5.

The heuristic which we used to account for the difference in contention of topology (i) and topology (ii) is the *number of links causing contention to two links.*

If link x is causing contention to two links y and z, then we represent this case as C[x→y,z]. A link x can cause contention to links y and z, when three of them are working on same channel and are present in topology such that x is adjacent to y and z. The CV of node 5 in topology (i) and (ii) of Figure 4.3, can be represented in terms of C[x→y,z] as given below:

Topology(i): C[Link(3-4)→Link(4-5),Link(2-3)] and
C[Link(2-3)→Link(1-2),Link(3-4)]

Topology(ii): C[Link(3-4)→Link(4-5),Link(2-3)]

The difference in the number of C[x→y,z] units is responsible for the high contention in topology(i).

In the above example topology, we considered the contention in terms of C[x→y,z] units. However, there may be some links in the topology which will cause contention only to a single link. Now we will show this scenario. Consider again the staircase topology in Figure 4.2. Now we will determine the position of a new radio through simulations, in order to maximize throughput of node 4. UDP traffic was sent by traffic source at node 4 at the rate of 6Mbps (1500 bytes packet every 2ms). All possible cases of adding a new radio to the topology in Figure 4.2 are shown in the Figure 4.4. Simulation results are shown in Table 4.2

Table 4.2 shows that the throughput value is maximum when the new radio is added at node 2. Throughput value is minimum when the new radio is added at node 1 (although the difference is very less). The topology obtained after adding a new radio at node 1 or node 2 can be represented as in Figure 4.4. Link 4-5 is not considered, because it is not causing any contention to traffic send by node 4.

Table 4.2 shows that throughput value for node 4 is less when new radio is added at node 1 as compared to when it is added at node 2. So contention in topology (i)

Position of new radio	No additional radio	Radio added at node 1	Radio added at node 2	Radio added at node 3
Throughput	1.82	2.42	2.6	2.48

Table 4.2: Throughput value of Node 4 in Mbps for different cases

(i) Radio added at node 1

(ii) Radio added at node 2

Figure 4.4: Topology for new radio at node 1 and 2

of Figure 4.4 is higher than that of topology (ii). Contention of node 4 in the above two topologies in terms of number of C[x→y, z] is given as:

Topology(i): C[Link(2-3)→Link(1-2),Link(3-4)]
Topology(ii): No cases of C[x→y,z]

However, the throughput of node 4 in topology (i) of Figure 4.4 is not very less than throughput obtained in topology (ii). This happens because topology (ii) has two links causing contention to a single link each. If link x is causing contention to a single link y, then we represent this case as C[x→y]. A link x will cause contention to link y, when they are working on same channel and are adjacent. Contention of node 4 in topology (i) and topology (ii) of Figure 4.4 can be represented in terms of number of C[x→y] as:

Topology(i): No cases of C[x→y]
Topology(ii): C[Link(0-1)→Link(1-2)] & C[Link(2-3)→Link(3-4)]

C[Link(1-2)→Link(2-3)] of topology (i) is not taken as it is already included in C[Link(2-3)→Link(1-2),Link(3-4)].

There is very less difference in the throughput value of node 4 in topology (i) and (ii). Thus the contention caused to traffic of node 4 in topology (i) and topology (ii) should be almost the same. So we stipulate that contention of C[x→y,z] is equal to twice the contention of C[x→y].

Now we will describe our contention calculation mechanism. This CV based heuristic measures the amount of contention to traffic of a node in terms of number of C[x→y,z] and C[x→y]. In other words, CV of a node is calculated in terms of number of C[x→y,z] and C[x→y]. From now on, we will use Cdouble and Csingle to denote C[x→y,z] and C[x→y] respectively (because contention of C[x→y,z] is twice of C[x→y]). So Cdouble is twice of Csingle. To obtain CV in numeric terms, we take Csingle as 1 unit and therefore Cdouble becomes 2 units. Thus Cdouble and Csingle can be represented as:

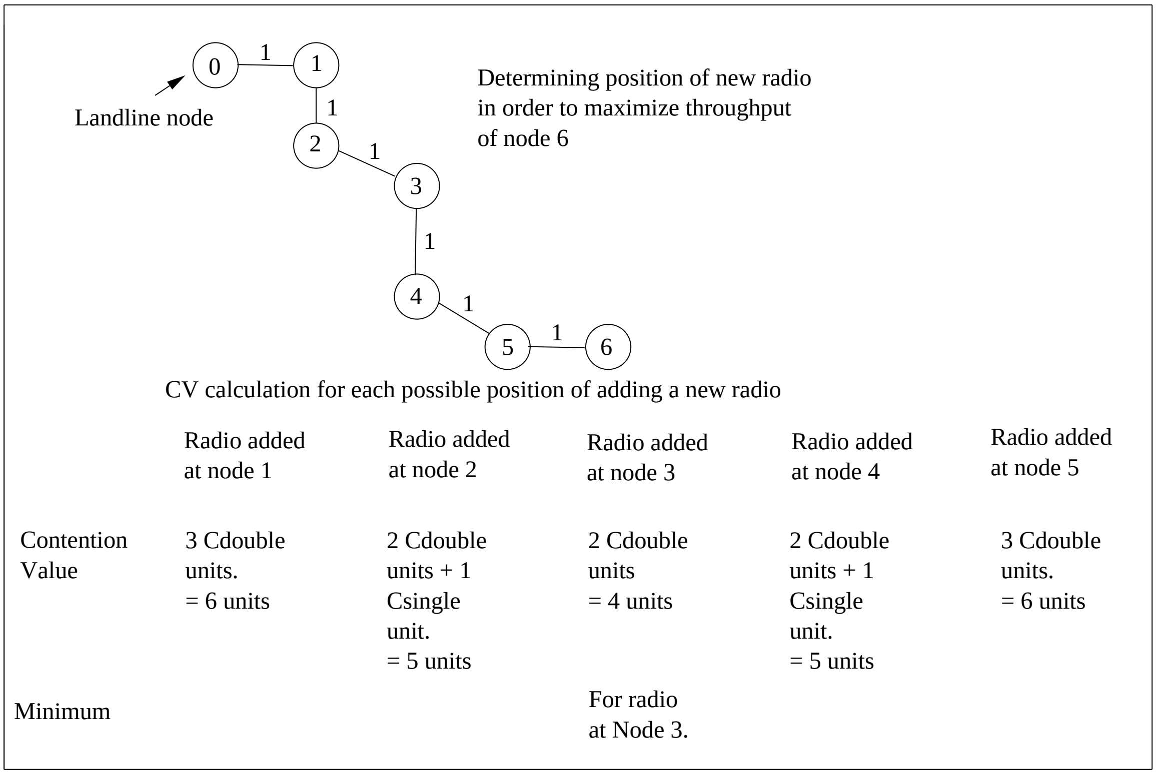
$$\begin{array}{lll} \text{Cdouble} = & \text{C[x}\rightarrow\text{y,z]} & = 2 \text{ units} \\ \text{Csingle} = & \text{C[x}\rightarrow\text{y]} & = 1 \text{ unit} \end{array}$$

The above contention calculation is used to determine position of a single new radio as follows. We determine the CV of a node for all possible positions of addition of a new radio. The position where the CV is minimum indicates that throughput of node is maximum for this position of a new radio. We term the above method as the *contention based heuristic* to determine the appropriate position for a given new radio.

We know summarize this section as follows:

- We defined two kinds of contention: C[x→y,z] and C[x→y].
- Two cases of C[x→y] seem to cause similar contention as a single case of C[x→y,z]. They are hence termed Csingle and Cdouble, and given the values 1 unit and 2 units respectively.
- The above values can be used to determine which topology has the minimum CV w.r.t a particular node. This in turn can be used to determine which topology results in maximum throughput for a particular node.

Above we had derived the contention calculation using two topologies. We now verify this calculation using another example. We will now show an example in which the contention based heuristic is used to determine the position of a new radio in order to maximize throughput of a node. Figure 4.5 shows the topology in which position of a new radio is to be determined in order to maximize throughput of node 6. Node 0 is the landline node. All the nodes are using a single radio to begin with. Figure 4.5 also shows CV of node 6 for all possible positions of adding a new radio in the topology. CV of node 6 is shown in terms of number of Cdouble and Csingle units. Figure 4.5 shows that CV is minimum when new radio is added at node 3.



CV calculation for each possible position of adding a new radio

	Radio added at node 1	Radio added at node 2	Radio added at node 3	Radio added at node 4	Radio added at node 5
Contention Value	3 Cdouble units. = 6 units	2 Cdouble units + 1 Csingle unit. = 5 units	2 Cdouble units = 4 units	2 Cdouble units + 1 Csingle unit. = 5 units	3 Cdouble units. = 6 units
Minimum			For radio at Node 3.		

Figure 4.5: Finding position of radio for node 6 through the contention based heuristic

We will now compare the result obtained by contention based heuristic with the results of simulation. Simulation is carried out on the topology in Figure 4.5 to determine position of new radio for node 6. Simulation results are shown in the Table 4.3. These result says that the throughput for node 6 is maximum when

Position of new radio	New radio not added	Radio added at node 1	Radio added at node 2	Radio added at node 3	Radio added at node 4	Radio added at node 5
Throughput (Mbps)	1.2	1.4	1.68	2.4	1.62	1.44
Throughput is maximum when new radio is added at node 3						

Table 4.3: Throughput value of Node 6

the new radio is added at node 3. So, simulation result matches with the results obtained by the contention based heuristic.

4.1.2 Topology having nodes with more than 2 links

In this Section, we will consider topologies in which node can have any number of links. When we determine position of a new radio in order maximize throughput of some node, we consider only that node as active. All other nodes are taken as inactive. So even in topologies with nodes having more than two links, if position of a new radio is to be determined to maximize throughput of some node, then only the path of that node to the landline node is taken as active. So the topology translates to simple topology in which node has atmost two links. We will illustrate this point through an example.

Consider the topology shown in the Figure 4.6. All the nodes are using a single radio to begin with. All the links are working on channel 1.

If the position of a new radio to maximize the throughput of node 6 is to be found, then we consider only node 6 as active node. So only links 6-5, 5-4, 4-1 and 1-0 are considered active. Links 1-2 and 1-3 are inactive. Thus the topology is similar to the stair case topology considered earlier (in both cases, nodes have atmost two links). In this case, the throughput of node 6 is maximum when new radio is added at node 4, because CV of node 6 when new radio is added at node 4 is minimum. CV of node 6 when the new radio is added at node 4 is equal to two Csingle units. Connecting new radio at any other node will results in atleast one Cdouble unit.

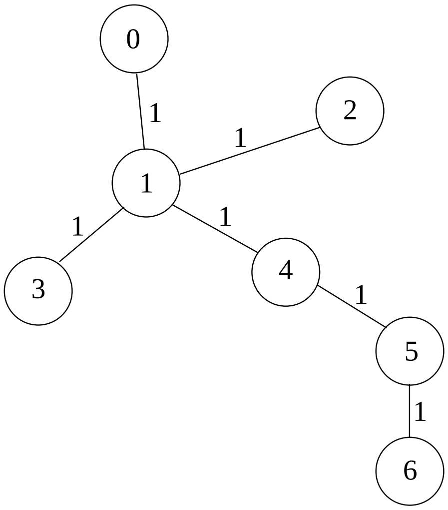


Figure 4.6: Tree topology having 7 nodes.

However in a network many nodes may be active. So we need a contention based heuristic to determine position of a new radio to maximize throughput of node, when many other nodes in the network could be active. We will now consider this scenario. Consider again the topology in Figure 4.6. We will now find the position of new radio to maximize the throughput of node 6, when all the nodes in the network are active. First, we determine position of a new radio through simulation and then we will design contention based heuristic for this scenario.

Simulation is carried out by connecting traffic source to all the nodes. Equal rate traffic pattern, as described in Section 2.2 is used. In this topology there are 6 nodes excluding the landline node. Thus each node is sending traffic at the rate of 1Mbps[1]. Table 4.4 shows the throughput value obtained for node 6 by connecting the new radio to various possible positions in the topology 4.6. Only the throughput value of node 6 is shown, because we are finding radio position to maximize the throughput of node 6.

Table 4.4 shows that throughput value is maximum when new radio is added at node 1. Recall from the earlier discussion that, if only node 6 had been sending

---

[1] Maximum throughput per channel at node 0 is 6Mbps, so T/n will be 1Mbps

Position of new radio radio	New radio not added	Radio added at node 1	Radio added at node 4	Radio added at node 5
Throughput (Mbps)	0.12	0.6	0.36	0.2
Throughput is maximum when radio is added at node 1				

Table 4.4: Throughput value of Node 6 for different cases of connecting a single new radio to topology 4.6

traffic, we would have had maximum throughput when the new radio was added at node 4.

The above results can be explained as follows. When the other nodes are also sending traffic, then links 1-2 and 1-3 of Figure 4.6 are also active. These two links are responsible for causing contention to links 0-1 and 1-4 which are carrying traffic from node 6 to landline node. Thus number of Cdouble units and Csingle units in CV of node 6, when all the nodes are active (corresponding to first column of Table 4.4) are:

C[Link(1-2)→Link(0-1),Link(1-4)]
C[Link(1-3)→Link(0-1),Link(1-4)]
C[Link(1-4)→Link(0-1),Link(4-5)]
C[Link(4-5)→Link(1-4),Link(5-6)]

Above, the first two cases of Cdouble unit would not be there, if only node 6 is considered active. We have considered only links 1-2 and 1-3 causing contention to 0-1 and 1-4, not the other way round. This is because we are considering the effect on the traffic of node 6 due to active links present at the intermediate nodes. When only node 6 is sending traffic, then links 1-2 and 1-3 are inactive. In this case, number of Cdouble units and Csingle units in CV of node 6 are:

C[Link(1-4)→Link(0-1),Link(4-5)]
C[Link(4-5)→Link(1-4),Link(5-6)]

To summarize, while calculating CV of given node in terms of number of Cdouble and Csingle units, all the active links present on the path of given node to the landline node and causing contention to traffic of given node are taken.

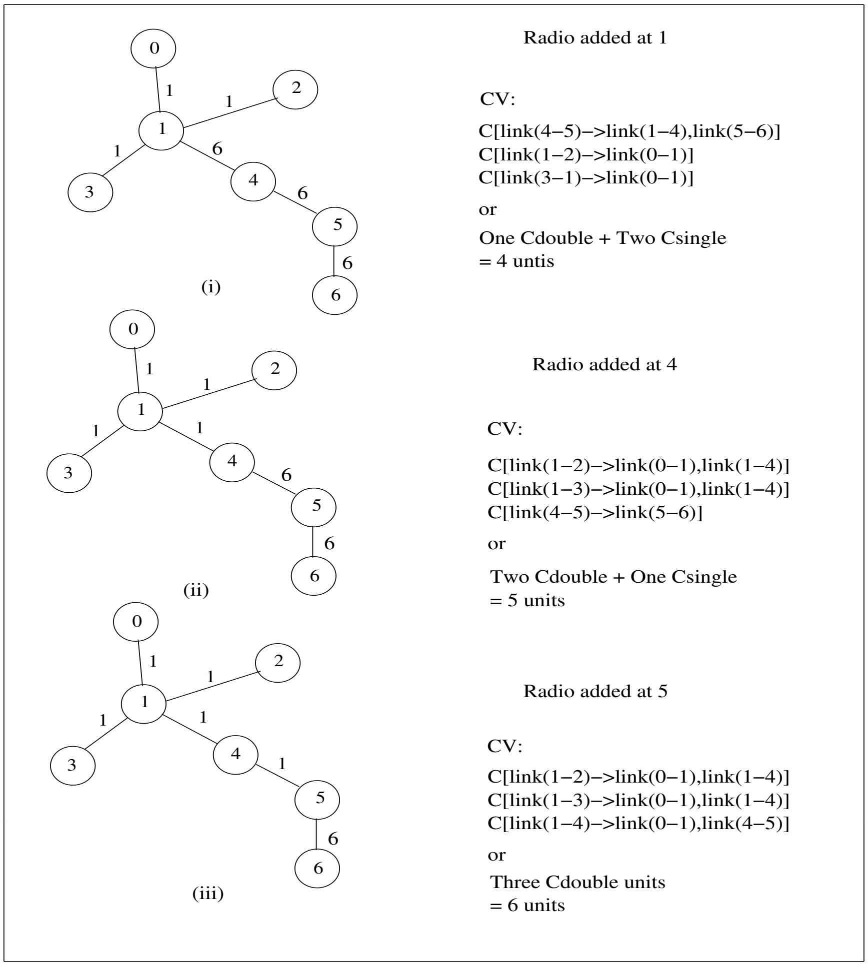


Figure 4.7: CV is minimum for new radio at node 1

Now we will determine CV of node 6 in the topology shown in the Figure 4.6 for all possible cases of adding a new radio. Figure 4.7 shows CV of node 6 for all possible cases of adding a new radio. This figure shows that CV is minimum i.e 4 units when new radio is connected to node 1. This indicates that throughput should be maximum for this radio position. This results is in accordance with the simulation results given in Table 4.6, which shows throughput is maximum i.e 0.6Mbps when new radio is added at node 1.

Now we will use the contention based heuristic to determine position of a new radio in order to maximize throughput of some node, when all the nodes in the network are active. We will illustrate this with an example.

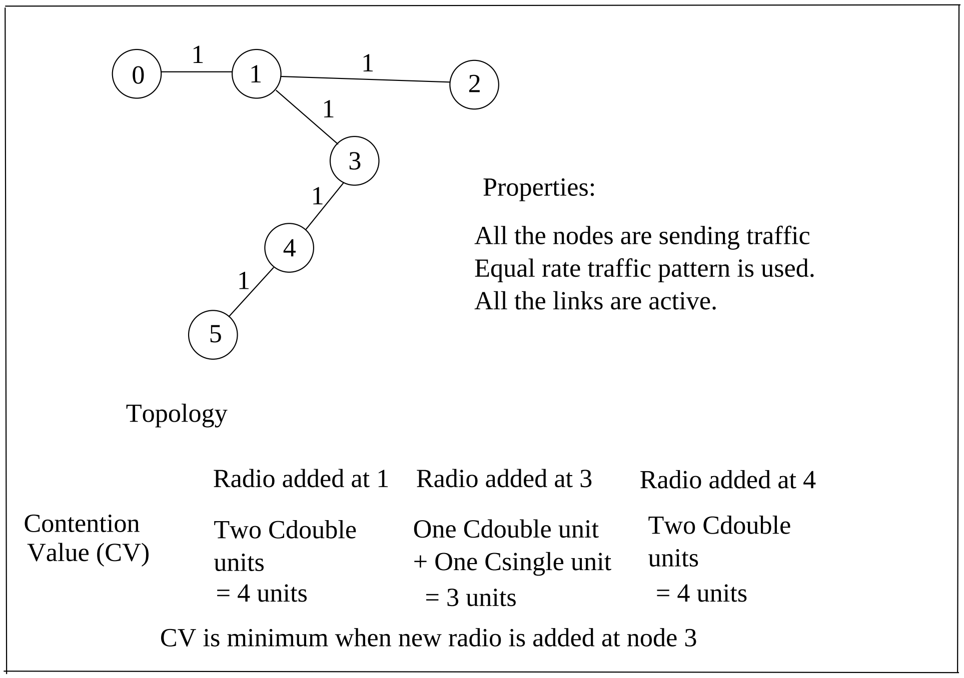


Figure 4.8: Contention is minimum when new radio is added at node 3

Figure 4.8 shows the topology in which the contention based heuristic is used to determine position of a single new radio in order to maximize the throughput of node 5. Node 0 is the landline node. All the nodes are using a single radio to being with. All the nodes are taken as active. Figure 4.8 also shows CV of node 5 for various possible cases of adding a single new radio. Figure 4.8 shows that adding a new radio at node 3 results in minimum CV. So the throughput of node 5 should be maximum when a new radio is added at node 3.

We will now compare this result with the results of simulation. Simulation was carried out using equal rate traffic pattern as described earlier. Table 4.5 shows the simulation results. The throughput value of node 5 is shown in the Table 4.5 for various possible positions of adding a new radio. The throughput of node 5 is

Position of new radio	New radio not added	Radio added at node 1	Radio added at node 3	Radio added at node 4
Throughput (Mbps)	0.1	0.22	0.48	0.2
Throughput is maximum when radio is connected to node 3				

Table 4.5: Throughput value of Node 5 for different cases of adding a new radio

maximum i.e 0.48Mbps when the new radio is added at node 3. So, the simulation result matches with the results obtained by the contention based heuristic.

4.2 Total Contention Value of Network

In the previous Section, we have described how contention value (CV) of a node in a network is determined. This Section will describe how to calculate the total contention value (TCV) of a network. While calculating the contention value of a network, all the links are taken to be active because we have to find out position of a new radio so that the total throughput of the network is maximized. Total throughput of the network is sum of throughput of all the nodes present in the network.

We will show how to calculate TCV of a network with an example. Consider the topology shown in the Figure 4.9. To begin with, all the nodes of this topology have only one radio except node 6 which has two radios. Links 6-9 and 9-4 are working on channel 6 and rest of the links are working on channel 1.

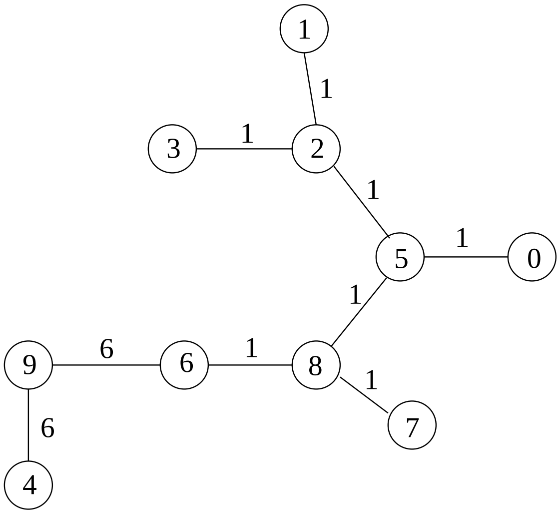


Figure 4.9: Topology with 10 nodes

We will first calculate the CV of node 4. For calculating the CV of node 4, all the links present in the path of node 4 to landline node along with the active links present at the intermediate nodes are taken in to account. The subgraph showing all the links taken into account while calculating the contention value of node 4 is given in Figure 4.10.

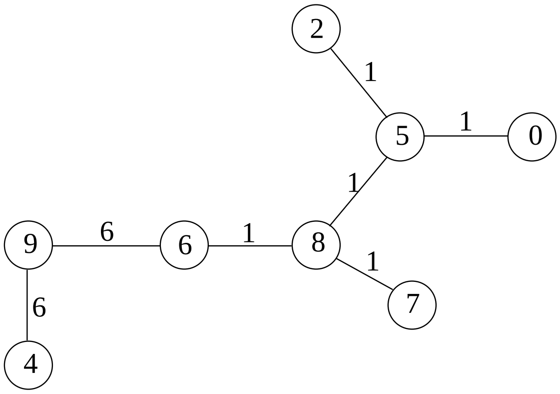


Figure 4.10: Subgraph of topology in figure 4.9

According to contention based heuristic, CV of node is calculated in terms of Cdouble and Csingle units. So, from the subgraph given in Figure 4.10 CV of node 4 is:

Contention Value =
C[Link(7-8)→Link(5-8)+Link(8-6)] +
C[Link(2-5)→Link(0-5)+Link(5-8)] +
C[Link(5-8)→Link(0-5)+Link(6-8)] +
C[Link(6-9)→Link(9-4)] = 3Cdouble+Csingle = 7 units

The contention value of node 4 contains 3 Cdouble and one Csingle unit. Contention value of node 4 includes link 7-8 and 2-5 because they are causing contention to traffic of node 4. We know that contention value of the network is sum of the contention values of all the nodes present in the network. So TCV of the network in Figure 4.9 is given by:

CV(Node 4)+CV(Node 9)+CV(Node 6)
+CV(Node 8)+CV(Node 7)+CV(Node 5)
+CV(Node 1)+CV(Node 2)+CV(Node 3).
= 7+9+6+6+6+2+6+6+6 = 52

In this way, TCV of any topology can be calculated.

To summarize, TCV of a network is sum of CV of all the nodes in the network. So to calculate TCV, CV of each node is first calculated using CV calculation mechanism . Summation of CV of all the nodes is then done to obtain TCV.

Chapter 5

Radio Placement Algorithm and its Evaluation

In this chapter, we describe the Radio Placement Algorithm (RPA) and evaluate it by comparing it with the optimal exhaustive search method. This chapter is divided into two sections. Section 5.1 will describe RPA and Section 5.2 will do evaluation of RPA.

5.1 Radio Placement Algorithm

In this section, we will explain the overall approach of RPA.

Approach

RPA finds out the position for connecting given new radios (one or more than one radio) to the network in *linear time*. In comparison, a naive but optimal exhaustive search method which is combinatorial. RPA also finds out the channel allocation for the network after connecting new radios. The basic idea behind RPA is to reduce the problem of connecting more than one new radios to a given network, to a problem of connecting a single new radio to the network one by one. Instead of using exhaustive search, RPA uses a *sequential approach.*

We will illustrate the difference between RPA and exhaustive search method with an example. Let us say we have a network with n nodes and k new radios are to be connected to this network. Suppose, there are p possible positions in the network for connecting a new radio. Number of positions where a single new radio can be added is $O(n)$, so p is $O(n)$. The naive exhaustive search scheme will find out all possible ways of connecting the k radios, which are $c(p, k)$. For each possible position of $c(p, k)$, link of each new single radio (there are k links) can be made to work on all available channels. Let ch be the maximum number of available channels. So for each possible position of $c(p, k)$, there are ch^k possibilities of allocating channel to k links. So complexity of exhaustive search method will be $ch^k * c(p, k)$ or $O(ch^k * p^k)$ ($c(p, k)$ is equivalent to $O(p^k)$, for p very less that k). However, with RPA, we are finding out positions for k new radios sequentially. So RPA run k times and each time $c(p, 1)$ positions are checked. So complexity of RPA is $ch * k * c(p, 1)$ or $O(ch * k * p)$.

We will evaluate this sequential approach in the next section by comparing it with exhaustive search method.

Methodology to add a single new radio

To connect a single new radio in the given network, RPA uses the *contention based heuristic*. The design of contention based heuristic is already described in the previous chapter. The contention based heuristic finds out the position of a single new radio in the network by calculating TCV (total contention value) of the network, for different possible positions of connecting the single new radio. The approach is to connect the single new radio to all possible positions and to calculate TCV (using contention calculation mechanism) of the network for each possible position. These TCVs are compared to find out the position for which TCV is minimum. This indicates the position where contention in the network is minimum, so we expect throughput of the network to be maximum, when new radio is connected to this position.

Channel Allocation by RPA

With the contention based heuristic, we find out the position of a single new radio, by connecting the new radio to all possible positions. A position in the network, is the *link at a node* to which new radio is connected. When we connect a single new radio, we change the channel of the link to all possible channels one by one and calculate TCV of network for each case. We repeat the same procedure with all the possible positions to which a single new radio can be connected. When we compare TCVs in the end, we take the position for which the TCV is minimum. For this position, we also know the channel of the corresponding link. So, through the contention based heuristic we also determine channel allocation after a single new radio is connected.

Pseudo code of RPA

The pseudo code of RPA is given in the Figure 5.1. The way in which this pseudo code works is already explained in the approach of RPA and methodology to connect a single new radio to the network.

To summarize, RPA takes as input the present topology of the network and the number of new radios to be connected. RPA then use the above mentioned methodology to determine the position of given new radios one by one. RPA gives the output in the form of position of the new radios and the channel of the corresponding links.

5.2 Evaluation of Radio Placement Algorithm

In this section, we will evaluate RPA by comparing it with the exhaustive search method. The methodology of evaluation is as follows. We find out the position of the given k new radios in the network using RPA. We then find out the position of k new radios using exhaustive search method. We then compare the throughput of the resultant network in either case. We show that the throughput improvement achieved by RPA compares well with the throughput improvement achieved by the exhaustive search method.

```
while(given_number_of_radio_connected)
{
// loop continues until given number of radios are connected

    for each (position = next position())
    { /* loop over the given network and find next position for
      single new radio */

        while(channel_available(position))
        { /* Apply loop for all channels on which link can be made
          to work when radio is connected to given position */
            connect_radio_position();
            /* connects radio to given position with link made to
            work on given channel */
            TCV=find_contention();
            // Find total contention value of network
            if (TCV <= Min_value)
            {
                Min_value=TCV;
                store_given_position();
            }
        } // End of while (channel_available) loop

        if (last(position)) break;
    } /*Position of a single new radio in the network is determined.*/

    decrement(given_number_of_radio_connected);
    obtain_new_network();
    /* Obtain new network by connecting new radio to position where
TCV is minimum. Position of next new radio is found on this newly obtained
network.*/
} // End of main loop
```

Figure 5.1: Pseudo Code of RPA

In the exhaustive search method, we consider all possible positions of the k new radios. For every possible position of the k new radios, the increase in throughput of network is found by simulation. Simulations are carried using equal rate traffic pattern. The position for which the increase in the throughput of network is maximum is taken as the desired position of the k new radios. So in the exhaustive search method, we try out all possible positions of connecting k new radios and determine the position for which the increase in throughput is maximum.

In this section, we will show the results of connecting single, two, three and four new radios to the network. So the value of k will be 1, 2, 3 and 4. However, RPA can be used for connecting any number of radios. We will not only use example topologies in which nodes are using a single radio but also the topologies in which some nodes have more than one radio. We will show results for topology in which some nodes have two radios. However, we expect RPA to work even if some nodes have three and more radios to begin with.

We will now explain how the example topologies are obtained. Topologies for the network are obtained by generating some nodes randomly in a area of size 8Km * 8Km and connecting them through a minimum spanning tree. We assume that minimum spanning tree represents the structure of large area community network, where each node has a single path to the landline node and connects to the node nearest to it. So distance between the nodes is used as a metric for constructing the minimum spanning tree. Link distance between the nodes vary from 1Km to about $8\sqrt{2}$Km . We have followed the convention of taking node 0 as the landline node in every topology. In some topologies, some nodes have two radios to begin with. Such nodes are selected as follows. We go through the list of Nodes in chronological order. So first node 0 is selected and if extra radio can be connected to it, which is possible if node 0 has more than 1 link, then radio is added to it. If radio cannot be added to node 0 then node 1 is taken and so on (The radio addition above is for the purpose of generating a random topology as input to RPA. It is not to be confused with the radio addition which is done by RPA itself).

We will now show the results of RPA for addition of single, two, three, four radios to the network.

Addition of a single radio

RPA will be evaluated for two topologies. Consider the first topology given in the Figure 5.2. The number written on each edge represents the channel used by the corresponding bidirectional link. In this topology, nodes 1, 2 and 6 have two radios. In this topology, the position of a single radio is found using RPA. Position of a single new radio found using RPA is node 12 (link 12-6, channel 11).

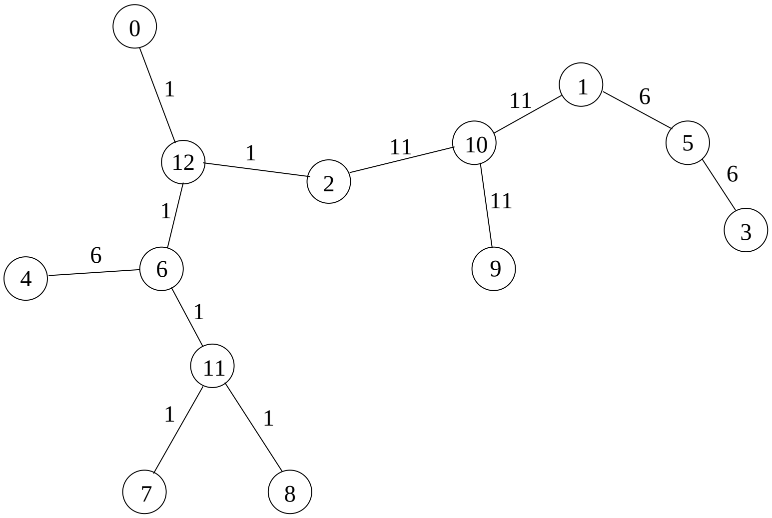


Figure 5.2: Topology with 13 nodes

Exhaustive search method is now used to find out the position of a single new radio. Simulation is done for all possible cases of connecting a single new radio and the increase in throughput is found for each case. Link distance between nodes, radiation pattern of directional antenna considered for simulation are already explained. Results of exhaustive search method are shown in the Figure 5.3 and are explained as follows. The graph in this figure has two curves. Dotted curve is showing percentage increase in throughput of network after addition of a single radio. X-axis is showing all possible cases of connecting k radios. In this case, k is 1, so possible cases of connecting a single radio by exhaustive search method are $c(p, 1)$. The cases for which percentage increase in throughput is very less are not shown. This applies to all the results of exhaustive search method shown after-wards.

In the graph in Figure 5.3, we also show the TCV of the network, for different possible positions of connecting a single new radio by exhaustive search method. TCV (contention of network) in the graph is shown by solid curve. This curve shows, that with the decrease in TCV, throughput of network increases.

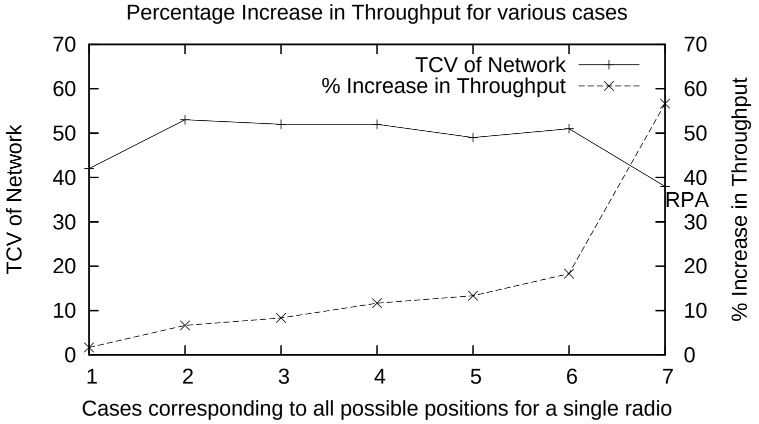


Figure 5.3: Graph showing plots of TCV and percentage increase in throughput for different radio positions for topology 5.2.

Now we will compare the results of exhaustive search method shown in the graph with the results of RPA. Dotted curve in the graph shows percentage increase in throughput in the increasing order. So the last case of the graph shows the position for which increase in throughput is maximum and this is the position to which a new single radio should be connected, according to exhaustive search method. This applies to all the graphs that will be shown after-wards. The position indicated by label 'RPA' in the graph shows the position found by RPA. It is clear from the graph, that this position corresponds to last case, and for this position percentage increase in throughput is maximum i.e 57%. So position of a single new radio found by RPA is same as the position found by exhaustive search method.

Consider the second topology given in the Figure 5.4. In this topology, nodes 1, 2, 4 and 5 have two radios. Position of a single new radio found using RPA is node 6 (link 6-9, channel 11). Results of exhaustive search method are shown in the Figure 5.5. The position indicated by label 'RPA' in the graph shows the position found by RPA. Last case of the graph gives the position found by exhaustive search method. So position of a single new radio found by RPA is same as the position found by exhaustive search method.

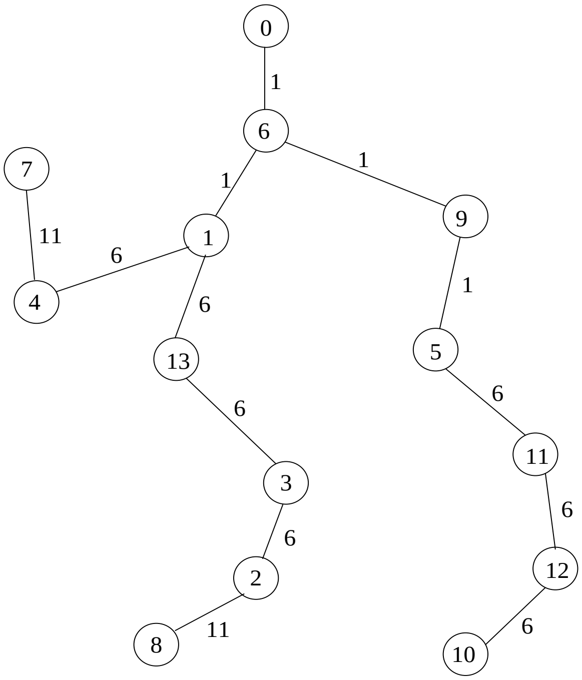


Figure 5.4: Topology with 14 nodes

Addition of two radios

We will now evaluate RPA for addition of two new radios to a network. RPA will be evaluated for two topologies. Results for both topologies will be shown through graph (as in the previous case). The X-axis will show all possible cases of connecting two new radios ($c(p,2)$) to the network. In both topologies, label 'RPA' gives the case of X-axis corresponding to position found by RPA. Graph of two topologies will show that label 'RPA' corresponds to the last case (position of two new radios by exhaustive search method). Give below are the main characteristics of two topologies and position of two radios found by RPA.

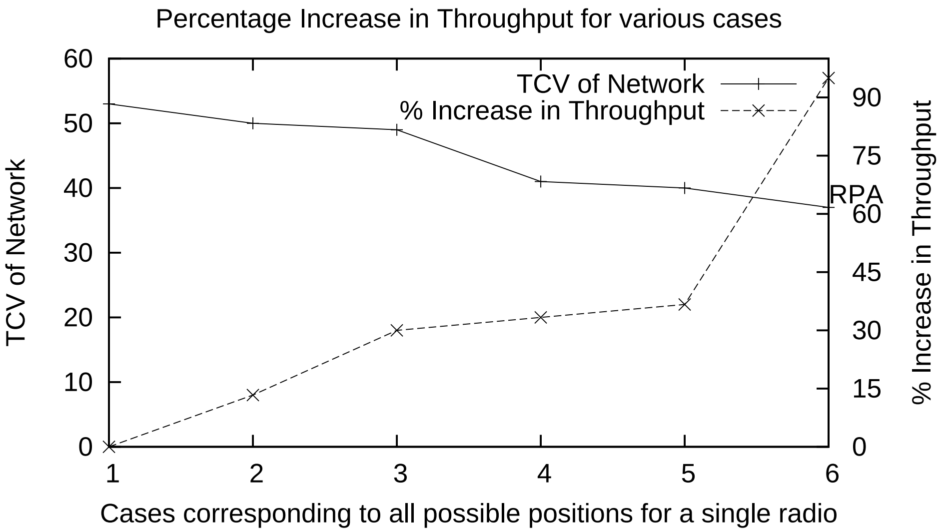


Figure 5.5: Graph showing plots of TCV and percentage increase in throughput for different radio positions for topology 5.4.

First topology is given in Figure 5.6. In this topology, node 0 has two radios. Position of two new radios using RPA is node 12 (link 12-5, channel 1) and node 2 (link 2-7, channel 11). Increase in throughput for this position is 42%. The Results of exhaustive search method are given in Figure 5.7.

Second topology is given in Figure 5.8. In this topology, nodes 0, 3 and 4 have two radios each. Using the RPA, position of two new radios is found to be at node 6 (link 6-12, channel 11) and node 5 (link 5-0, channel 11). Increase in throughput for this position is 80%. The results of exhaustive search method for this topology are shown in the graph given in the Figure 5.9.

Addition of three radios

We will now evaluate RPA for the addition of three new radios to a network. Consider the topology given in Figure 5.10. In this topology, nodes 0 and 1 have two radios each. Using the RPA, position of three new radios is found to be at node 6 (link 6-5, channel 11), node 8 (8link 8-2, channel 1) and node 2 (link 2-3, channel

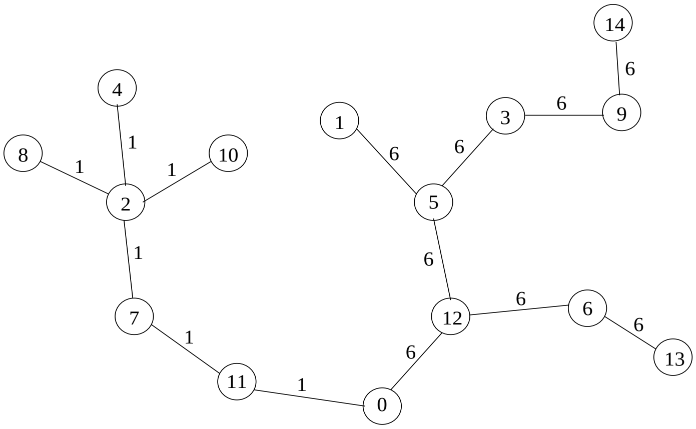


Figure 5.6: Topology with 15 nodes

6). The results of exhaustive search method are shown in the graph given in the Figure 5.11. Label 'RPA' correspond to last case of the graph and so matches with the result of exhaustive search method. Increase in throughput for this position is 30%.

Addition of four radios

We will now evaluate RPA for addition of four new radios to a network. RPA will be evaluated for two topologies. Consider the topology given in Figure 5.12. In this topology, nodes 0, 1 and 3 have two radios each. Using the RPA, position of four new radios for this topology is found to be at node 11 (link 11-1, channel 6), node 6 (link 6-0, channel 11), node 8 (link 8-10, channel 1) and node 8 (link 8-7, channel 11). The results of exhaustive search method for this topology are shown in the graph given in the Figure 5.13. Label 'RPA' indicates the position found by RPA and it corresponds to last case of the graph. Increase in throughput for this position is 45%.

Consider the second topology shown in Figure 5.14. In this topology, nodes 1, 4 and 9 have two radios each. Using the RPA, position of four new radios is found to be at node 14 (link 14-10, channel 11), node 9 (link 9-0, channel 1), node 10 (link 10-6, channel 1) and node 10 (link 10-14, channel 6). The results of exhaustive

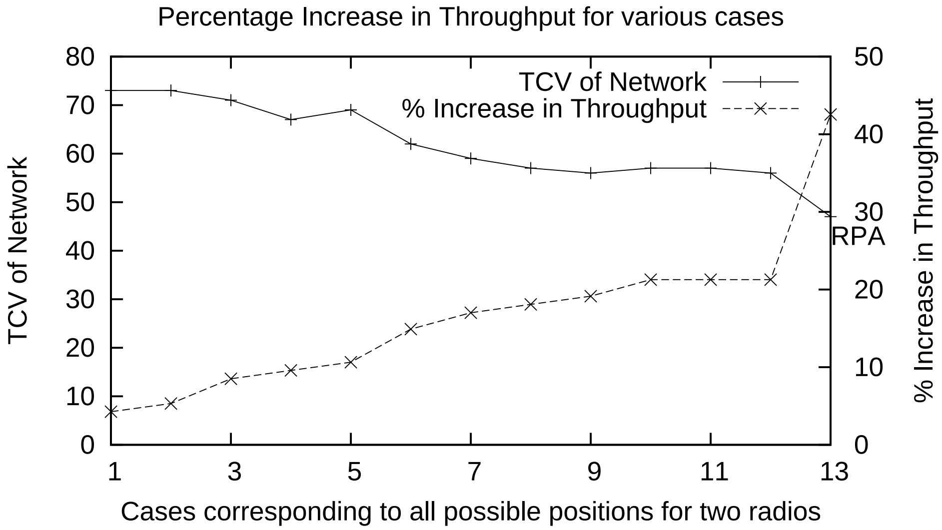


Figure 5.7: Graph showing plots of TCV and percentage increase in throughput for different radio positions for topology 5.6.

search method for this topology are shown in the graph given in the Figure 5.15. Label 'RPA' indicates the position found by RPA. Label 'RPA' is not pointing to the last case of the graph. Label is pointing at case 71 (second last) of the graph. However increase in throughput for this case is 130% which is just 1% less than the increase in throughput of last case (131%). So increase in throughput achieved by RPA is comparable to increase in throughput achieved by exhaustive search method.

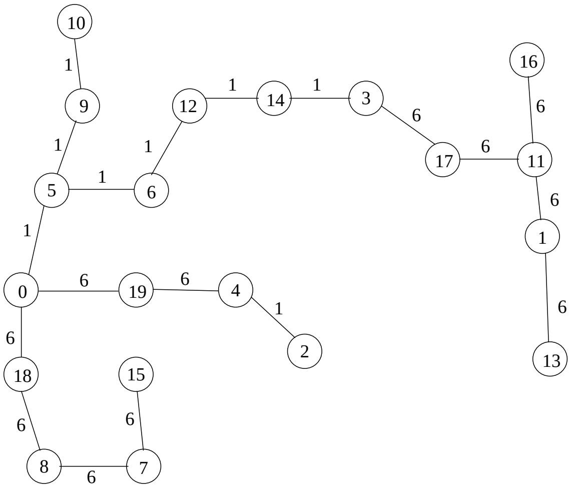


Figure 5.8: Topology with 20 nodes

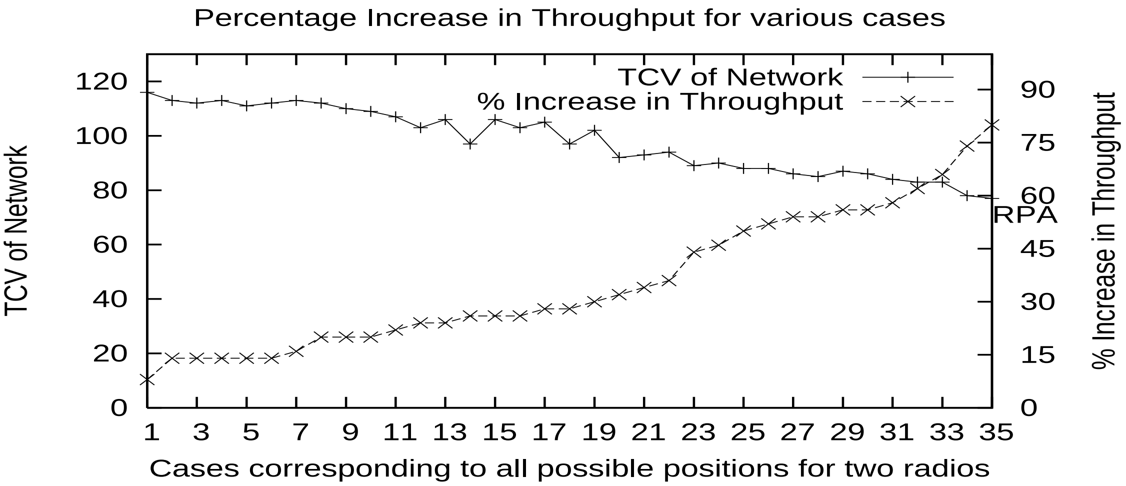


Figure 5.9: Graph showing TCV plotted along with percentage increase in throughput for different radio positions for topology 5.8.

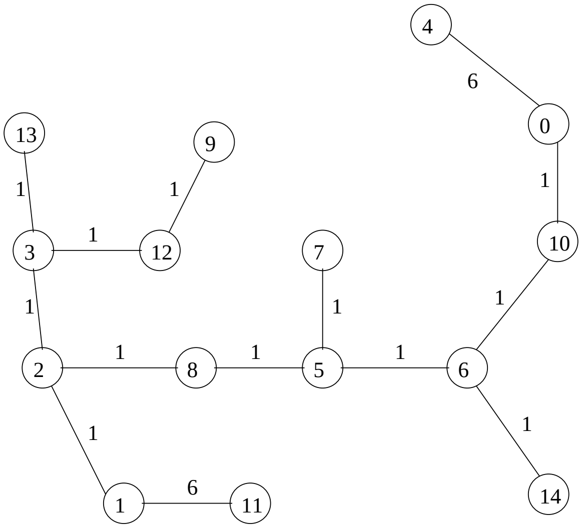


Figure 5.10: Topology with 15 nodes

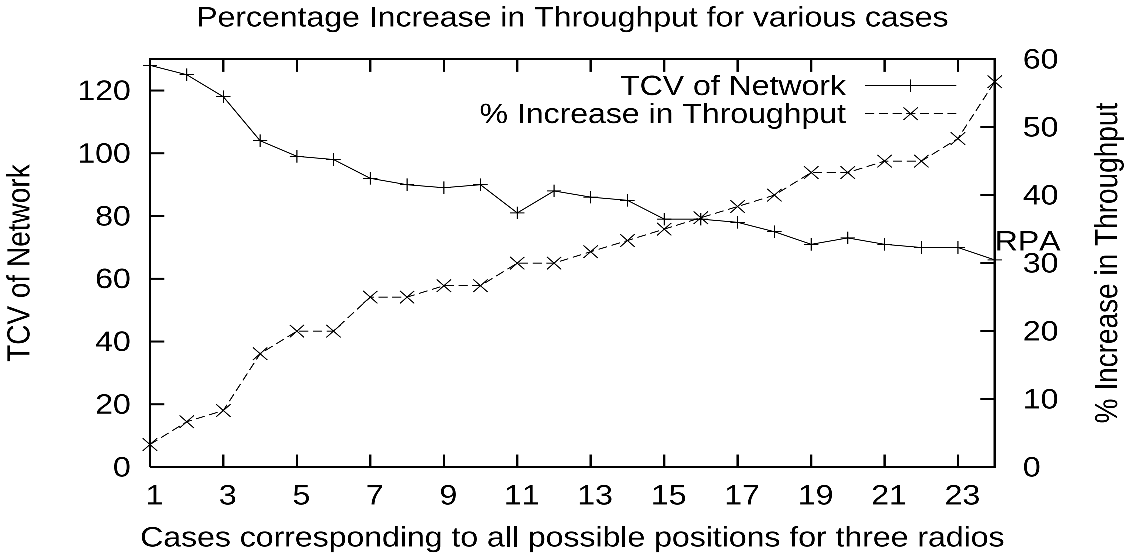


Figure 5.11: Graph showing TCV plotted along with percentage increase in throughput for different radio positions for topology 5.10.

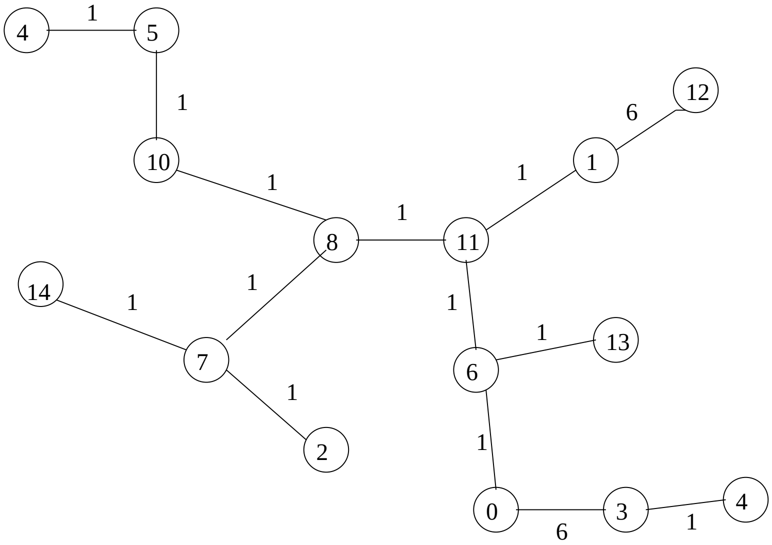


Figure 5.12: Topology with 15 nodes

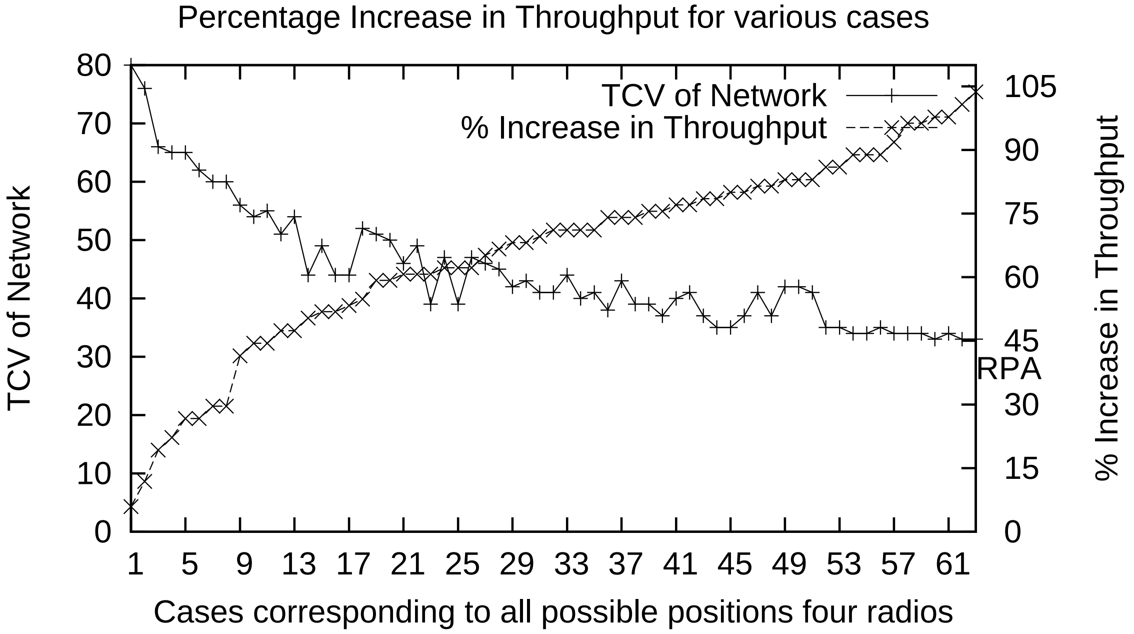


Figure 5.13: Graph showing TCV plotted along with increase in throughput for different radio positions for topology 5.12.

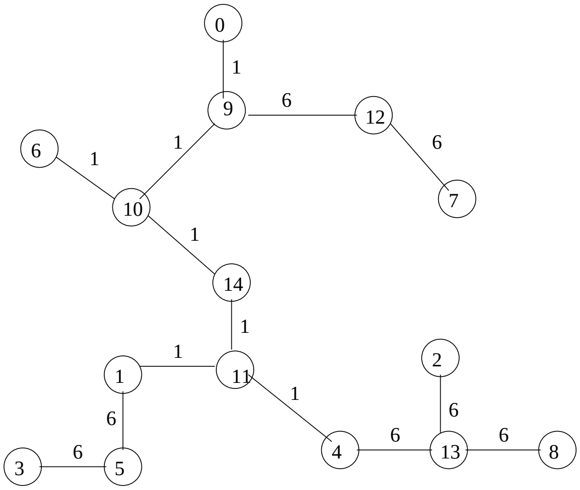


Figure 5.14: Topology with 15 nodes

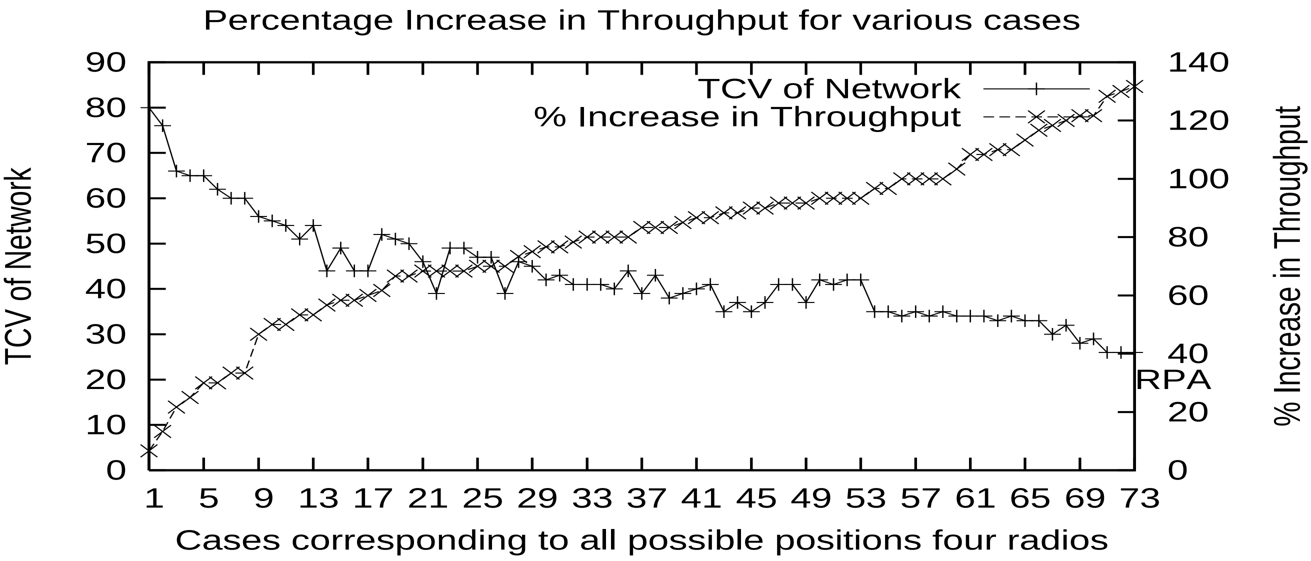


Figure 5.15: Graph showing TCV plotted along with increase in throughput for different radio positions for topology 5.14.

Chapter 6

Dynamic Channel Allocation

This chapter describes a new scheme for channel allocation in large area community networks. Here we assume that we have several nodes in the network which have more than one radio.

Dynamic Channel Allocation (DCA) assigns channel dynamically in the given network, a shift from the use of statically assigned channels by large area community networks. Use of statically assigned channels can increase the contention at node which can be avoided by dynamic allocation of channels, as explained through an example below.

Consider the topology in Figure 6.1. Node 0 is the landline node. Node 1 has four links to nodes 0, 2, 3 and 4, with each link having a separate radio at node 1. Links 1-2 and 1-4 are working on same channel (because there are only 3 available channels). Channels are assigned statically to the network.

Suppose, nodes 3 and 5 are active (a node is said to be active when it is getting any service like web connectivity etc. from the landline node). Nodes 1 and 3 are inactive. In this case, there will be contention between links 1-2 and 1-4. Even though there is channel 11 available at node 1, it is not being used by any of the active links at node 1.

This happens because statically allocated channels are used. Static allocation is done considering all the nodes in the network. In the above example, dynamically allocating the channels will lead to assignment of channel 6 and 11 to links 1-2 and

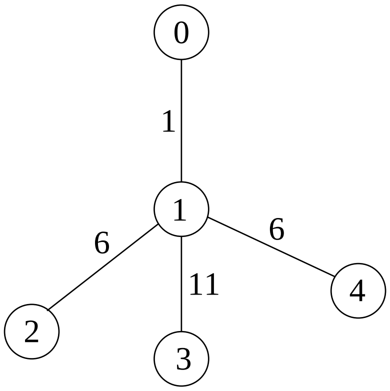


Figure 6.1: Simple Topology with 4 nodes

1-4 and thus the contention can be reduced. So if the network has a behaviour, that all the nodes of the network will not be active all the time, then DCA can be used to increase the throughput of the network. While allocating channels dynamically, we use the free channels available at any node only for the active links. Also, if free channels are not available, channels are allocated such that the contention of the network is minimized.

The main idea behind this scheme is to minimize the contention of the active part of the network, instead of the whole network. In this chapter, we will first describe the basic approach of the scheme, followed by the algorithm. We subsequently outline an intuitive proof for why DCA works.

6.1 Basic Approach

In this section, we will explain how the channels are assigned dynamically, the steps taken, the approach, and why this approach is used. Examples are also used to explain the point. This section is divided in to various subsections, each explaining a particular part of the overall approach.

6.1.1 Channel allocation is done only for the part which has newly become active

When a node becomes active in the network, it means path of the node to the landline node has become active. In this case, new channel allocation is done only for the inactive part a part of the network which is going to become active. We explain this through an example. Consider the topology given in Figure 6.2. Node 0 is the landline node. In this topology, nodes 3 and 5 have separate radio for each of their link and all other nodes are working on a single radio.

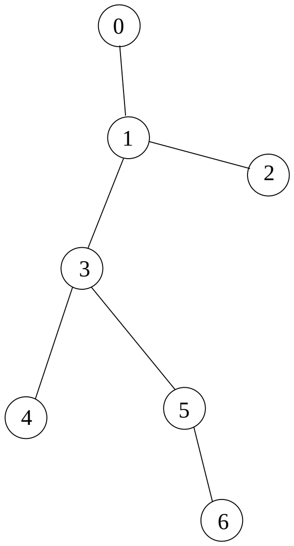


Figure 6.2: Simple Topology with 7 nodes

In this example, if node 4 becomes active, then it means that the path from node 4 to node 0 has become active. This path includes links 0-1, 1-3, and 3-4. So, channels are chosen for these three links. Let us say, after some time node 5 becomes active. It means path from node 5 to node 0 has become active, but as node 4 is already active, links 0-1 and 1-3 has already some channels allocated to them. In this case, new channels are chosen only for the newly active part, which is link 3-5. So, when any node in the network becomes active, then channels are allocated to the newly active part of the path.

6.1.2 Channel allocation is started from node nearest to the landline node

Channel allocation to the newly active part of the path is started from the node nearest to the landline node. So, in the topology given in Figure 6.2, when node 4 becomes active, then channel allocation for the path is started from node 0, as node 0 is the landline node. When node 5 becomes active, then channel allocation is started from node 3, as node 3 is nearest to the landline node, in the newly active part from node 5 to the landline node.

We use this approach, because it gives greater freedom for the selection of channel, at a node. We will illustrate it through an example. Consider again the topology 6.2. Let us say, node 4 is active, so links 0-1, 1-3 and 3-4 are active. If node 6 becomes active now, then channel allocation for links 3-5 and 5-6 has to be done. Let us say, we start the channel allocation from bottom i.e node 6. When we reaches node 5, then channel of link 3-5 is to be selected such that it should be different from the channel of links 1-3, 3-4 and 5-6. In comparison, if we start channel allocation from node 3, then at node 3, channel of link 3-5 is to be selected such that it is different from links 1-3 and 3-4. Thus in the latter case, there is more freedom in channel allocation. So we start allocation from the node nearest to the landline node.

6.1.3 Channel selection at a node

In this section, we will describe how the channel selection is done at any node. When selecting the channel for the new active link at a node, we assign a free channel to it, if a free channel is available. We will explain it through an example.

Consider the topology in Figure 6.2 (nodes 3 and 5 have separate radio for each of their links, all other nodes are working on a single radio). Suppose, node 4 becomes active. So channels are to be allocated to the links 0-1, 1-3, and 3-4. As explained earlier, channel allocation is started from the node nearest to the landline node. In this case, it is started from node 0. At node 0, all the three channels are available (remember, there are 3 independent channels available at 2.4Ghz band). So channel

1 is assigned to link 0-1. Now we reach at node 1. At node 1, link 1-0 is using channel 1 and node 1 is working on a single radio, so link 1-3 will work on channel 1. Now we reach at node 3. At node 3, link 3-1 is using channel 1, but other two channels are free. So channel 6 is assigned to link 3-4. If node 6 becomes active now, then channel allocation is done for links 3-5 and 5-6. Now channel allocation will start from node 3. At node 3, link 3-1 is using channel 1 and link 3-4 is using channel 6, so channel 11 is free and it is assigned to link 3-5 and so on.

Now we consider the case, when a free channel is not available. In this case, channel for the link is selected such that TCV (total contention value) of the network is minimum. This can be done by trying all the three possible channels for the link and calculating the TCV for each case. The channel for which the TCV is minimum, is allocated to the link. We will illustrate it through an example.

Consider the topology in Figure 6.3. Node 0 is the landline node. Node 1 is using single radio for it links 1-0 and 1-2 and node 5 is using single radio for all of it links. Node 3 has separate radio for each of it links (this kind of topology with some nodes using a single radio and some nodes with more than one radio is taken to show, that our DCA mechanism works for any general topology). Nodes 5 and 7 are active. The number written on the edge between the two nodes represents the channel used by the corresponding bidirectional link. Links 3-5 and 5-6 are working on the same channel because node 5 has a single radio (channels are allocated to the links using the method described in the above paragraph i.e free channel available at the node is allocated to the new active link).

Suppose, node 7 becomes active, then channel of the link 3-7 is to be selected. At node 3, no free channel is available. In this case, channel is assigned to link 3-7 such that TCV of the network is minimized. As already mentioned, all the channels are tried one after another and the TCV is determined for each case (to obtain TCV, nodes 4, 6, and 7 are taken, as they are the only active nodes). The TCV of the network for the three channels assigned to link 3-7 is given in Table 6.1. The TCV is minimum for channel 1 and 11, so either of them can be allocated to link 3-7.

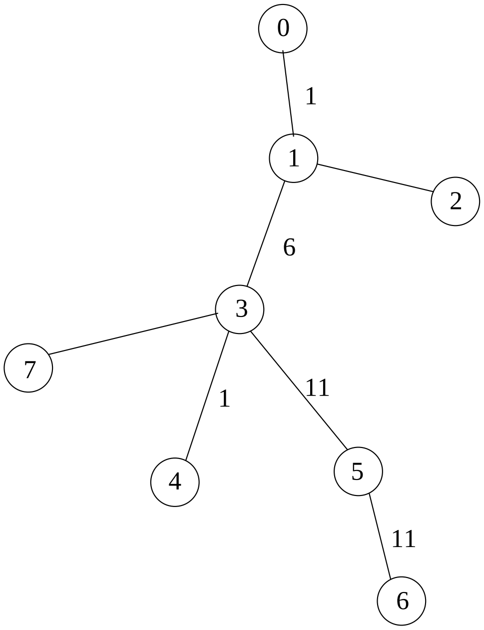


Figure 6.3: Topology with 8 nodes, node 5 and 7 are active

Channel	TCV
1	3
6	4
11	3

Table 6.1: TCV for different channels assigned.

6.1.4 Channel Shifting

The goal of DCA is not only to select the channels dynamically, but also to do it in a way, so that TCV of network is minimum.

To achieve this objective, a test is done at all the nodes present on the path from the node becoming active to the landline node. This test determines, whether TCV of network can be decreased by *channel shifting*. Channel shifting means shifting the channel of the link to a different channel. We will describe channel shifting through an example.

Consider the topology given in Figure 6.3. We have already found that channel 1 or channel 11 can be assigned to link 3-7, when node 7 becomes active. Suppose, channel 11 is assigned to link 3-7. The new topology (showing channel 11 allocated to link 3-7) is shown in Figure 6.4.

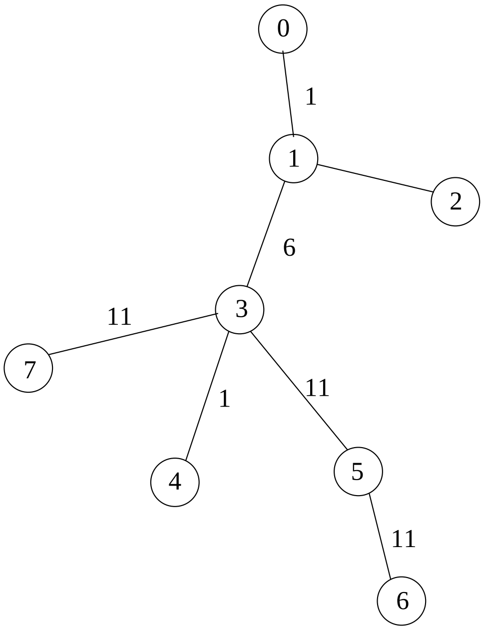


Figure 6.4: Topology with 8 nodes, node 5, 7 and 8 are active

Let us say, node 5 becomes active next. Now, channel allocation is first done for the newly active part. However, the path of node 5 to node 0 is already active, thus no channel allocation is done. As mentioned above, we do a test at each node on the path of node 5 to the landline node. First, this test is done at node 3, this test determines whether TCV can be decreased by channel shifting. Present TCV is 5. Suppose, we do channel shifting of the link 3-7. Its current channel is 11. The TCV obtained by shifting the channel of the link 3-7 to 6 and 1 is given in Table 6.2.

So by shifting channel of link 3-7 from 11 to 1, the TCV of the network can be decreased. So channel shifting is done for link 3-7. When such testing is completed at node 4, we move on to node 2 and so on till the landline node.

Channel	TCV
6	6
1	4

Table 6.2: TCV by shifting channel of link 4-8.

6.1.5 Overall Approach

The above subsections sums up our overall approach for DCA. When a node becomes active, then channels are allocated to the newly active part. Channel allocation is started from the node nearest to the landline node. Channel selection at a node is done to minimize the TCV of network. After channel allocation is done, a test is done at each node on the path of the given node to the landline node. This test determines whether the TCV can be decreased further by channel shifting. If it can be decreased, then we do channel shifting.

6.2 DCA Algorithm and Intuitive Proof

In this section, we will describe the pseudo code of the DCA algorithm and the intuitive proof to show that a network of minimum contention is obtained finally.

We know that when a node becomes active in a network, the following two steps are carried out:

- Channel allocation is done for the newly active part starting from the node nearest to the landline node.

- Channel shifting test is done at all the nodes present on the path of the node becoming active to the landline node.

The pseudo code of DCA algorithm is divided between the following three subsections. Each one will explain particular part of the whole algorithm. Subsection 6.2.4 will describe the intuitive proof of the overall algorithm.

6.2.1 The Distributed Protocol

The DCA algorithm is implemented by a distributed protocol (running at each node). Nodes exchange messages with each other according to this protocol. Nodes exchange messages using statically allocated channels. Once new channels are selected, communication is carried out using these new channels thereafter. The pseudo code of the distributed protocol is given in Figure 6.5.

According to this distributed protocol, a node can be in three different states.

- *Inactive state*: It means node is not sending any traffic to the landline node. Node may be forwarding traffic of some other nodes, but it is not generating or receiving any traffic of its own.
- *Active state*: It means node is active and is sending traffic to or receiving traffic from the landline node.
- *Becoming_Active*: It means node is going to become active. In this state, the node communicates according to the distributed protocol given in Figure 6.5, to allocate channels dynamically to the newly active part. Once the channels are allocated, the node shifts to the active state.

In the distributed protocol given in Figure 6.5, the following messages are sent by nodes.

- *Do_Channel_Selection*: When node state changes to the Becoming_Active state, it sends this message to the next hop on the path to the landline node. When any node X receives this message from node Y, then node X does channel selection for the link connecting it to node Y.
- *Channel_Selected*: When a node X receives the Do_Channel_Selection message from node Y, it selects the channel of the link connecting it to node Y. This selected channel is send to node Y through the Channel_Selected message.

We will now explain the pseudo code given in Figure 6.5. When any node needs to obtain service from the landline node, its state becomes 'Becoming_Active'. When

```
if (Node_State == Becoming_Active)
{
    if (!Active(landline_path))
        Send_msg(Do_Channel_Selection);
        /* Send the msg to next hop on the path to landline node */
}

if(Received(msg)) == Do_Channel_Selection)
{
    if(Active(landline_path))
    {
    /* Check whether the path to landline node is active or not.*/
        channel = Channel_Selection_Algorithm();
        // Channel selection algorithm is called.
        Send_msg(Channel_Selected, channel);
        /* Send selected channel to node from which
Do_Channel_Selection message was received. */
        Some_delay; Switch_Link_To_Given_Channel();
    }
else
    Send_msg(Do_Channel_Selection);
    /* If path to the landline node is not active, send
Do_Channel_Selection msg to next hop on the path to landline node. */
}

if(Received(msg) == Channel_Selected)
{
        Switch_Link_To_Given_Channel();
        if ( Node_State == Becoming_Active )
            exit;
        /* Check if this is the node becoming active, then algorithm
stops here */
        else
        {
            channel = Channel_Selection_Algorithm();
            Send_msg(Channel_Selected, channel);
        }
}
```

Figure 6.5: Pseudo Code for allocation of channels for inactive part

a node changes to this state and path to the landline node is currently inactive, it means that channel allocation has to be done for this current inactive link. So the node sends a Do_Channel_Selection message to the next hop on the path to the landline node. When a node receives a Do_Channel_Selection message, it checks whether the path to the landline node is active or not. If path to the landline node is active, it means channel allocation will start from this node, as it is the node nearest to the landline node on the inactive part. If path to landline node is currently inactive, the node sends a Do_Channel_Selection message to the next hop on the path to the landline node and so on.

When a node X receives Do_Channel_Selection message from node Y and the path to the landline node is currently active at node X, then node X will do channel selection for the link connecting it to node Y. A channel is selected for the link using the Channel_Selection_Algorithm (described in the next sub section). The selected channel is sent to node Y using a Channel_Selected message. After some delay, node X switches the channel of the link to the newly selected channel.

When a node receives a Channel_Selected message, it switches the channel of the link to the new channel received in this message. Now, if the state of this node is Becoming_Active, it means this node has started the channel allocation algorithm, so the algorithm stops here. Otherwise, this node selects the channel for the link connecting it to the node, from which it received the Do_Channel_Selection message. The channel of this link is selected using the Channel_Selection_Algorithm. This node will send the selected channel through Channel_Selected message and same process is repeated until the node in the state Becoming_Active is reached.

To summarize, the Do_Channel_Selection message is transferred until we reach at the node, after which the path to the landline node is active. At that node, the channel allocation will start. It will select the channel using the Channel_Selection_Algorithm and the selected channel is sent downwards through a Channel_Selected message. Now channels will be selected at each node, and a Channel_Selected message will be sent in a direction opposite to the original Do_Channel_Selection message, until the node with state 'Becoming_Active' is reached.

We will now explain the process through an example. Consider the topology given in Figure 6.2. Suppose, node 4 needs to obtain service from the landline node. It state changes to Becoming_Active, and sends a Do_Channel_Selection message to node 3. At node 3, the path to the landline node is currently inactive. So node 3 sends Do_Channel_Selection message to node 1 and similarly node 1 sends a Do_Channel_Selection message to node 0. Node 0 is the landline node. At node 0, the channel of the link 0-1 is selected using the channel_Selection_Algorithm. This channel is sent using a Channel_Selected message to node 1. After some delay, node 0 will switch the channel of the link 0-1 to the new selected channel. At node 1, when a Channel_Selected message is received, it will switch the channel of the link 0-1 to the new channel received. Node 1 is not in the state Becoming_Active, so it selects the channel for the link 1-3 and sends the selected channel through a Channel_Selected message to node 3. The same process is repeated at node 3, and node 5 is reached in the next step, where the algorithm stops.

6.2.2 Channel Selection Algorithm

The distributed protocol given in the above section defines the way in which nodes communicate and allocate channels dynamically to the newly active part. In this protocol, when a channel is to be selected for any link at the node, then Channel_Selection_Algorithm is called. We will now describe this algorithm.

The pseudo code of channel selection algorithm is given in Figure 6.6. We first find out if any free channel is available at the node. If any free channel is available, then that channel is allocated to the link, otherwise the procedure *Find_ Channel_ Minimum_ Contention* is called. This procedure allocates one channel after another to the new link, and finds the one for which the TCV of the network is minimum.

However, instead of trying all the three channels, it is enough to try just two channels. Channel assigned to the link between the node and its parent is not taken, because using this channel for the new link will always increase the contention as compared to taking the other channels.

We will first explain why this happens through an example. Consider the topology given in Figure 6.7. Node 0 is the landline node. A and B are the two networks

```
 if(Free_Channel_Available)
     return Free_Channel;
else
{
     channel = Find_Channel_Minimum_Contention();
     return channel;
}
```

Figure 6.6: Pseudo Code for Channel Selection Algorithm

having k1 and k2 nodes respectively. Let us say, k1 nodes of network A and k2 nodes of network B are active. The root node of A is connected to 1 with channel 6 and that of B with channel 11. Node 1 has a separate radio for each of its link.

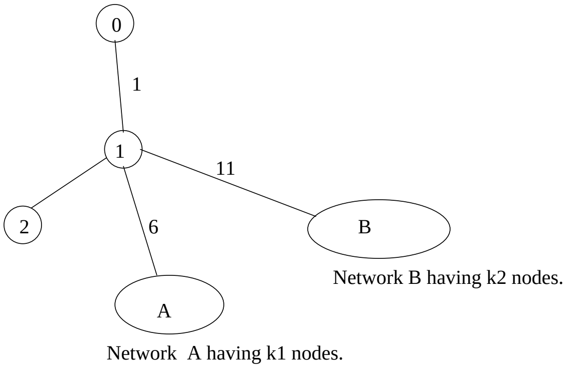


Figure 6.7: Channel is to be assigned to link 1-2

Suppose, node 2 now becomes active. Channel allocation will start from node 1. At node 1, channel selection algorithm given in Figure 6.6 is called. There is no free channel available at node 1, thus the channel which will keep the TCV minimum is selected. If we assign channel 1 to the link 1-2, TCV of network will increase by 1+k1+k2. This is because, CV (contention value) of node 2 becomes 1, as link 0-1 and 1-2 are working on channel 1 (so for node 2, contention value has one Csingle unit). Network A has k1 active nodes. The path of all the k1 nodes to the landline node is through link 0-1. Link 0-1 and 1-2 are working on same channel i.e 1. So link 1-2 will cause contention to link 0-1. As there is one link causing contention to one link (or one Csingle unit), so for all the k1 nodes, CV increases by one. The same is the case with all the k2 nodes present in the network B.

However, if either channel 6 or 11 is assigned to link 1-2, then TCV will increase by k1+1 or k2+1. Let us say, channel 6 is assigned. Path of node 2 to the landline node is 2-1 and 1-0. Link A-1 (link from root node of network A to 1) is causing contention to link 2-1 as they are working on channel 6. So for node 2, contention is one Csingle unit or 1.

Same is the case for all k1 nodes in network A. Link 2-1 will cause contention to link A-1 and CV of all the k1 nodes will increase by one. So, increase in CV of network A is k1. For k2 nodes in network B, path to landline node is B-1 and 1-0. However, neither 1-2 is causing contention to these two links nor A-1. This is because B-1 and 1-0 are working on different channel than that of 1-2 and A-1. So there is no increase in contention for k2 nodes. Thus, total increase in TCV is k1+1, if channel 6 is assigned to link 1-2.

Above example shows that assigning channel 1 increases contention of all nodes as compared to channel 6 and 11, which increase contention of some nodes. Thus assigning channel which is being used by the link between the node and its parent node (i.e link 1-0 in above case), will always increase the contention more than the other two channels. So this channel is not considered in Channel_Selection_Algorithm.

The generic proof of this is very simple and is explained as follows. We will term the link between the node X and its parent node (or link between node X and next hop node on the path to the landline node) as *landline link* (LL). All the nodes whose path to the landline node goes through node X will use link LL of node X. Consider the topology given in Figure 6.8. In this topology, nodes 1, 2, 3, and 4 are all active and will use link LL of node X. If at node X, there is one other link l1 working on same channel as the channel of LL, then all the nodes getting service through node X will face contention at node X (because channel of l1 and LL is same, so for each node getting service through node X, increase in contention is one Csingle unit). Thus if we assign channel of LL to new active link at node X, it will increase the contention of all the nodes getting service through it. In topology shown in Figure 6.8, contention of nodes 1, 2, 3, and 4 will increase if new active link use the same channel as that of LL.

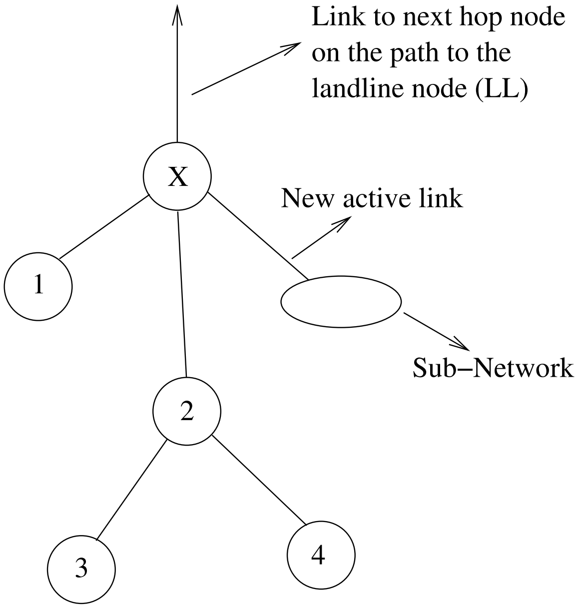


Figure 6.8: Topology showing various nodes getting service from landline node through node X

In comparison, if we use any other channel C for the new active link, then it will increase the contention of only those nodes, which are connected to node X with a link working on channel C. In the given topology, suppose channel of links X-1 and X-2 are different. So, if channel of new active link is same as that of link X-1, then it will only increase contention of node 1. Nodes 2, 3, and 4 are not effected. Same is the case if new active link uses channel of link X-2. So if any channel other than that of link LL is assigned to new active link, then it will increase contention of particular fraction of nodes getting service through node X.

6.2.3 Channel Shifting Algorithm

We have already explained that once channels are allocated dynamically to the newly active part, then we do a test at each node to find out if TCV can be reduced further by channel shifting. To determine if TCV can be reduced, test has to be done for all the links at the node. However in channel shifting algorithm (CSA), we avoid doing testing of some links for which TCV can not be decreased by shifting the channel. Before describing pseudo code of CSA, we will describe methodology used by CSA to apply channel shifting at any node. The methodology is described as follows:

- *Determine CV at node*: We will first describe what is CV at node. CV at node is contention faced by all the active nodes in the network at this node.

  CV at node is determined as follows. We have explained that we consider only two channels (channel used by LL is not considered). Suppose these two channel are c1 and c2. We describe CV at any node X as as (CV[c1] + CV[c2]), where CV[c1] is contention faced by all the active nodes at node X due to channel c1 and CV[c2] is contention due to channel c2.

  We will now show how CV at node is determined through example. Consider the topology given in Figure 6.7 (k1 nodes of network A and k2 nodes of network B are active). We will determine CV at node 1. In this case, c1 and c2 are 6 and 11. Only link 1-A is working on channel 6 at node 1, so there is no contention due to channel 6 at node 1. Thus CV[6] is zero. Same is the case with CV[11]. So CV at node 1 is ((CV[6]=0) + (CV[11]=0)).

- *Determine channel responsible for increase in CV at node*: We apply channel shifting, when a node becomes active or inactive in the network. To apply channel shifting at any node, we determine the channel responsible for increase in CV at node. We will explain it through an example as follows.

  Consider the topology given in Figure 6.9. Network A and B has k1 and k2 nodes respectively and k1 is greater than k2. In this topology, suppose k2 nodes in network A, and k2 nodes in network B, and node 2 are active. At node 1, CV due to channel 6 is 1+k2 and due to channel 11 is 0.

  Suppose another node now becomes active in network A. So we will apply channel shifting at nodes. Consider the case of channel shifting at node 1. To apply CSA, we determine channel responsible for increase in CV at node 1. Say node X in network A has become active. Node X's path at node 1 is

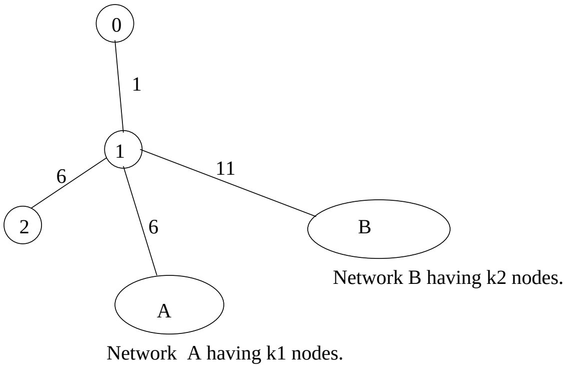


Figure 6.9: Channel shifting applied at node 1.

1-A and 0-1. Link 1-A at node 1 is facing contention from link 1-2 (they are working on same channel i.e 6). So X's CV at node 1 is one Csingle unit or 1. At node 1, CV due to channel 6 and 11 now is 2+k2 and 0 respectively. The increase in CV at node 1 is due to channel 6. In this way, we can easily determine channel responsible for increase in contention. The use of finding out channel responsible for increase in contention at a node is given in next step.

- *Find the links to test for CSA*: In this step, we find the links which are tested for CSA. Links which are selected for testing are working on the channel, which is responsible for increase in contention at the node.

  In the topology given in Figure 6.9, when node X becomes active in network A, contention due to channel 6 is increased at node 1. So for CSA, we consider links at node 1 which are working on channel 6. Links working on channel 6 are 1-A and 1-2.

- *Apply CSA*: In this final step, we apply CSA. We will now explain how CSA is applied with the above example. In the topology shown in Figure 6.9, links 1-A and 1-2 are selected for CSA. In CSA, we change the channel of the link to the other channel and find out the new CV at the node. If there is a decrease in the CV, then channel shifting is done.

```
/* Two channels c1 and c2 are considered, channel used by link at the node
with which it is connected to parent node is not taken. */
/* S1 and S2 are set of links at node working on channel c1 and c2 */
if (contention increased at node due to channel c1)
{
    if (link = Shift_Channel(S1,S2))
    /* Shift channel of links in set s1 to c2 and find if there is decrease in
    contention, if it is the case it will return link whose channel should be shifted.
    */
        Assign_Channel(link,c2);
        // assign channel c2 to this link
}
else
{
    if (link = Shift_Channel(S2,S1))
        Assign_Channel(link,c1);
}
```

Figure 6.10: Pseudo Code for Channel Shifting Algorithm

In this case, we will consider link 1-A first for CSA. Channel of link 1-A is changed to 11. CV at node 1 after channel shifting is ((CV[6]=0) + (CV[11]=2k2+1)). Initially CV at node was ((CV[6]=k2+2) + (CV[11]=0)). So CV has increased. Now we consider link 1-2. Its channel is changed to 11. CV at node 1 after channel shifting is ((CV[6]=0) + (CV[11]=k2+1)). Hence CV at node 1 has now decreased, so we apply channel shifting for link 1-2.

To summarize the above methodology, to apply CSA at a node, we find out the channel responsible for the increase in contention. Links working on that channel are then tested for channel shifting.

CSA is also applied when any node becomes inactive. In this case, the channel C due to which contention is decreased is found. Links which are not working on this channel C are then tested for channel shifting. The pseudo code for the CSA is given in Figure 6.10.

The pseudo code given in 6.10 shift the channel of the link at the node, if contention is decreased by shifting. Two channels c1 and c2 are considered at the node, channel used by LL is not taken as explained above. Sets S1 and S2 correspond to the links working on the channel c1 and c2 at the node. If contention increases due to channel c1 then testing is done by shifting channel of links in S1 to c2 and vice versa. When channel of one link is shifted it also results in some rearrangement.

Consider the topology given in Figure 6.11. In this topology, k1 nodes of network A, k2 nodes of network B, and nodes 2, 3, 4 are active.

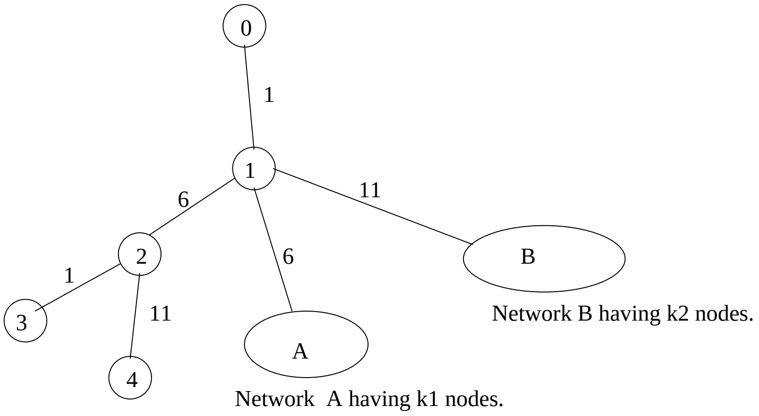


Figure 6.11: Channel rearrangement for subtree rooted at node 2.

In this topology, when channel of link 1-2 is shifted to 11, it will result in rearrangement of the tree whose root is node 2. In this case, link 2-4 is shifted to 6. In this way, contention at node 1 is decreased because of shifting of the channel of link 1-2 and there is no effect any where else due to rearrangement. Channel shifting is applied at all the nodes from the node becoming active to the landline node. If channel shifting take place at any node, then rearrangement of that sub tree is also done. Channel shifting is also applied when a node becomes inactive. In that case, CSA runs at each node from the node becoming inactive to the landline node.

6.2.4 Intuitive proof

In this Section, we are explaining the intuition behind the proof that the network generated using DCA will have minimum contention.

We will first explain that if the network has maximum of three links, then DCA will generate network of minimum contention, then we will move to general network having nodes with any number of links.

We know that channel selection algorithm allocates free channel available at the node to the new active link. The topology of network here is tree topology in which each node has only one path to the landline node. So in a network with nodes having maximum of three links, even if all the links at any node become active then the three available channels can be allocated to them. Thus all the links at the same node have different channels and contention of network is minimum. If we consider a network in which every node has a separate radio for each of its link, then the contention of network will be zero, as no two links at the same node are working on the same channel. If some nodes are using a single radio for their links, then contention will be minimum, because at each node, links working on different radios are using different channels.

We will now consider a network in which nodes can have any number of links. In this case, more than three links at a node can be active. When no free channel is available at a node, then channel selection algorithm allocates channel to the link such that TCV of the network is minimum. This is the best way in which allocation of channels to currently inactive part, which is going to become active, can be done. Consider the topology given in Figure 6.12. Node 0 is the landline node. Some nodes in the network A, B and C are active, so links 0-A, 1-2, 1-C and 1-B are active(A, B and C are taken as root node of network A, B and C).

When node 3 becomes active, then the best possible way to allocate channels to inactive part(links 1-2 and 2-3) is to assign channels which will minimize the TCV of the network. Same thing is done by channel allocation algorithm which will assign all possible channels to link 1-2 and select the one for which contention is minimum.

After allocating channels to inactive part, a global analysis of topology is done to determine if contention can be reduced further. This is done by channel shifting

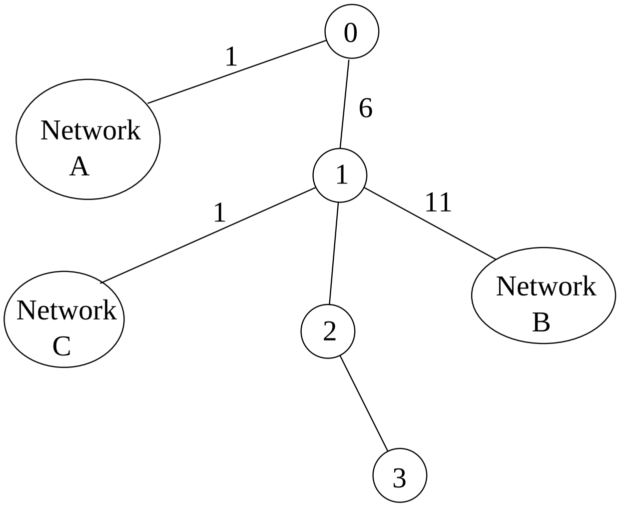


Figure 6.12: Some nodes in network A, B and C are active.

algorithm.

When any node becomes active, then channels are selected for the newly active part which will keep contention minimum. Now the contention of the network has increased, as one more node is active. The contention of node X which has become active, is because in its path to the landline node, some links are working on same channel and are adjacent. These nodes at which some links are working on same channel can be responsible for causing contention to traffic of node X (which has become active). These nodes are some intermediate nodes on the path of node X to the landline node. So, when a node becomes active, then its traffic faces contention at some intermediate nodes on its path to the landline node and this increases contention at those nodes also. So in a global analysis of topology, only these nodes (node on the path of given node to the landline node) are considered, as contention has increased only at these nodes. The channel shifting algorithm is applied at these nodes to find out if contention can be decreased further.

When we apply channel shifting, we consider each possible case of shifting the channel to find out if contention can be decreased. Thus global analysis of network is done with each node becoming active or inactive to minimize the contention. This global analysis includes all the nodes at which contention has changed (increased or decreased corresponding to any node becoming active or inactive). Thus all the nodes which are effected are taken in to account.

In this way using DCA algorithm, contention of network containing active nodes is minimized. Thus the throughput of the network is maximized. The intuition behind our proof is that the we have considered all the cases in which contention can be decreased, there is no way left which can decrease the contention further.

Chapter 7

Conclusions and Future Work

In this report we have proposed a Radio Placement Algorithm (RPA) and the Dynamic Channel Allocation (DCA) scheme. Both of these will find use in large area community networks, in which nodes are using directional antennas to establish links with each other. In such networks, RPA addresses the need of enhancing the capacity of network by adding radios. It finds out the best position for adding the new radios along with the channel allocation for the network. RPA finds out the position for the given new radios in linear time and thus is better than a naive but optimal exhaustive scheme which is combinatorial. This report shows that the throughput improvement achieved by RPA compares well with that of the exhaustive search scheme. Results are shown for adding single, two, three, four radios to some topologies.

However while finding out position of a single radio in the network, RPA gives equal importance to all the nodes. This may not represent an exact picture of real network in which some nodes have more up-time or more demand than others. Future work in RPA is to use information from network like node up time, bandwidth used by nodes during their up-time and utilize it in finding out better position for placement of a new radio.

DCA in a network keeps the throughput maximum for active nodes by keeping the contention minimum. Every time a node becomes active or inactive, rearrangement of the channels of some links are done to decrease the contention of the network.

It not only utilizes all the available channels but allocate them in such a way that network contention is minimized. DCA shifts the channel of the link in between the ongoing communication. So proper synchronization is required between the two nodes, when they shift the channel of the link between them.

We determined the decrease in throughput by implementing this scheme over one hop. Two nodes fitted with D-link PCMCIA 802.11b cards were used for the operation. Modification was done in HostAP driver to change the channel of the link after some n (for over experiment, we have taken n as 50) number of packets are transferred. Effect of change in channel of the link on ongoing communication is determined for both UDP and TCP connection. Fall in amount of throughput is about 3Mbps or 60% (for both UDP and TCP traffic) during the particular second in which channel was shifted. After that connection works normally. This fall in throughput is very high, considering that around 100ms of time is wasted in synchronizing the two nodes, for shifting the channel of the link between them. We have not tested different methods of changing the channel. One possible method is to make the nodes work in Pseudo Ad-hoc mode (supported by the HostAP driver) and then change the channel.

The advantage of Dynamic Channel Allocation can be obtained only if the packet loss can be decreased during channel shifting. So, future work in this direction is to test this scheme over multiple hops and to do better synchronization between two nodes, when they shift the channel, so that packet loss can be decreased.

Bibliography

[1] `http://ofcn.org/networks/By_State.txt.html`. List of Community networks.

[2] `www.djurslands.net`. Large Area Community Network.

[3] `http://pdos.csail.mit.edu/roofnet/doku.php`. MIT Roofnet.

[4] `www.wirelessleiden.nl`. Community network in Netherlands.

[5] `http://www.dekalbnet.org/`. DeKalb Community Network.

[6] `www.iitk.ac.in/mladgp`. Digital Gangetic Plains.

[7] `http://www.atlantafreenet.org/home.php`. AtlantaFreeNet.

[8] `http://www.seattlewireless.net/`. Seattle Wireless.

[9] `http://www.austinwireless.net/`. Austin Wireless Community Network.

[10] `http://www.bcwireless.net/`. BC Wireless network for information sharing.

[11] `http://www.aacis.net/`. Community network established by Non-profit Organization.

[12] `www.hyperlinktech.com/`. Cost of Antenna.

[13] A. Muir and J. J. Garcia-Luna-Aceves *A Channel Access Protocol for Multihop Wireless Network with Multiple Channels.* In *IEEE ICC, 1998.*

[14] Asis Nasipuri and Samir R. Das *A Multichannel CSMA MAC Protocol for Mobile Multihop Networks.* In *IEEE WCNC, 1999.*

[15] `http://www.radiolabs.com/products/antennas/accessories/2-way-splitter.php`. Cost of 2-Way splitter for 2.4Ghz Band.

[16] `http://www.jawug.za.net/`. Large area community network established by non-profit group.

[17] Ashish Raniwala, Kartik Gopalan and Tzi-cker Chiueh *Centralized Channel Assignment and Routing Algorithms for Multi-Channel Wireless Mesh Networks.* In *SIGMOBILE Mobile Computing and Communications Review, 2004.*

[18] `http://www.streakwave.com/`. Cost of 802.11b 2.4Ghz radio.

[19] Venkat Rao Chimata *Implementation and Performance Issues of VoIP in Long Distance 802.11b Networks.* In *Master Thesis under the supervision of Dr. Bhaskaran Raman, IIT Kanpur, June 2005*

[20] `www.cse.iitk.ac.in/~bhaskar/tens/`. The Enhanced Network Simulator.

[21] *Antennat Tutorial by AEROCOMM.*

[22] Ashwini Kumar, Sabyasachi Roy *Realistic Support for IEEE 802.11b MAC in NS.* In *B. Tech. Project Report, 2004, SupervisorDr. Bhaskaran Raman*

[23] Bhaskaran Raman, Kameswari Chebrolu. *Design and Evaluation of a new MAC Protocol for Long-Distance 802.11 Mesh Networks.* In *11th Annual International Conference on Mobile Computing and Networking(MOBICOM), Aug/Sep 2005, Cologne, Germany.*

[24] Bhaskaran Raman, Kameswari Chebrolu. *Revisiting MAC Design for an 802.11-based Mesh Network.* In *Third Workshop on Hot Topics in Networks(HotNets-III), 15-16 Nov 2004, San Diego, CA, USA.*