Resource Allocation and Throughput Analysis for Multi-radio Multi-channel Networks

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In IEEE 802.11, multiple orthogonal channels have long been available for use. In wireless mesh networks (WMNs), one base station now can afford to have multiple radio interfaces. This forms the multi-channel multi-interface (radio) WMNs. This kind of network is very useful in the arena of next-generation wireless communications. It can provide users with both higher throughput and more flexibility.

In this thesis, we investigate throughput relations in a wireless mesh network. We derive an upper bound for the maximum throughput of an m-radio n-channel network in terms of the maximum throughput of a 1-radio 1-channel network without network coding. In addition, we show that with network coding, we can further increase the throughput of the multi-radio multi-channel network. Finally, we investigate some possible methods to reduce the interfaces used at each base station without affecting the maximum throughput.

摘要

在 IEEE 802.11 協議中，多個正交信道已經使用了很長時間。在無線網狀網絡中 (WMNs), 一個基站可以擁有多個通信接口。這樣就形成了多接口，多信道無線網狀網絡。這種網絡在下一代無線通信中非常有用。它可以提供給用戶更高的吞吐量和更多的靈活性。

在這篇論文裏，我們研究無線網狀網絡中吞吐量的關係。在一個沒有使用網絡編碼的網絡中，依據 1 接口 1 信道網絡的最大吞吐量，我們可以得出一個 m 接口 n 信道網絡的最大吞吐量的上限。與此同時，我們用一個例子表明了使用網絡編碼可以提高多接口多信道網絡的吞吐量。最後，在不降低最大吞吐量的前提下，我們研究了一個方法來減少每一個基站使用接口的數量。

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Chapter 1

Introduction

Summary

This chapter aims to give a brief overview of the development of the wireless communications and some recent development.

In today's information age, access to information has become essential regardless of time and location. Fulfilling this need entails the use of technologies that do not restrict users to specific locations. In this perspective, wireless networking is transforming this need for ubiquitous information access into a reality. Wireless networks enable us to connect devices without wires, which are not only disruptive but also very costly. Not surprisingly, we see wireless-capable devices becoming increasingly used in our daily lives. For example, mobile phones, text-messaging devices like Blackberry, PDAs, video game devices such as Playstation Portable and NDS, and laptops are essential tools for many of us. The increasing popularity of wireless networking is confirmed by the soaring sales of related products. As a result of the perceived benefits and the resulting high demand, there is a great deal of research work under way in the area to meet ever-increasing expectations from users.

Present wireless services include voice calls, text messages, email access, small-file exchanges, *etc.* Services that can be provided are presently constrained by the capacity of the underlying wireless networks. The vision of pervasive computing suggests many more services, such as permanent connection, video streaming, *etc.* It is anticipated that we will become more dependent on wireless connectivity, and more so with the increasing use of embedded devices. The research community is endeavouring to improving wireless networks in order to meet these expectations. Motivated by the various benefits of wireless networks, the research community has explored many avenues to address nemerous challenges in the area. While some researchers are working at improving the physical layer, others are exploring enhancements at higher layers. Even though a lot of progress has been made, researchers are still striving to make wireless networks a viable alternative to their wired-line counterparts.

The IEEE 802.11 has become the most popular standard for communication in a wireless local area network. Since the 802.11 standard was specified, 802.11-based products have seen a tremendous growth in sales. Most of the present deployments of 802.11-based wireless networks consist of coverage at fixed locations that are supported by wired-line backbones. Such setups are called infrastructure-based wireless networks. The required infrastructure necessitates a significant initial investment and tends to be intrusive. Large deployments of such networks are currently restricted to business intranets or public access networks, many of which are funded for marketing purposes.

In the past few years, the idea of infrastructure-less networks has been much publicized, mostly driven by applications in the military. These instantaneous mobile networks are called ad hoc networks. For example, during a battle, soldiers in range of each other can form, on the fly, a temporary network. Much research has gone into ad hoc networks, as they present many challenges because of the lack of a stable core and their highly-dynamic nature. Ad hoc networks, as deployed and proposed today, typically employ a single radio channel for communication. Due to the shared nature of the wireless channel, the performance of such networks is poor. Ad hoc networking is also plagued with other problems that have hindered its wildspread adoption. Nevertheless, the various advantages of ad hoc networks have motivated to look for alternatives that provide similar benefits, but that do not suffer from some of their constraints.

1.1 Motivation

At present, many real-life deployments of purely wireless networks are based on ad hoc networking, which does not require any pre-existing infrastructure. However, such networks not only present capabilities that are not always needed, but also suffer from various shortcomings. Ad hoc networks employ a single radio channel, and thus allocate this shared resource among competing devices. Such a share may be too small for many applications. Ad hoc networks also need either a practical business model or a reward mechanism in order to become viable and emerge as a useful technology.

Ad hoc networks based on the 802.11 standard mostly utilize a single shared channel. As such, the bandwidth is divided between the nodes trying to communicate. The throughput per node decreases as a function of the active node density in a particular area. Gupta and Kumar [1] show that per-user capacity is an inverse function of the square-root of the number of users, assuming that nodes are identical and are optimally located. The fundamental issue here relates to physical limitations of the wireless channel. One way to circumvent such limitations is to use more than one independent wireless channel. For example, when 802.11 is used with Direct Sequence Spread Spectrum

(DSSS) at the physical layer, there exist three non-overlapping channels. Instead of using only one channel, if we leveraged all of the available resources, we could achieve higher performance.

The proposal of using multiple radio interfaces on a node can address important weaknesses of ad hoc networks. Such nodes can either be used in an ad hoc fashion such as in a community wireless network, or they can be employed in an infrastructure-like setup to meet requirements of a temporary wireless network, which is exactly one of the basic structures of wireless mesh networks.

Despite the lack of knowledge about the performance of multi-channel multi-hop wireless networks, some products are already available. Pure wireless networks in mesh-like topology have begun to be deployed, especially in community wireless networks and are being proposed as a cost-effective solution for Metropolitan Area Networks (MAN). The related products have preceded a thorough study of the potential benefits of using multi-channel solutions.

Since the advent of network coding, the traditional technique for multicasting in a network has been challenged. People realize that if coding is applied at the nodes in a network, rather than routing alone, the network capacity caan be increased.

Application of network coding in wired network has been a hot research topic and some promising results are already available. Random network coding has been implemented in the new version of Microsoft Windows operating systems. In addition, some researchers have already begun to investigate the possibility of applying network coding into wireless networks.

Since multi-radio multi-channel wireless mesh networks (WMNs) can address the weaknesses of ad hoc networks and network coding can help to improve the network capacity, we investigate the throughput relations in WMNs and the effect of applying network coding into multi-radio multi-channel WMNs.

1.2 Contributions

This thesis provides the following contributions towards a better understanding of multi-radio multi-channel wireless networks:

1. We prove that the throughtput of the m-radio n-channel wireless mesh network is bounded by n times the throughput of 1-radio 1-channel wireless mesh network.

2. We show that applying network coding to multi-radio multi-channel wireless mesh networks can improve the throughput.

3. We show that there is no need to place any equal amount of radio interfaces at each base station to achieve the maximum throughput.

4. We propose an algorithm to reduce the total number of radio interfaces used at each base station while trying to maintain the maximum throughput in a grid topology and extend the algorithm to more general topologies.

1.3 Thesis Scope

This thesis is organized as follows: In Chapter 2 we give the overview of wireless mesh networks and network coding. In Chapter 3 we analyze the throughput relation in wireless mesh network with and without network coding. In Chapter 4 we propose an algorithm to reduce the radio interfaces used in the wireless mesh network. In Chapter 5 we conclude our work and comment on some future work.

□ **End of chapter.**

Chapter 2

Background Study

Summary

In this chapter we review the basics of wireless mesh networks with an emphasis on the usage of multiple radios and multiple channels. We also briefly describe the basics of network coding.

2.1 Wireless Mesh Networks

2.1.1 Overview of Wireless Mesh Networks

As various wireless networks evolve into the next generation to provide better services, a key technology, wireless mesh networks (WMNs) [3], [4], [5], has emerged recently. In WMNs, nodes are comprised of mesh routers and mesh clients. Each node operates not only as a host but also as a router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations. A WMN is dynamically self-organized and self-configured, with the nodes in the network automatically establishing and maintaining mesh connectivity among themselves (creating, in effect, an ad hoc network). This feature brings many advantages to WMNs such as low up-front cost, easy network maintenance, robustness, and reliable service coverage.

WMNs consist of two types of nodes: mesh routers and mesh clients. Other than the routing capability for gateway/repeater functions as in a conventional wireless router, a wireless mesh router contains additional routing functions to support mesh networking. To further improve the flexibility of mesh networking, a mesh router is usually equipped with multiple wireless interfaces built on either the same or different wireless access technologies. Mesh clients also have necessary functions for mesh networking, and thus, can also work as a router. However, gateway or bridge functions do not exist in these nodes. In addition, mesh clients usually have only one wireless interface. Mesh routers usually have minimal mobility, while mesh clients can be stationary or mobile nodes. Mesh routers usually do not have strict constraints on power consumption. However, mesh clients may require power efficient protocols.

The architecture of WMNs can be classified into three main groups based on the functionality of the nodes:

- Infrastructure/Backbone WMNs. This type of WMNs includes mesh routers forming an infrastructure for clients that connect to them. The mesh routers form a mesh of self-configuring, self-healing links among themselves. With gateway functionality, mesh routers can be connected to the Internet. This approach, also referred to as infrastructure meshing, provides backbone for conventional clients and enables integration of WMNs with existing wireless networks, through gateway/bridge functionalities in mesh routers. Infrastructure/Backbone WMNs are the most commonly used type.

- Client WMNs. Client meshing provides peer-to-peer networks among client devices. In this type of architecture, client nodes constitute the actual network to perform routing and configuration functionalities as well as providing enduser applications to customers. Hence, a mesh router is not required for these types of networks. In Client WMNs, a packet destined to a node in the network hops through multiple nodes to reach the destination. Client WMNs are usually formed using one type of radios on devices.

- Hybrid WMNs. This architecture is the combination of infrastructure and client meshing. Mesh clients can access the network through mesh routers as well as directly meshing with other mesh clients. While the infrastructure provides connectivity to other networks such as the Internet, Wi-Fi, WiMAX, cellular, and sensor networks; the routing capabilities of clients provide improved connectivity and coverage inside the WMN.

Compared with conventional ad hoc networks, the hybrid structure has the following features:

- Wireless infrastructure/backbone. The wireless backbone provides large coverage, connectivity, and robustness in the wireless domain. However, the connectivity in ad hoc networks depends on the individual contributions of end-users which may not be reliable.

- Multiple radios. As discussed before, mesh routers can be equipped with multiple radios to perform routing and access functionalities. This enables separation of two main types of traffic in the wireless domain. While routing and configuration are performed between mesh routers, the access to the network by end users can be carried out on a different radio. This significantly improves the capacity of the network. On the other hand, in ad hoc networks, these functionalities are performed in the same channel, and as a result, the performance decreases.

- Mobility. Since ad hoc networks provide routing using the end-user devices, the network topology and connectivity depend on the movement of users. This imposes additional challenges on routing protocols as well as on network configuration and deployment.

2.1.2 Challenges of Wireless Mesh Networks

Although the WMN techonology is promising, there are still some research issues in this area.

A. Data Link Layer

At the data link layer, the design of the MAC protocol is the most likely challenge in WMN. An interesting problem in WMNs (and ad hoc networks in general) is how to efficiently utilize multiple physical channels (if supported by the physical layer).

There are many possible channel assignments for a WMN with $C = 3$ channels and $M = 1$ transceivers in each router. Which of the possible assignments maximizes the capacity of the network depends on the offered load at each node in the network. Potentially, there can be a very large difference in network capacity among the possible channel assignments [6]. The problem is further complicated by an increase in the number of transceivers $M > 1$.

With a MAC capable of changing the channels, and multiple transceiver nodes, it is possible to transmit and receive simultaneously or to use more than one channel for one transmission. This freedom can lead to an increase of the overall performance at the expense of a more complex MAC layer and a costlier physical layer [7], [8].

A multi-channel MAC can be implemented on several different hardware platforms, which also impacts the design of the MAC. A multi-channel MAC may belong to one of the followingn categories:

- Multi-channel single-transceiver MAC. If the cost and compatibility are the concern, one transceiver on a radio is a preferred hardware platform. Since only one transceiver is available, only one channel is active at a time in each network node. However, different nodes may operate on different channels simultaneously in order to improve system capacity.

- Multi-channel multi-transceiver MAC. In this scenario, a radio includes multiple parallel RF front-end chips and baseband processing modules to support several simultaneous channels. On top of the physical layer, there is only one MAC layer to coordinate the functions of multiple channels.

- Multi-radio MAC. In this scenario, a network node has multiple radios each with its own MAC and physical layers. Communications in these radios are totally independent.

B. Network Layer

The main function of the networking layer is to transfer the packets from the source to the destination over multiple hops. The routing protocol is an important factor in any network, but in WMNs it can mean the difference between failure and success. The entire performance of a WMN is affected by its routing protocol. Loading balancing [9], [10], avoiding congested routes, and taking into account interference patterns existent in a WMN are just some of the factors that directly affect the performance of WMNs.

A considerable number of routing protocols were developed for MANETs [11], [12]. Most of these protocols work well for MANETs. However, in MANETs, the traffic is assumed to be flowing between arbitrary pairs of nodes while the mobility of MANET nodes is usually similar, in WMNs, the nodes can be distinctly classified as either mobile or stationary. It is thus likely that for WMNs a custom routing protocol can significantly outperform general MANET protocols [13].

2.1.3 Capacity Analysis of Wireless Mesh Networks

Up to now, much research has been carried out to study the capacity of WMNs [14], [15], [16], [17], [18], [19].

In [14], it tackled the problem of determining the exact capacity of a 1-radio 1-channel WMN. The key concept introduced to enable the calculation is the bottleneck collision domain that is defined as the geographical area of the network that bounds from above the amount of data that can be transmitted in the network. They showed that for WMNs the throughput of each node decreases as $O(\frac{1}{n})$, where n is the total number of nodes in the network. In particular, for a given topology, they provided exact upper-bounds on the throughput of any node.

In [15], it addressed the channel assignment problem for multi-channel multi-interface (radio) wireless mesh networks. They focused on static wireless mesh networks where multiple nonoverlapping channels are available for each wireless interface. The objective is to find a fixed channel assignment which maximizes the number of bidirectional links that can be activated simultaneously, subject to interference constraints. Two mixed integer linear programming models for solving the fixed channel assignment problem with multiple radios were proposed.

In [16], it investigated the achievable performance gain, by jointly optimizing routing and scheduling in a multi-radio multichannel multi-hop network. They formulated the optimization under a deterministic model, and tried to minimize overall system activation time in use to satisfy given end-to-end traffic demands subjected to the multi-access interference among neighboring transmissions and the radio interface constraint at each node. The exact solution to such an optimization problem is prohibitively complex due to the combinatorial complexity, particularly with the deployment of multi-radio and multi-channel, so they developed a column generation based approach to solve this problem, which decomposes the original problem into subproblems and solves them iteratively.

In [17], they considered the channel assignment problem in a multi-radio wireless mesh network that involves assigning channels to radio interfaces for achieving efficient channel utilization. They proposed the notion of a traffic-independent base channel assignment to ease coordination and enable dynamic, efficient and flexible channel assignment. They presented a novel formulation of the base channel assignment as a topology control problem, and showed that the resulting optimization problem is NP-complete. A new greedy heuristic channel assignment algorithm for finding connected, low interference topologies by utilizing multiple channels was proposed.

In [18], it reexamined the general requirements of the problem of how to assign wireless channels to interfaces to avoid collisions extremely while the network keeps a good topology for multi-radio wireless mesh networks. They proposed an algorithm to solve it effectively and efficiently. They regarded it as a particular edge coloring problem, and propose a strategy of two steps: edge grouping and coloring edge groups. A heuristic algorithm was proposed to solve the coloring problem for edge groups. And, in order to obtain a good edge grouping, they combined topology simplification techniques with edge grouping so as to make this problem simplified.

In [19], the paper presented an interference-aware channel assignment algorithm and protocol for multi-radio wireless mesh networks that address the interference problem. The proposed solution intelligently assigned channels to radios to minimize interference within the mesh network and between the mesh network and co-located wireless networks. It utilized a novel interference estimation technique implemented at each mesh router. An extension to the conflict graph model, the multi-radio conflict graph, was used to model the interference between the routers. They reported on an extensive evaluation via simulations. In a sample multi-radio scenario, the solution yields performance gains in excess of 40% compared to a static assignment of channels.

However, there are still some problems need solving. First, in [14], a theoretical bound is given in a 1-radio 1-channel WMN. They didn't address the bound in a m-radio n-channel WMN. Second, in [15], [16], [17], [18], [19], capacity analysis was conducted by some heuristic algorithms in multi-radio multi-channel WMNs and no theoretical results were given.

This thesis handles these two problems in some way. We derive an theoretical upper bound for the capacity of the m-radio n-channel WMN in terms of the capacity of the 1-radio 1-channel WMN. Thus, by using [14], we can get the upper bound for the capacity of any m-radio n-channel WMN, simplifying the channel assignment process.

2.2 Network Coding

2.2.1 Overview of Network Coding

In analog telephony, when a point-to-point call is established, there is a physical connection between the two parties. When a conference call is established, there is a physical connection among all the parties involved. In computer communication (which is digital), we used to think that for multicasting, there must be a logical connection among all the parties involved such that raw information bits are sent to the destinations via such a connection. The notion of a logical connection in computer communication is analogous to the notion of a physical connection in analog telephony. As a result, multicasting in a computer network is traditionally being thought of as replicating bits at the nodes, so that each sink eventually receive a copy of all the bits. In existing computer networks, each node functions as a switch in the sense that it either relays information from an input link to and sends it to a certain set of output links.

However, the traditional technique for multicasting in a computer network in general is not optimal. Rather, we should think of information as being "diffused" through the network from the source to the sinks by means of network coding. In classical information theory for point-to-point communication, we can think of information as a "fluid" or some kind of physical entity. For network information flow with one source, this analogy continues to hold when there is one sink, because information flow conserves at all the intermediate nodes in an optimal scheme. However, the analogy fails for multicasting because information needs to be replicated or coded at the nodes. The problem becomes more complicated when there are more than one source. From the information-theoretic point of view, there is no reason to restrict the function of a node to that of a switch. Rather, a node can function as an encoder in the sense that it receives information from all the input links, encoders, and sends information to all the output links, encodes, and sends information to all the output links. From this point of view, a switch is a special case of an encoder.

Yeung and Zhang [20] and Ahlswede et al. [21] established that if coding is applied at the nodes in a network, rather than routing alone, the network capacity can be increased. The advantage of network coding [22] over routing is explained by means of a simple example. We will use a finite directed graph to represent a point-to-point communication network. A node in the network corresponds to a vertex in the graph, while a communication channel in the network corresponds to an edge in the graph. We will not distinguish a node from a vertex, nor will we distinguish a channel from an edge. In the graph, a node is represented by a square. Each edge carries one information symbol taken from some finite alphabet that can be transmitted over the channel per unit time. For simplicity, we assume every transmission on a channel incurs no delay. In this chapter, we assume that the information symbol is binary. When there is only one edge from node A to node B, we denote the edge by (A, B). The simple example is the well-known Butterfly Network in Fig. 2.1. In this network, two bits b_1 and b_2 are generated at the source node S, and they are to be multicast to two sink nodes T and U. It can be easily seen that no routing scheme enable T and U. It can be easily seen that no routing scheme enable T and U to decode the two bits per unit time. If network coding is allowed, Fig. 2.1 shows a scheme which multicasts both b_1 and b_2 to nodes T and U, where '+' denotes *modulo* 2 addition. In this scheme, node A receives b_1 and b_2 and sends the encoded symbol $b_1 + b_2$ on channel (A, B). At node T, b_1 is received and b_2 can be recovered by adding b_1 and $b_1 + b_2$, because

$$b_2 = b_1 + (b_1 + b_2).$$

Similarly, U can recover b_1 and b_2.

It is proved that linear network coding is sufficient to achieve the maximum capacity in a single-source finite acyclic network. Consequently, linear network coding for single-source finite acyclic networks has been a subject of much research interest. Linear network codes for single-source finite acyclic networks into four types: (a) generic; (b) linear dispersion; (c) linear broadcast; (d) linear multicast. These four types of linear network code possess properties of decreasing strength.

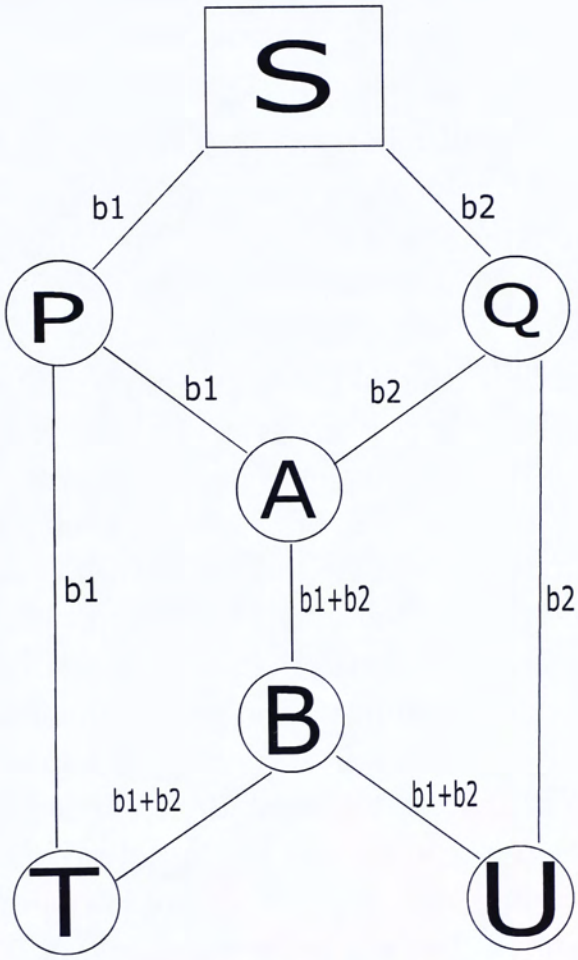

Figure 2.1: Butterfly Network

2.2.2 Network Coding in Wireless Networks

Some researchers has already investigated the possibility of applying the network coding in wireless networks [23], [24], [25], [26], [27].

In [23], they established a new framework for network coding in ad hoc wireless networks. First, they considered a simple wireless network topology to illustrate how network coding can improve throughput and energy efficiency objectives beyond routing solutions. Then, they extend the network coding problem to general wireless networks in conjunction with scheduling-based medium access control (MAC). They verified via numerical results the superior performance of network coding over routing in terms of throughput and energy efficiency.

In [24], they gave a brief overview of the marriage of network coding and wireless packet networks and hoped, thereby, to provide a firm theoretical basis from which practical implementations and theoretical extensions can be developed.

In [25], they evaluated the gain from using network coding for file sharing applications running on top of wireless mesh networks. With extensive simulations carried out on a simulator they developed specifically for the study, they confirmed that network coding can improve the performance of the file sharing application, but not as in wired networks. The main reason is that nodes over wireless cannot listen to different neighbors simultaneously. Nevertheless, one can get more from network coding if the information transmission is made more diverse inside the network.

In [26], it applied network coding to wireless mesh networks and presented the first implementation results. It introduced COPE, an opportunistic approach to network coding, where each node snoops on the medium, learns the status of its neighbors, detects coding opportunities, and codes as long as the recipients can decode. This flexible design allows COPE to efficiently support multiple unicast flows, even when traffic demands are unknown and bursty, and the senders and receivers are dynamic. Their results showed that COPE substantially improves the network throughput, and as the number of flows and the contention level increases, COPEs throughput become many times higher than current 802.11 mesh networks.

In [27], they overviewed some of the main features of network coding that are most relevant to wireless networks. In particular, they discussed the fact that random distributed network coding is asymptotically optimal for wireless networks with and without packet erasures. The coded network lends itself, for multicast connections, to a cost optimization which not only outperforms traditional routing tree-based approaches, but also lends itself to a distributed implementation and to a dynamic implementation when changing conditions, such as mobility, arise.

However, all the previous works concentrated on application of network coding in the 1-radio 1-channel wireless networks. In this thesis, we investigate the application of network coding in the m-radio n-channel wireless mesh networks.

□ **End of chapter.**

Chapter 3

Throughput Analysis

Summary

This chapter aims to analyze the throughput relation between the m-radio n-channel case and 1-radio 1-channel case with and without network coding in a wireless mesh network.

3.1 Introduction

IEEE 802.11 is a widely used standard for wireless local area networks. It offers multiple non-overlapping channels that are separated in frequency. In particular, the IEEE 802.11b/g standard and IEEE 802.11a standard provide 3 and 12 orthogonal frequency channels, respectively. Nowadays many base stations still deploy only one radio interface at each base station. However, recent developments in circuit designs have made it feasible to equip nodes with multiple 802.11 radio interfaces, especially those in WMNs.

For many reasons, traditional multi-hop wireless networks are unable to effectively scale to exploit the increasing system bandwidth available. One main reason is that such networks cannot fully utilize all the available orthogonal channels. Consequently, with multiple interfaces at one base station available, the use of multiple radio nodes in a mesh network appears to provide the most promising approach to overcoming the above problem.

Many research works have focused on the optimization of the total throughput in the multi-radio multi-channel networks [15], [16], [17], [18], [19]. All these papers used heuristic algorithms to optimize the maximum throughput in the network.

Some other researchers have already studied how to apply network coding into 1-radio 1-channel wireless networks [23], [24], [25], [26], [27].

In this chapter we focus on throughput characteristics between two cases: m-radio n-channel and 1-radio 1-channel. By m-radio n-channel case, we mean that there are n orthogonal channels available in the network and each node has m radio interfaces. We derive an upper bound of the maximum throughput in the m-radio n-channel case in terms of the maximum throughput of the 1-radio 1-channel case without network coding. We also investigate the application of network coding in the multi-radio multi-channel WMNs and show that using network coding can further increase the total throughput of the network.

3.2 Preliminaries

We model a wireless network as a collection of homogeneous wireless nodes deployed within a two-dimensional geographical territory [28]. Each node is equipped with some omni-directional antennas. Data packets are relayed from the source nodes to the destination nodes via intermediate nodes in a multihop manner. In the network, n orthogonal channels are available and each node has m radio interfaces.

Before giving our main result, we require the following assumptions:

1. Time is slotted and transmissions only occur at the beginning of each time slot.

2. The capacity for each orthogonal channel is the same. We further assume traffic loads are in integral units of the channel capacity.

3. We adopt the interference contention model presented in previous work [29]: that is, if either the transmitter or the receiver of one link is not separated from the transmitter or the receiver of another link by more than a distance of x, these two links interfere with each other.

4. We assume the traffic pattern in the network is periodic with a period of P time slots. Let $Q_i(t)$ represents the arriving source traffic to link i at time slot t, then this implies $Q_i(t + P) = Q_i(t)$ for all i and t.

5. We define a one time slot schedule as follows: For each time slot, we define one $n \times L$ matrix to represent the schedule:

$$\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1L} \\ a_{21} & a_{22} & \cdots & a_{2L} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nL} \end{pmatrix}$$

where L is the total number of links in the network and

$$a_{ij} = \begin{cases} 1 & : \text{when channel i is assigned to link j in the time slot} \\ 0 & : \text{otherwise} \end{cases}$$

where $1 \leq i \leq n$ and $1 \leq j \leq L$.

A one time slot schedule is said to be feasible when none of the channels assigned in the time slot will cause interference to other concurrent transmissions.

A network schedule is a collection of one time slot schedules. Because the source traffic is periodic, we also assume the network schedule is periodic.

6. Suppose the network generates source traffic for $k \times P$ time slots and then the source traffic stops at all nodes. Given an m-radio n-channel network and a network schedule, define $T_{mn}(k)$ as the number of time slots needed to successfully route all generated source traffic to the destination nodes. Define $T^*_{mn}(k)$ as the minimum one among all $T_{mn}(k)$s.

7. Let S be the set of source nodes, and d_i^{mn} be the amount of source traffic transmitted by node i during the schedule in one period (that is over P time slots) in an m-radio n-channel WMN. We define the throughput as follows:

$$R(m,n) = \lim_{k \to \infty} \frac{1}{T_{mn}} \sum_{i \in S} k \times d_i^{mn} \tag{3.1}$$

   Denote $R^*(m,n)$ as the maximum throughput of an m-radio n-channel WMN.

8. In the m-radio n-channel network, each node has an arbitrarily large buffer so that we can delay the traffic.

9. For each source generated traffic, the routing from the source to the destination passes through finite number of nodes.

10. Given a traffic pattern and a network schedule, there must be at least one routing path which the traffic transmitted from the source to the destination passes the most number of intermediate nodes. Denote this path as the longest routing path and the length of the path as L, the number of intermediate nodes it passes.

Theorem 3.2.1 $R^*(m,n) \leq n \times R^*(1,1)$.

The proof of Theorem 3.2.1 is based on two claims:

1. $R^*(n, n) \leq n \times R^*(1, 1)$;
2. $R^*(m, n) \leq n \times R^*(1, 1)$.

3.3 Proof of Theorem 3.2.1 when $n = m$

To prove the first claim, we need the following lemma:

Lemma 3.3.1 *In an n-radio n-channel WMN, given any feasible schedule for $k \times P$ time slots, it can always be transformed into a feasible schedule in a 1-radio 1-channel WMN with the same topology using $n \times k \times P$ time slots.*

We define two kinds of transformations for the traffic in a n-radio n-channel network:

1. Transformation 1 (Source Generated Traffic):

   Buffer and reroute the source generated traffic from the n-radio n-channel network to the 1-radaio 1-channel network according to the following rule: If the source traffic is generated in the n-radio n-channel network at time slot t, we reroute it to the 1-radio 1-channel network such that it will be generated at the time slot $n \times (t-1) + 1$ in the 1-radio 1-channel network. That is to say:

   $$S_i^{11}(j) = \begin{cases} S_i^{nn}((j-1)/n + 1) & : \quad j = n \times (k-1) + 1, \\ 0 & : \quad \text{otherwise.} \end{cases}$$

   where k is an interger.

2. Transformation 2 (Transmitted Traffic in Each Time Slot):

   Split each time slot in the n-radio n-channel network into n time slots in the 1-radio 1-channel network so that the traffic transmitted in one time slot in the n-radio n-channel network will be transmitted in n time slots in the 1-radio 1-channel network. In each time slot in the n-radio n-channel network, if traffic is transmitted using channel j, it will be transmitted in the j_{th} time slot among all the n time slots split from the time slot in the n-radio n-channel network.

Now let us consider the issue of starvation. Starvation refers to the situation that some of the links in a network which can be transmitted at the same time slot do not transmit at the same time slot because some of these links have no traffic to send.

For the n-radio n-channel network, the only reason to cause starvation is that at the beginning of the transmission, some of the links have no traffic to send because the source traffic has not reached these links yet. However, this kind of starvation will not last forever since the network schedule is periodic (which is proved in Claim 1).

For the 1-radio 1-channel network, there are two possible reasons to cause starvation:

1. The first possible reason is the same as the one for the n-radio n-channel network. If the n-radio n-channel network does not transmit at its full capacity at the beginning of the transmission, the transmission in the 1-radio 1-channel network after transformation will suffer starvation as well.

2. The second possible reason is that in the n-radio n-channel network, we have multiple orthogonal channels and multiple radio interfaces. However, in the 1-radio 1-channel network, we only have 1 orthogonal channel and 1 radio interface. When we do the transformation, it is possible that some of the transmission which can be transmitted at the same time slot in the n-radio n-channel network using the same orthogonal channel cannot be transmitted at the same time slot in the 1-radio 1-channel network, which results in starvation. Nevertheless, we can show that for the 1-radio

1-channel network, only the first not the second reason will cause starvation (which is proved by Claim 2).

Claim 1 *Starvation will last for at most L periods in an m-radio n-channel network.*

Proof The network schedule is periodic, but the network schedule may not work at its full capacity at the first few periods because of the problem of starvation. Starvation will not last forever because of two points:

1. The number of nodes in the m-radio n-channel network is finite.

2. The length of the routing path is finite.

It is obvious that these two points are satisfied, so the starvation will not last forever.

Consider the worst case that given a traffic pattern and a network schedule, we have a longest path with length L, the network schedule is such that in each period, it schedules the last link in the path to transmit at the first time slot, the last but one link to transmit at the second time slot,$\cdots$, the second link to transmit at the last but one time slot and the first link to transmit at the first time slot. In this case, the network needs L periods to transmit the source traffic to the last link and then the network can transmit at its full capacity.

Look at the definition of the throughput. Suppose the network schedule for one period of source generated traffic is Q time slots. If the network can work at its full capacity at the beginning of the transmission, then we need $Q \times k$ time slots to finish transmitting all the source generated traffic to the destination nodes. However, because of starvation, the network cannot work at full capacity at the first L periods. So the time slots needed at most to transmit the source generated traffic now become $Q \times (L+k)$. So it becomes

$$\begin{aligned}\lim_{k\to\infty}\frac{1}{Q\times k}\sum_{i\in S}k\times d_i^{mn} &= \lim_{k\to\infty}\frac{1}{Q\times(L+k)}\sum_{i\in S}k\times d_i^{mn}\\ &\le R(m,n)=\lim_{k\to\infty}\frac{1}{T_{mn}}\sum_{i\in S}k\times d_i^{mn}\\ &\le \lim_{k\to\infty}\frac{1}{Q\times k}\sum_{i\in S}k\times d_i^{mn}.\end{aligned}$$

Thus, the definition of the throughput will converge to a constant when we take the limit even if there are starvation problems at the first few periods of the network schedule. ∎

Claim 2 *If the n-radio n-channel network does not have starvation problem at a certain time slot, then the 1-radio 1-channel network does not have starvation problem at the n time slots split from the time slot in the n-radio n-channel network, either.*

Proof We prove this by induction.

For the n-radio n-channel case, we define:

1. $B_i^{nn}(t)$, which stands for the amount of traffic buffered at the beginning of time slot t at node i;
2. $T_{ij}^{nn}(t)$, which stands for the amount of traffic transmitted during time slot t at node i using channel j.

$$T_{ij}^{nn}(t)=\begin{cases}1 & : \text{at time slot } t \text{ node } i \text{ transmits on channel } j\\ 0 & : \text{at time slot } t \text{ node } i \text{ doesn't transmit on channel } j\end{cases}$$

3. $S_i^{nn}(t)$, which stands for the amount of source traffic generated at node i at time slot t.

4. $A_i^{nn}(t)$, which stands for the amount of arriving traffic buffered at node i during time slot t.

For the j_{th} 1-radio 1-channel network, we define:

1. $B_i^{11}(t)$, which stands for the amount of traffic buffered at the beginning of time slot t at node i.

2. $T_i^{11}(t)$, which stands for the amount of traffic transmitted during time slot t at node i.

$$T_{ij}^{11}(t) = \begin{cases} 1 & : \text{at time slot } t \text{ node } i \text{ transmits} \\ 0 & : \text{at time slot } t \text{ node } i \text{ doesn't transmit} \end{cases}$$

3. $S_i^{11}(t)$, which stands for the amount of source traffic generated at node i at time slot t.

4. $A_i^{11}(t)$, which stands for the amount of arriving traffic buffered at node i during time slot t.

We have the following two equations:

$$B_i^{nn}(t+1) = B_i^{nn}(t) - \sum_{j=1}^{n} T_{ij}^{nn}(t) + A_i^{nn}(t) + S_i^{nn}(t). \tag{3.2}$$

$$B_{ij}^{11}(t+n) = B_{ij}^{11}(t) - \sum_{j=1}^{n} (S_i^{11}(t+j-1) + A_i^{11}(t+j-1) - T_i^{11}(t+j-1)). \tag{3.3}$$

At the beginning of the whole transmission, $B_i^{nn}(1) = B_i^{11}(1) = 0$, for all i.

At the end of the first time slot, for each node in the n-radio n-channel network, the traffic buffered includes the source generated traffic in the first time slot at each node, the arriving traffic at each node caused by transmission from other nodes in the first time slot and the transmitted traffic which is transmitted by each node.

At the end of the n_{th} time slot, for each node in the 1-radio 1-channel network, the traffic buffered includes the source generated traffic in these n time slots at each node, the arriving traffic at each node caused by transmission from other nodes in these n time slots and the transmitted traffic which is transmitted by each node.

Let us compare the relations between the source generated traffic, arriving traffic and transmitted traffic in the n-radio n-channel network and 1-radio 1-channel network:

1. Source generated traffic: For those two networks, they will receive the same amount of source generated traffic at the beginning of the first time slot according to Transformation 1, $S_i^{nn}(1) = \Sigma_{j=1}^{n} S_i^{11}(j)$.

2. Transmitted traffic: In the n-radio n-channel network, the transmitted traffic at each node comes from source generated traffic because at this time slot there is no arriving traffic to each node. According to Transformation 2, $\Sigma_{j=1}^{n} T_{ij}^{nn}(1) = \Sigma_{j=1}^{n} T_i^{11}(j)$.

3. Arriving traffic: In the n-radio n-channel network, the arriving traffic at each node comes from the transmitted traffic during the first time slot. In the 1-radio 1-channel network, the arriving traffic at each node also comes from the transmitted traffic during the first n time slots. Because the transmitted traffic in the first time slot in the n-radio n-channel network is the same as the transmitted traffic in the first n time slots in the 1-radio 1-channel network, the amount of arriving traffic in each node in these two networks are the same.

Based on these three points, we have $B_i^{nn}(2) = B_i^{11}(n+1)$.

Now assume $B_i^{nn}(m) = B_i^{11}((m-1) \times n+1)$, where $m \geq 2$. Let us compare the relations between the source generated traffic, arriving traffic and transmitted traffic in the n-radio n-channel network and the 1-radio 1-channel network.

1. Source generated traffic: For those two networks, they will receive the same amount of source generated traffic at the beginning of the m_{th} time slot according to Transformation 1, $S_i^{nn}(m) = \Sigma_{j=1}^{n} S_i^{11}((m-1) \times n + j)$.

2. Transmitted traffic: In the n-radio n-channel network, the transmitted traffic at each node comes from source generated traffic because at this time slot there is no arriving traffic to each node. According to Transformation 2, $\Sigma_{j=1}^{n} T_{ij}^{nn}(m) = \Sigma_{j=1}^{n} T_i^{11}((m-1) \times n + j)$.

3. Arriving traffic: In the n-radio n-channel network, the arriving traffic at each node comes from the transmitted traffic during the first time slot. In the 1-radio 1-channel network, the arriving traffic at each node also comes from the transmitted traffic during the first n time slots. Because the transmitted traffic in the first time slot in the n-radio n-channel network is the same as the transmitted traffic in the first n time slots in the 1-radio 1-channel network, the amount of arriving traffic in each node in these two networks are the same.

Based on these three points, we have $B_i^{nn}(m+1) = B_i^{11}(m \times n+1)$. ∎

Consider Fig. 3.1. This shows how we can reroute the traffic from a 3-radio 3-channel network with a period of 3 time slots to 1 1-radio 1-channel network. In this figure, $S1$ in the 3-radio 3-channel network represents the source generated traffic at the beginning of time slot 1 in that network.

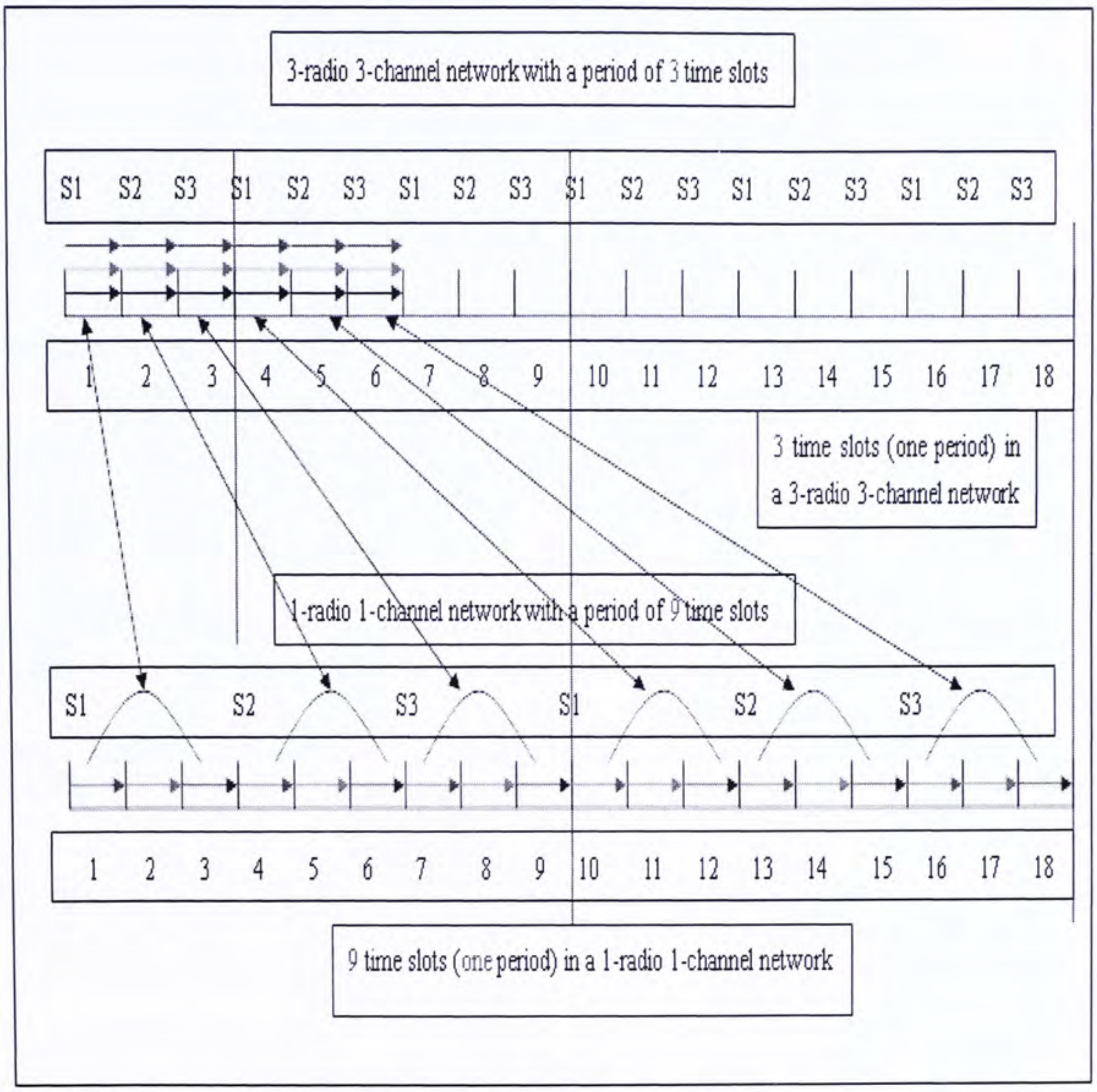

Figure 3.1: One Example Which Shows the Way We Reroute the Traffic from the 3-radio 3-channel Network with a Period of 3 Time Slots to a 1-radio 1-channel Network

Claim 3 *If the original scheduling in the n-radio n-channel network is feasible, the transformation is also feasible.*

Proof We prove Claim 3 by contradiction.

Suppose the transformation is not feasible, there must be at least two links which interfere with each other when they both transmit at the same time slot t, say link p and q. However, p and q transmit at some time slot t' using the same channel j in the n-radio n-channel network, which causes interference in the n-radio n-channel network, resulting in a contradiction. ∎

Claim 4 *The maximum throughput of the n-radio n-channel network is bounded by n times the maximum throughput of the 1-radio 1-channel network.*

Proof By Claim 2, we know that we can transform the schedule for the n-radio n-channel network to the 1-radio 1-channel network. Moreover, the 1-radio 1-channel network need at most n times time slots to transmit the source generated traffic in the n-radio n-channel network because we can split each time slot in the n-radio n-channel network into n time slots in the 1-radio 1-channel network. Furthermore, we know the transformed schedule in the 1-radio 1-channel network is just one way to transmit the traffic, so the throughput in this case must be less than or equal to the maximum throughput in the 1-radio 1-channel network given the source generated traffic. So we have:

$$
\begin{aligned}
R(n,n) &= \lim_{k\to\infty} \frac{1}{T_{nn}} \sum_{i\in S} k \times d_i^{nn} \\
&= \lim_{k\to\infty} n \times \frac{1}{n \times T_{nn}} \sum_{i\in S} k \times d_i^{nn} \\
&= \lim_{k\to\infty} n \times \frac{1}{T_{11}} \sum_{i\in S} k \times d_i^{nn} \\
&= \lim_{k\to\infty} n \times \frac{1}{T_{11}} \sum_{i\in S} k \times d_i^{11} = n \times R(1,1)
\end{aligned}
$$

Table 3.1: The network schedule for the 3-radio 3-channel network

time slot	transmitted link(s)	channel used
1	1,4	1,2
2	1,4,(2,5)	1,2,3
3	(1,6),(3,4),(2,5)	1,2,3
4	(1,6),(3,4),(2,5)	1,2,3

$$\leq \lim_{k\to\infty} n \times \frac{1}{T_{11}^{*}} \sum_{i\in S} k \times d_i^{11} = n \times R^{*}(1,1). \quad (3.4)$$

According to Lemma 3.3.1, we can do the transformation for any schedule in the n-radio n-channel WMNs, in particular the optimal schedule. In addition, we know the transformation is one way to do the scheduling in the 1-radio 1-channel WMNs. We denote $R^*(n,n)$ as the maximum throughput in the n-raddio n-channel network and denote $R(1,1)$ as the throughput for each 1-radio 1-channel network. So we have:

$$R^{*}(n,n) = n \times R(1,1) \quad (3.5)$$
$$\leq n \times R^{*}(1,1). \quad (3.6)$$

This means the maximum throughput of the n-radio n-channel WMNs is bounded by n times the maximum throughput of the 1-radio 1-channel WMNs, which completes our proof.

Now we consider a more detailed example. Consider Fig. 3.2. This is a 3-radio 3-channel network. The source node is S and the destination nodes are $D1$ and $D2$. At each time slot, there will be two packets arriving at source node S. The network schedule for the 3-radio 3-channel network is listed in Table 3.1.

The corresponding network schedule for the 1-radio 1-channel network after transformation is listed in Table 3.2.

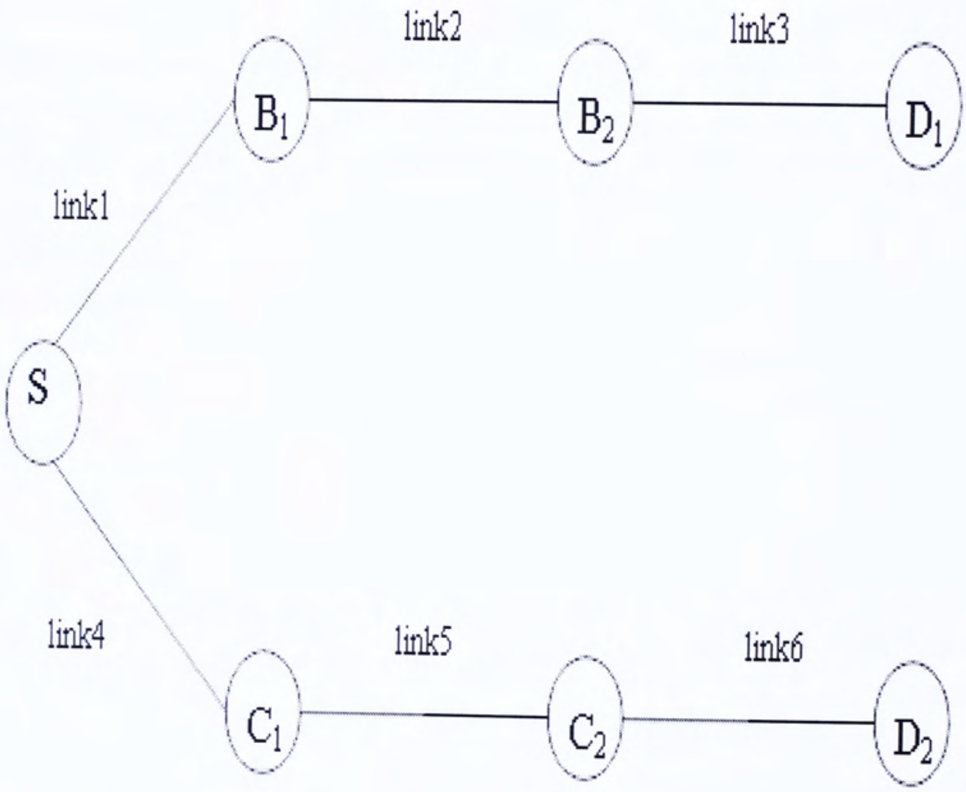

Figure 3.2: A Detailed Example

Table 3.2: The network schedule for the 1-radio 1-channel network after transformation

time slot	transmitted link(s)
1	1
2	4
3	No transmission
4	1
5	4
6	2,5
7	1,6
8	3,4
9	2,5
10	1,6
11	3,4
12	2,5

Referring to these two schedules, we get two conclusions which correspond to Claim 1 and Claim 2, respectively:

1. At the beginning few time slots, the 3-radio 3-channel network does not transmit at its full capacity because of starvation problem, such as time slot 1 and 2. For example, Link 1 and Link 6 can transmit at the same time but Link 6 has nothing to send at the first time slot. However, since the network schedule is periodic, starting from time slot 3, the network transmits at its full capacity. When we consider k periods when $k \to \infty$, the throughput is 2.

2. When we do the transformation, we split each time slot in the 3-radio 3-channel network into 3 time slots in the 1-radio 1-channel network. The correspondence is summarized in Table 3.3.

   For the first and second time slots in the 3-radio 3-channel network, because of starvation problem, not all the links can transmit. However, starting from the third time slot, the 3-radio 3-channel network starts to transmit at its full capacity. This is verified by Claim 1, which says starvation in n-radio n-channel network would not last forever since the schedule is periodic and all routes are finite.

   In addition, we see that since at time slot 1 and time slot 2 in the 3-radio 3-channel network, the network does not transmit at the full capacity due to starvation problem. So the corresponding time slots split from these two time slots, which are time slots (1,2,3),(4,5,6) in the 1-radio 1-channel network, have starvation problems. For example, at time slot 1 Link 6 does not transmit because of starvation; at time slot 5, Link 3 does not transmit because of starvation as well. So when there are starvation problem at a certain time slot in the 3-radio 3-channel network, after transformation, at least one of the time slots spilt from that time

Table 3.3: The network schedule for the 1-radio 1-channel network after transformation

time slot in the 3-radio 3-channel network	the corresponding split time slots in the 1-radio 1-channel network
1	1,2,3
2	4,5,6
3	7,8,9
4	10,11,12
n	3n-2, 3n-1, 3n

slot in the 1-radio 1-channel network has the same starvation problem.

However, when the 3-radio 3-channel network transmit at its full capacity (no starvation) such as time slot 3, the split time slots in the 1-radio 1-channel network will also work at its full capacity, such as time slot (7,8,9). This is verified by Claim 2.This is easy to understand, if the n-radio n-channel network works at its full capacity, which means all the orthogonal channels are fully utilized (no more links can be added to transmit without causing interference), then after transformation, in each split time slot, the 1-radio 1-channel network also works at its full capacity.

3.4 Proof of Theorem 3.2.1 when $n \neq m$

3.4.1 Proof of Theorem 3.2.1 when $m < n$

Claim 5 *The maximum throughput will not be increased if the number of radio interfaces at each node is less than the number of orthogonal channels available in the network.*

Proof Compared with an m-radio n-channel network ($m < n$), an n-radio n-channel network can realize whatever throughput an m-radio n-channel can because we can simply add $n - m$ dummy radio interfaces at each node in an m-radio n-channel network to turn it into an n-radio n-channel network. So we have

$$R^*(m,n) = R(n,n) \leq R^*(n,n), m < n. \quad \blacksquare \qquad (3.7)$$

3.4.2 Proof of Theorem 3.2.1 when $m > n$

Claim 6 *The maximum throughput will not be increased if the number of radio interfaces at each node is larger than the number of orthogonal channels available in the network.*

Proof For a network with n orthogonal channels, a base station needs at most n radio interfaces. So the additional $m - n$ radio interfaces at each base station are redundant. So we have

$$R^*(m,n) = R^*(n,n), m > n. \quad \blacksquare \qquad (3.8)$$

From Claim 5 and Claim 6, we have the following equation:

$$R^*(m,n) \leq R^*(n,n) \leq n \times R^*(1,1), \forall m \neq n. \qquad (3.9)$$

3.5 Applying network coding into multi-radio multi-channel networks

In section 3.3, we say that the throughput for the m-radio n-channel network is bounded by n times that of the 1-radio 1-channel network without network coding. Actually, if we use network coding, then the maximum throughput in the m-radio n-channel case can exceed n times the maximum throughput in the 1-radio 1-channel case. The following is a concrete example.

Let us consider Fig. 3.3. Suppose source node $S1$ wants to send data $f1$ to both destinations $D1$ and $D2$ and source node

Table 3.4: Scheduling scheme for the 1-radio 1-channel case in Fig. 3.3 without network coding

time slot	active link(s)	data on the link(s)
1	1,3	f1
2	7	f1
3	5	f1
4	2,6	f2
5	7	f2
6	4	f2

$S2$ wants to send data $f2$ to both destinations $D1$ and $D2$. We need to arrange 6 time slots for the whole transmission session without network coding. The throughput is just $1/3$. The scheduling scheme is in Table 3.4.

Now we consider the case if we have 4 orthogonal channels and each node equips with 4 radio interfaces. Without network coding, we know from equation 3.6 that the maximum throughput will not exceed $4 \times 1/3$ or $4/3$, where $1/3$ is the maximum throughput in the 1-radio 1-channel case without network coding. With network coding, if we use scheduling scheme in Table 3.5, the throughput in this case is 2, which exceeds $4/3$.

Actually, if we look at the scheduling scheme in Table 3.5 more carefully, we can see that in fact each node only needs 3 radio interfaces. In a word, if we apply network coding into the multi-radio multi-channel networks, not only the maximum throughput is improved, but the number of radio interfaces needed may be reduced as well.

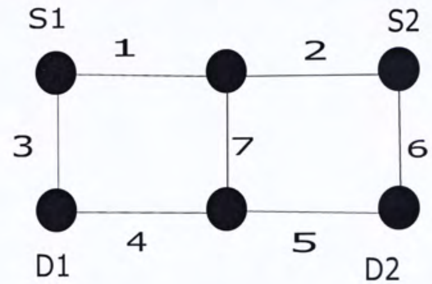

Figure 3.3: One topology which shows network coding can increase throughput in the multi-radio multi-channel environment

Table 3.5: Scheduling scheme for the 4-radio 4-channel case in Fig. 3.3 with network coding

time slot	active links	data on the links
1	1,3; 2,6	f1,f3; f2
2	1,3; 2,6; 7	f5; f4; f1 ⊕ f2
3	1,3; 2,6; 7; 4,5	f7; f6; f3 ⊕ f4; f1 ⊕ f2
⋮	⋮	⋮
n	1,3; 2,6; 7; 4,5	f2n+1; f2n; f2n-3 ⊕ f2n-2; f2n-5 ⊕ f2n-4

Table 3.6: Periodic schedule scheme in a 2-radio 2-channel network for string topology

time slot	transmitted links	channels used
1	(1,4),(2,5)	1,2
2	(1,4),(2,5)	1,2
3	3	1,2

3.6 Some simulation results

In this section, we investigate some simple topologies to substantiate our proof. For the string topology and Grid topology, since the topologies are relatively simple, we get number for the maximum throughput by exhausted search. As for the random topology, we cite the result of the experiment done by other researches.

3.6.1 String Topology

Let us consider Fig. 3.4. Suppose we transmit data from left to the right. We label the links from left to right as from 1 to 5. In this case, we can get Table 3.7. For example, let us consider the $Ch = 2$ and $r = 2$ case. By exhausted search, following the schedule in Table 3.6, you can get that the throughput is $\frac{2}{3}$.

In this case, even if we apply network coding, the maximum throughput is just the same as those calculated in Table 3.7 because of the special topology. We see that although the maximum throughput relations when number of radios do not equal the number of channels are not so clear, our results hold in this topology.

Table 3.7: Maximum throughput for string topology

	Ch=1	Ch=2	Ch=3	Ch=4
r=1	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
r=2	-	$\frac{2}{3}$	1	1
r=3	-	-	1	$\frac{4}{3}$

Table 3.8: Periodic schedule scheme in a 3-radio 3-channel network for grid topology without network coding

time slot	transmitted links	channels used
1	(1,3),7,5	1,2,3
2	(2,6),7,4	1,2,3
...	...	...
2n	(2,6),7,4	1,2,3
2n+1	(1,3),7,5	1,2,3

3.6.2 Grid Topology

Let us consider Fig. 3.3 again. We can get Table 3.9 and Table 3.10, respectively. We can tell from these two tables that applying network coding really can improve maximum throughput. For example, let us consider the $Ch = 3$, $r = 3$ case. By exhausted search, following the schedule in Table 3.8, you can get that the throughput is 1.

Figure 3.4: 6-Node String

Table 3.9: Maximum throughput for Fig. 3.3 without network coding

	Ch=1	Ch=2	Ch=3	Ch=4
r=1	$\frac{1}{3}$	$\frac{1}{2}$	$\frac{1}{2}$	$\frac{1}{2}$
r=2	-	$\frac{2}{3}$	1	1
r=3	-	-	1	$\frac{4}{3}$

Table 3.10: Maximum throughput for Fig. 3.3 with network coding

	Ch=1	Ch=2	Ch=3	Ch=4
r=1	$\frac{1}{2}$	$\frac{2}{3}$	$\frac{2}{3}$	$\frac{2}{3}$
r=2	-	1	$\frac{4}{3}$	$\frac{4}{3}$
r=3	-	-	$\frac{3}{2}$	2

3.6.3 Random Topology

In [16], some simulations have been done using heuristic algorithms in some random topology, and the simulation results match our result quite well. The results are summarized in Table 3.11.

□ **End of chapter.**

Table 3.11: Maximum throughput for random topology

	Ch=1	Ch=2	Ch=3	Ch=4
Joint Routing (r=1)	5.02	3.8	3.8	3.8
Joint Routing (r=2)	-	2.51	1.94	1.9
SP Routing (r=1)	6.2	4.6	4.6	4.6
SP Routing (r=2)	-	3.1	2.37	2.3

Chapter 4

Interface Reduction in Wireless Mesh Networks

Summary

This chapter aims to propose an algorithm to reduce the total number of radio interfaces used under a given traffic load while trying to maintain the maximum throughput in a wireless mesh network.

4.1 Introduction

Many research works have focused on the optimization of total throughput in the multi-radio multi-channel networks [15], [16], [17], [18], [19]. All these papers assumed the m-radio n-channel scenario, that is, each base station has m radio interfaces in control.

Recently, some other researchers [30] have discovered that it is not necessary to place an equal amount of radio interfaces at each base station. Moreover, the placement of radio interfaces should depend on the distribution of traffic load in a WMN. This means the m-radio n-channel scenario may not be the most suitable model to consider when we try to analyze the characteristics of WMNs.

In this chapter we propose a heuristic algorithm to minimize the total number of radio interfaces used at each base station (node) in a netowrk with a grid topology. By simulations, we show that there is no need to place an equal amount of interfaces at each base station in order to achieve the maximum throughput if the traffic is not balanced. Rather, it should be based on how the traffic load is at each node. Finally, we generalize the algorithm to the more general case.

4.2 Preliminaries

We model a wireless network as a collection of homogeneous wireless nodes deployed with a two-dimensional grid structure. Each node is equipped with some omni-directional antennas. Data packets are relayed from the source nodes to the destination nodes via intermediate nodes in a multihop manner.

4.2.1 Assumptions and Objectives of the Algorithm

Before giving our algorithm, we require the following assumptions:

1. The nodes are located on a rectangular grid with equal spacing in the vertical and horizontal direction. Denote the vertical and the horizontal sapcing by x.

2. We adopt the interference contention model presented in previous work [29]: that is, if either the transmitter or the receiver of one link is not separated from the transmitter or the receiver of another link by more than x, these two links interfere with each other.

3. Each base station has at least one radio interface.

4. The capacity for each orthogonal channel is the same. We further assume traffic loads are in integral units of the channel capacity.

5. The traffic load on each link of the network is known and periodic in time.

6. A link schedule is defined by means of equal length time slots. All link schedules are assumed to have a common period, T. In the network, n orthogonal channels are available.

The objectives of our algorithm are as follows:

1. Try to maintain the maximum throughput we can get when there is no restrictions on the number of radio interfaces used.

2. Based on objective 1, minimize the total number of radio interfaces used at each base station.

4.2.2 Definitions

Since the traffic load pattern is periodic in time, the amount of traffic accumulated over one period is a constant for any given link, definde as Traffic Load Vector $V = (V_1, V_2, \cdots, V_{L-1}, V_L)$. We further assume that the transmit nodes buffer one period of traffic at the beginning of the link schedule.

In our algorithm, we will periodically update the traffic load information in each time slot after we assign a channel to the network, so we define another row vector called Dynamic Traffic Load Vector as

$$D(k) = (V_1(k), V_2(k), \cdots, V_{L-1}(k), V_L(k)),\ 1 \leq k \leq nT.$$

$V_i(k)$, where $k = (t-1)n+j$, represents the traffic load needed to be transmitted on link i at time slot t before we assign channel

j. It follows that

$$V = (V_1, V_2, \cdots, V_{L-1}, V_L) = D(1) \tag{4.1}$$

To account for the effect of interference, we follow the common approach of using a Contention Clique (CC). A contention clique is a set of links in which any two of them interfere with each other when transmitting at the same time. In addition, define the traffic load of CC as the summation of all the traffic load on each of the links in the CC. That is

$$\lambda(D(k)) = \sum_{i \in CC} V_i(k). \tag{4.2}$$

We define the Maximum Contention Clique (MCC) as the one, among all the CCs, which has the largest traffic load. If M is a MCC, we denote the traffic load of M as

$$\lambda_M(D(k)) = \sum_{i \in M} V_i(k). \tag{4.3}$$

In our algorithm, we need to estimate the time slots needed in one period. We use the following equation

$$T = \left\lceil \frac{\lambda_M(D(1))}{n} \right\rceil, \tag{4.4}$$

to get the approximate number of time slots needed in a period, where n denotes the number of orthogonal channels available in the network. According to [28], T is a fairly good approximation for the minimum time slots needed in one period, given a specific traffic pattern.

For all nodes in the network, we denote each as from 1 to m. Denote the links connected to the nodes in the following ways:

1. Denote the right link connected to node i as R_i.

2. Denote the bottom link connected to node i as B_i.

Consider Fig. 4.1 and suppose the grid network is in an $a \times b$ structure, where $a \times b = m$. Notice that for the rightmost nodes, they do no have R_i. For the bottommost nodes, they do no have B_i. However, we artificially add links to these nodes such that $V_{B_i}(k) = 0$, for $i = -a+1, -a+2, \cdots, -1, 0$ and $(b-1)a+1, (b-1)a+2, \cdots, ba-1, ba$; $V_{R_i}(k) = 0$, for $i = 0, a, \cdots, (b-1)a, ba$.

For each node in the network, calculate the following parameter:

$$Y_i(k) = \left\lceil \frac{V_{R_i}(k) + V_{B_i}(k) + V_{B_{i-a}}(k) + V_{R_{i-1}}(k)}{T-t+1} \right\rceil, \qquad (4.5)$$

where $k = (t-1)n+1, 1 \le t \le T$, $t \in N$. $Y_i(k)$, where $k = (t-1)n+1$, represents the average number of transmissions node i has to make in time slot t.

For each node, define an indicator variable Id_i. $Id_i = 0$ means we first consider the right link originating from node i, while $Id_i = 1$ means we consider the bottom link originating from node i first.

At time slot t before we assign channel j to the network, we can find MCC(s) according to $D(k)$, where $k = (t-1)n+j$. Denote $S(k)$ as the set containing all the MCC(s) at time slot t before we assign channel j.

We define the link schedule for one time slot as follows:

For each time slot, we define one $n \times L$ matrix to represent the schedule:

$$\begin{pmatrix} a_{11} & a_{12} & \cdots & a_{1L} \\ a_{21} & a_{22} & \cdots & a_{2L} \\ \vdots & \vdots & \ddots & \vdots \\ a_{n1} & a_{n2} & \cdots & a_{nL} \end{pmatrix}$$

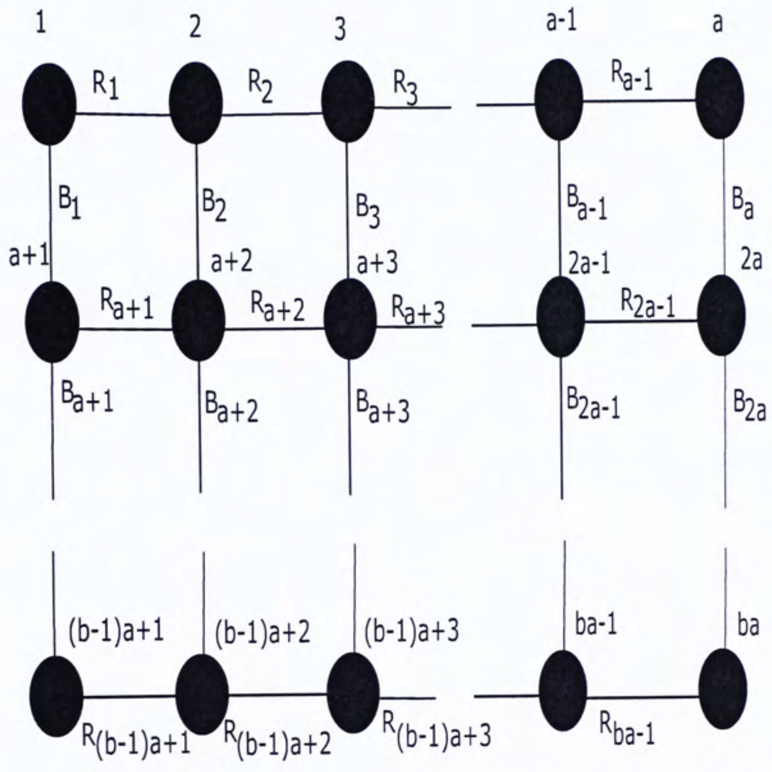

Figure 4.1: Labels of Links and Nodes

where L is the total number of links in the network and

$$a_{ij} = \begin{cases} 1 & : \text{when channel i is assigned to link j in the time slot;} \\ 0 & : \text{otherwise.} \end{cases}$$

where $1 \leq i \leq n$ and $1 \leq j \leq L$.

A one time slot schedule is said to be feasible when none of the channels assigned in the time slot will cause interference to other concurrent transmissions.

A network schedule is a collection of one time slot schedules. Because the source traffic is periodic, we also assume the network schedule is periodic.

4.3 Steps of the Algorithm and an Example

In this section, we introduce our algorithm and implement the algorithm in a simple example.

ALGORITHM

Input: A Traffic Load Vector (V) and a grid network.

Output: The link schedule for the given traffic load.

Steps:

```
Calculate T
for each time slot 1 ≤ t ≤ T
    calculate Y_i(k), where k = n(t − 1) + 1
    set the right link to have the higher priority
    for each orthogonal channel j at time slot t compute
        MCC(s) using D(n(t − 1) + j)
      for each MCC ∈ S(k), which can be randomly picked
        while channel j not allocated in this MCC yet
            randomly pick up one link, p, in this MCC which
            has not been picked up before in this time slot
          if the node from which p originates has Y_i(k) > 0
            if link p has traffic to transmit
              allocate channel j to link p
```

13: $Y_i(k+1) = Y_i(k) - 1$
$V_i(k+1) = V_i(k) - 1$
$Id_i = Id_i \oplus 1$
14: **else** skip
15: **for** all the other links in this MCC
16: $V_i(k+1) = V_i(k)$
17: **for** each node i from 1 to ab in the network
18: **if** node i has right or bottom link that does not belong to any MCC
19: **if** $Y_i(k) > 0$
20: **if** link with high priority has traffic to transmit
21: **then if** link with high priority causes no interference to the previosly assigned links
22: **then** allocate channel j to this link
23: update according to step 13
24: **else if** link with low priority has traffic to transmit
25: **then if** link with low priority causes no interference to the previosly assigned links
26: **then** allocate channel j to the link
27: update according to step 13
28: **else** skip
29: **if** channel j not allocated to either of the two links originated from node i
30: $l_{B_i}(k+1) = l_{B_i}(k)$
$l_{R_i}(k+1) = l_{R_i}(k)$
$Y_i(k+1) = Y_i(k)$
31: **if** any traffic load not transmitted after T time slots
32: go back to step 1 and redo the iteration

Now we illustrate the algorithm by a simple example. Let us consider Fig. 4.2, which shows a 5×6 grid topology. Assuming there are 4 orthogonal channels available. After calculation, we know T is 2 because $\lambda_M(D(1))$ is 8 in this case (labelled by a circle in Fig. 4.2).

In the first time slot, we assign channel 1 to B_9 in the MCC. Then we begin from node 1 and we see that it satisfies all the three conditions, so we assign channel 1 to R_1 according to the priority criterion. Repeat the steps until we come to node 17,

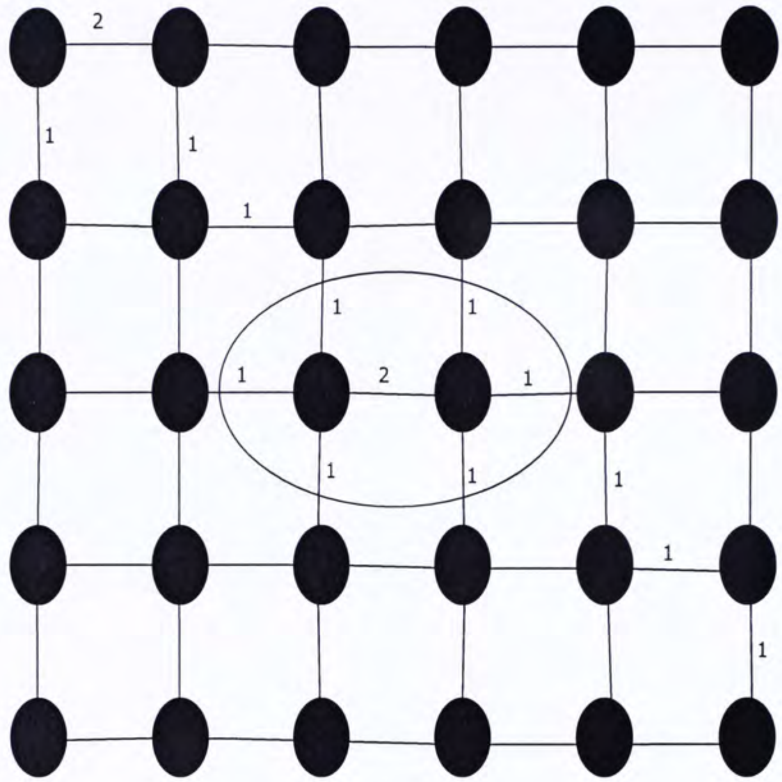

Figure 4.2: A Simple Example

which satisfies all the three conditions again, so we assign channel 1 to B_{17}.

In the first time slot, we assign channel 2 to B_{10} in the MCC. Then we begin from node 1 again, node 1 still satisfies all the three conditions, this time we assign channel 2 to B_1 because the priority has interchanged. When we come to node 23, because $Y_{23}(2)$ has decreased to 0 in the previous assignment, we don't assign channel 2 to it. We assign channel 2 to B_{24}.

Following the same procedure, we finish the whole assignment process. The detailed channel assignment result is provided in TABLE 4.1.

Table 4.1: Channel Assignment in a Simple Topology

Time Slot and Channel	Links Selected	$Y_i(k)$ Changed Nodes
T=1, Ch=1	B_9, R_1, B_{17}	1, 2, 9, 15, 17, 23
T=1, Ch=2	B_{10}, B_1, B_{24}	1, 7, 10, 16, 24, 30
T=1, Ch=3	B_{15}, B_2	2, 8, 15, 21
T=1, Ch=4	B_{16}	16, 22
T=2, Ch=1	R_{14}, R_1, R_{23}	1, 7, 14, 15, 23, 24
T=2, Ch=2	R_{15}	15, 16
T=2, Ch=3	R_{15}	15, 16
T=2, Ch=4	R_{16}, R_8	8, 9, 16, 17

4.4 Simulation Results and Discussions

In this section, we will do some simulations to substantiate our result. We consider the same grid topology as Fig. 4.2. By varying the traffic load in the network, we shall find out the gain of our algorithm in different scenarios with different traffic loads.

We define a parameter called Balance Level to measure how balanced the traffic load is in the network, which is calculated as follows:

$$\text{Balance Level} = \frac{\text{traffic load in one period}}{\lambda_M(D(1))}. \tag{4.6}$$

It follows that $1 \leq \text{Balance Level} \leq \left\lceil \frac{\text{links in the netwok}}{8} \right\rceil$.

Balance Level is an indicator to tell how the traffic is located with respect to the MCC. Given a fixed traffic pattern and a finite topology, the Balance Level is always finite. The larger the Balance Level is, the more traffic is located outside the MCC. That is to say, traffic is not totally saturated in MCC, so the traffic is more balanced. However, for a certain number of Balance Level, the corresponding traffic pattern in the topology may not be the same so that the number of radio interfaces needed in our algorithm may not be the same, either. In the simulation, we vary the value of Balance Level to test how well our algorithm works under different traffic load situations, without changing the traffic load in MCC. For each Balance Level, we consider some possible traffic patterns with respect to this Balance Level and take the average of the numbers of radio interfaces needed in these traffic patterns using our algorithm.

Consider Table 4.2 and Fig. 4.3, we notice the trend is that when the value of Balance Level increases, the gain of our algorithm decreases. This matches our intuition quite well. The core of our algorithm is to average the number of transmissions of each node in each time slot. When the balance level becomes

Table 4.2: Gains under different traffic load in a grid topology

Balance Level	Normal case	In our algorithm	Gain (%)
1	90	34	62
2	90	38	58
3	90	42	53
4	90	46	49
5	90	50	44
6	90	54	40

larger and larger, it indicates that the traffic is not concentrated in the MCC any more. We must add more radio interfaces to the base stations so that the total number of radio interfaces used increases and the gain decreases. The worst case is that the traffic load on each link is the same. In this case, there should be very little gain of our algorithm, if any.

4.5 Generalization

In this section, we generalize the algorithm for the grid topology to more general cases. Recall the two objectives of the algorithm:

1. Try to maintain the maximum throughput in the network;
2. Based on objective 1, minimize the total number of radio

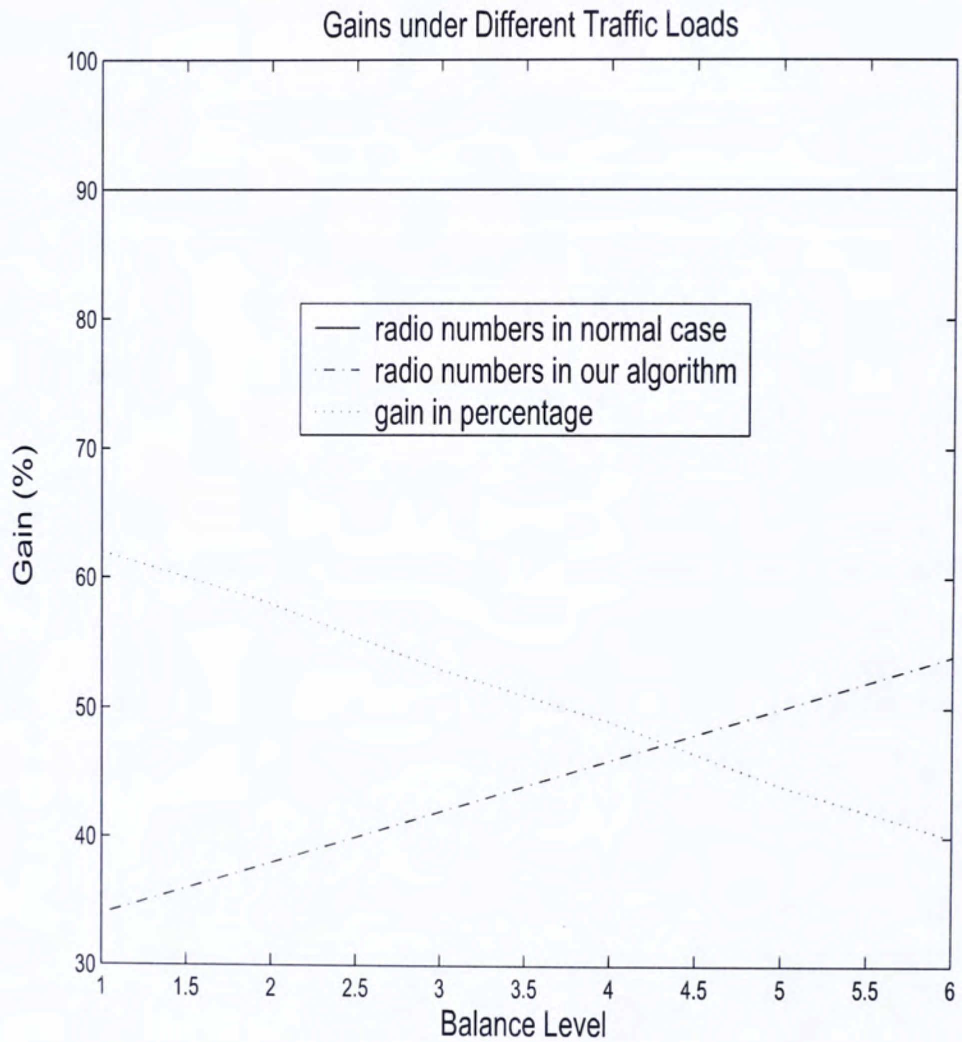

Figure 4.3: Gains of Radio Interface Reduction in a Grid Topology

interfaces used at each base station.

Suppose now we have a much more complicated network topology, how can we implement the algorithm? First of all, we need to estimate the smallest number of time slots needed in one period T so that all the traffic load can be transmitted from the source to the destination. Define $Link_i$ as the set which contains all the links that connect to node i. Define the vector $V_i(k)$ in the same way as in the grid topology. Then for each node in the network, we can calculate $Y_i(k)$ in the following way:

$$Y_i(k) = \frac{\sum_{i \in Link_i} V_i(k)}{T - t + 1}, \tag{4.7}$$

where t is the current time slot.

In order to achieve the first objective, we need to use minimum time slots to transmit the given traffic load. That means each time we assign a channel, we need to assign it to one of the links in the MCC so that λ_M will decrease after each assignment. If there are multiple MCCs, we need to assign the channel to one of the links in each MCC so that after the assignment λ_M will decrease. By doing so, we can make sure the first objective will be achieved.

In order to achieve the second objective, the main idea is to make each node transmit an equal amount of times in each time slot so that the number of radio interfaces needed in each base station is minimized. $Y_i(k)$, which equals to the total traffic load left which goes into and out of node i divided by the number of time slots left in the current period, gives an good estimate about the average times node i needs to transmit in the current time slot. Be careful that the value of $Y_i(k)$ will change according to the current traffic load in the whole network so updating $Y_i(k)$ using dynamic traffic load vector $D(k)$ is conducted when we finish the channel assignment in each time slot.

When we try to assign a channel to the network, we need to go through all the nodes and check all the three conditions

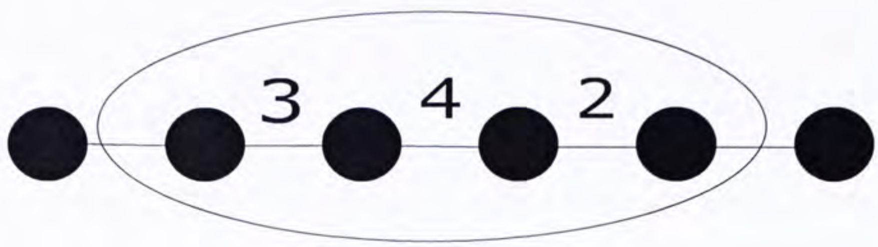

Figure 4.4: A String Topology

to see whether we should assign the channel to the link. If we finish assigning all the channels in one time slot, we go to the next time slot until we finish transmitting all the traffic from sources to destinations. We need to figure out a sequence to go through all the nodes in the topology. One way to do this is that we can label the nodes and then go from the smallest label to the largest label, which is used in our simulation. However, different ways to go through all the nodes may cause the number of radio interfaces used to be different, so how to find an efficient sequence to go through all the nodes is a big challenge for the generalization.

In summary, there are two main differences between our algorithm in a gird structure and a general topology:

1. When calculate $Y_i(k)$, consider the degree of the node rather than the four links in the grid topology.

2. We need to figure out a sequence to go through all the nodes in a more general topology.

Consider Fig. 4.4. This is an example of a string topology. We assume there are three orthogonal channels available. The simulation result is summarized in Table 4.3 and shown in Fig. 4.5 and Fig. 4.6.

Consider Fig. 4.7. This is an example of a random topology. We assume there are four orthogonal channels available. The simulation result is summarized in Table 4.4 and shown in Fig. 4.8 and Fig. 4.9.

Table 4.3: Gains under different traffic load in a string topology

Balance Level	Normal Case	Our Algorithm	Gain (%)
1	18	9	50
$\frac{10}{9}$	18	9.5	47
$\frac{11}{9}$	18	10	44
$\frac{4}{3}$	18	10.7	41
$\frac{13}{9}$	18	11	39
$\frac{14}{9}$	18	11	39

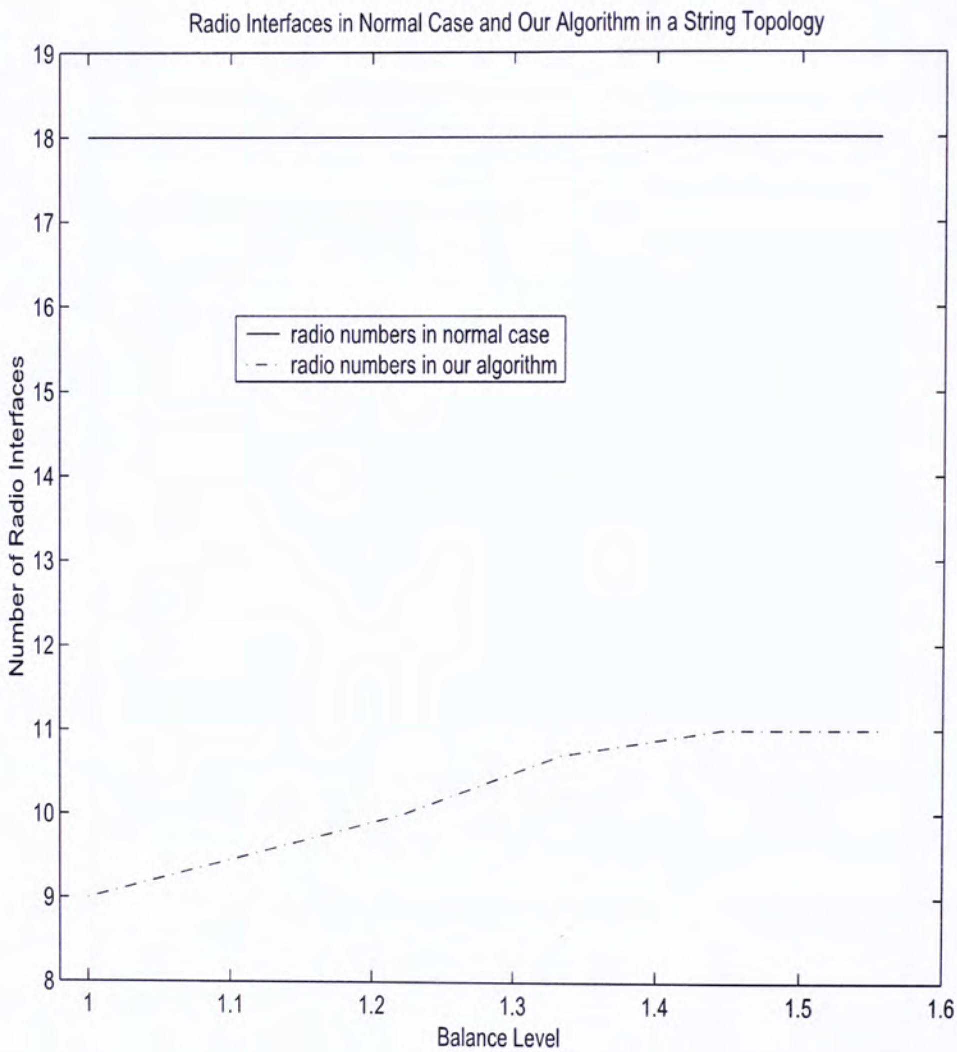

Figure 4.5: Number of Radio Interfaces in a String Topology

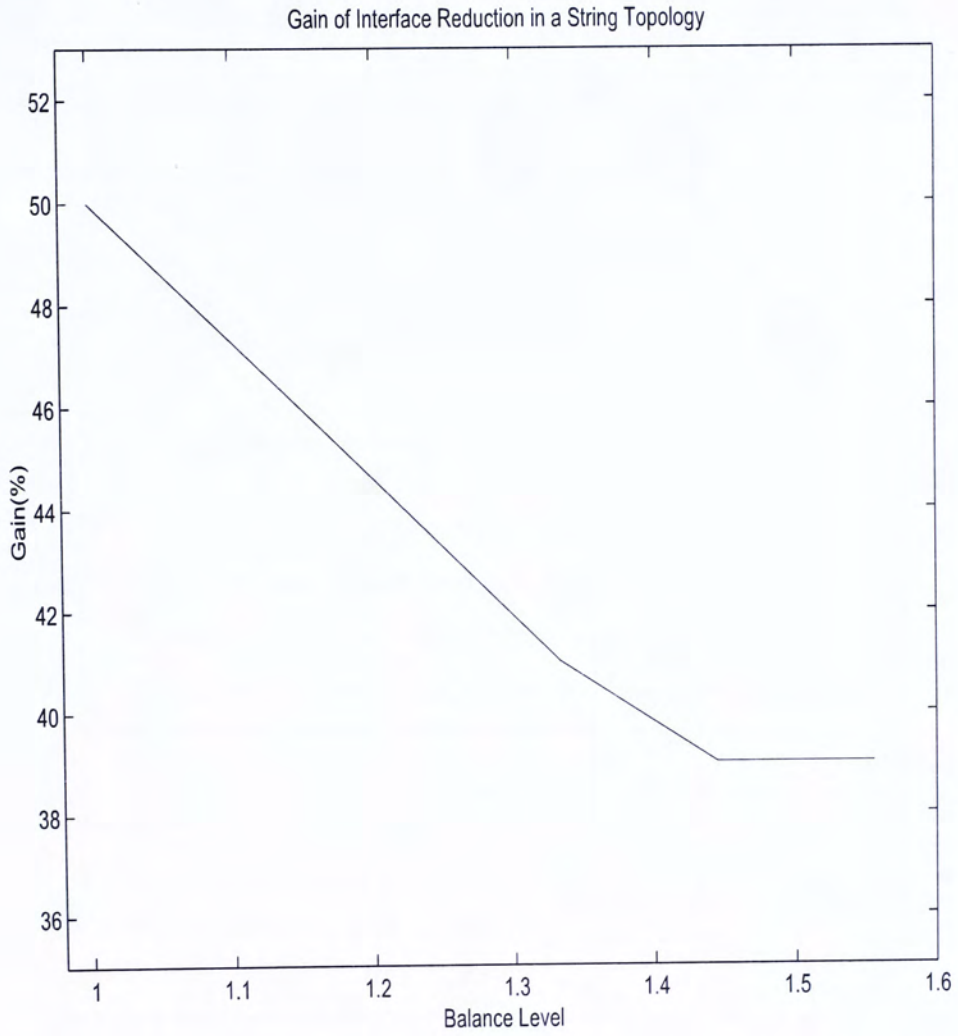

Figure 4.6: Gains of Radio Interface Reduction in a String Topology

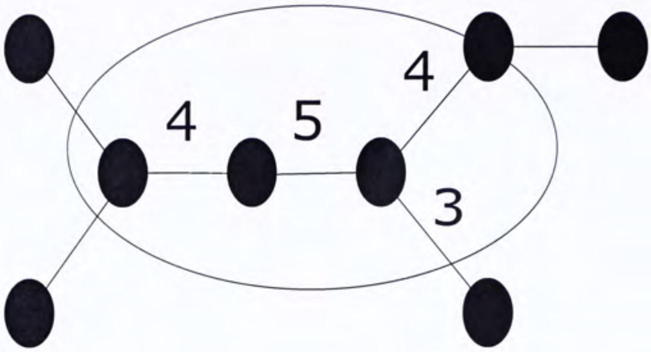

Figure 4.7: A Random Topology

Table 4.4: Gains under different traffic load in a random topology

Balance Level	Normal Case	Our Algorithm	Gain (%)
1	24	12	50
$\frac{9}{8}$	24	13.7	43
$\frac{5}{4}$	24	13.8	42.5
$\frac{11}{8}$	24	14	42
$\frac{3}{2}$	24	14.4	40
$\frac{13}{8}$	24	15	38
$\frac{27}{16}$	24	15	38

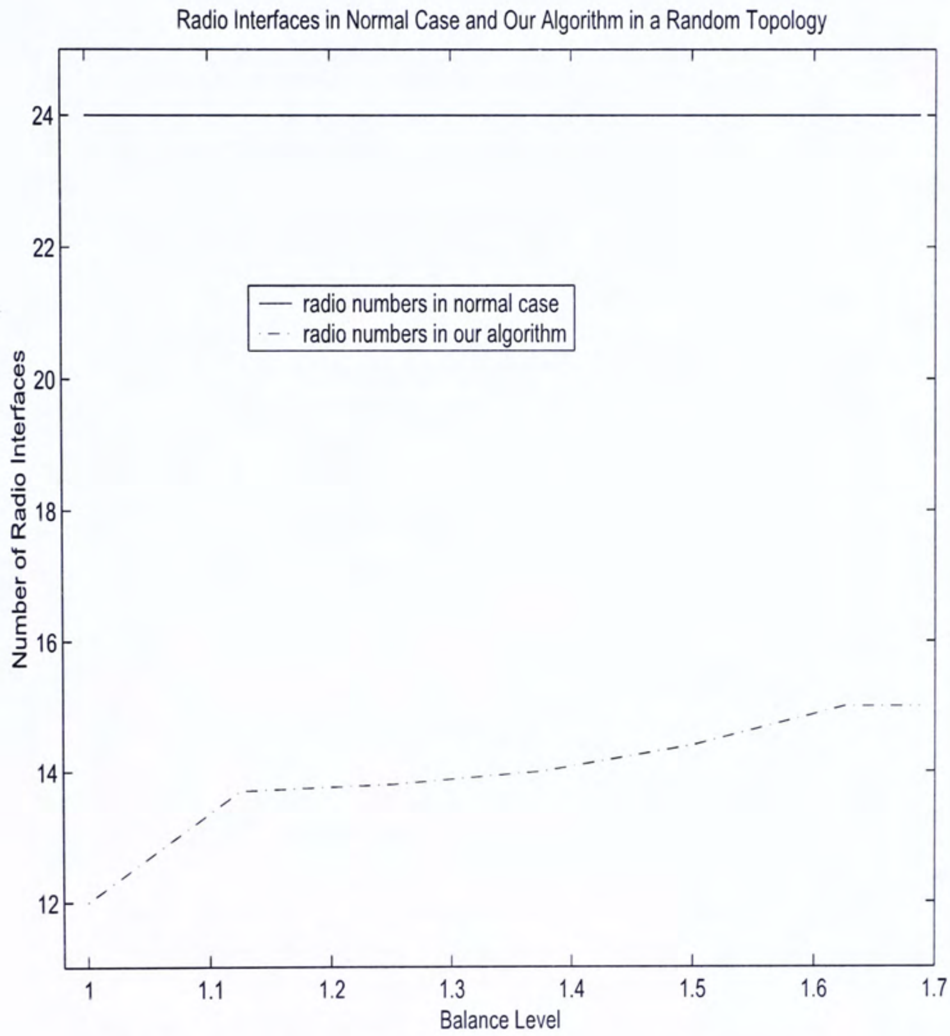

Figure 4.8: Number of Radio Interfaces in a Random Topology

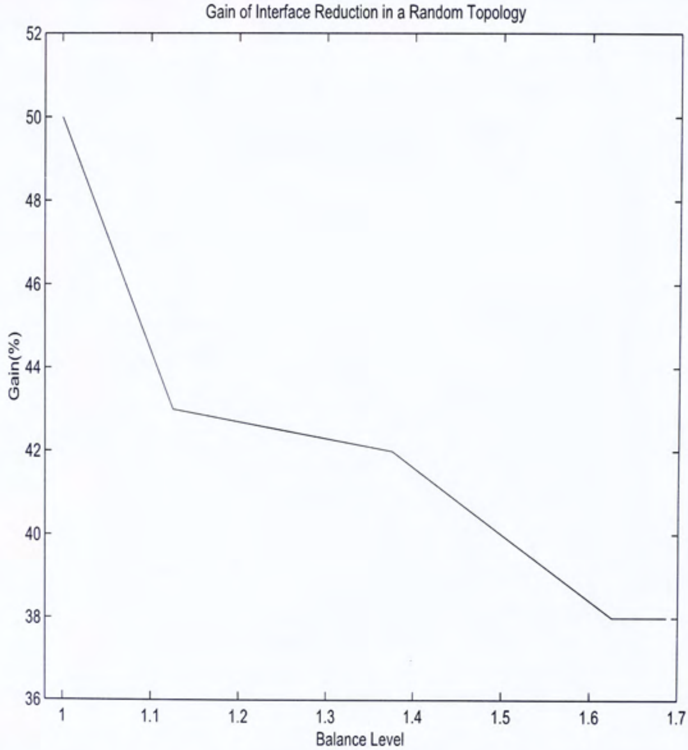

Figure 4.9: Gains of Radio Interfaces Reduction in a Random Topology

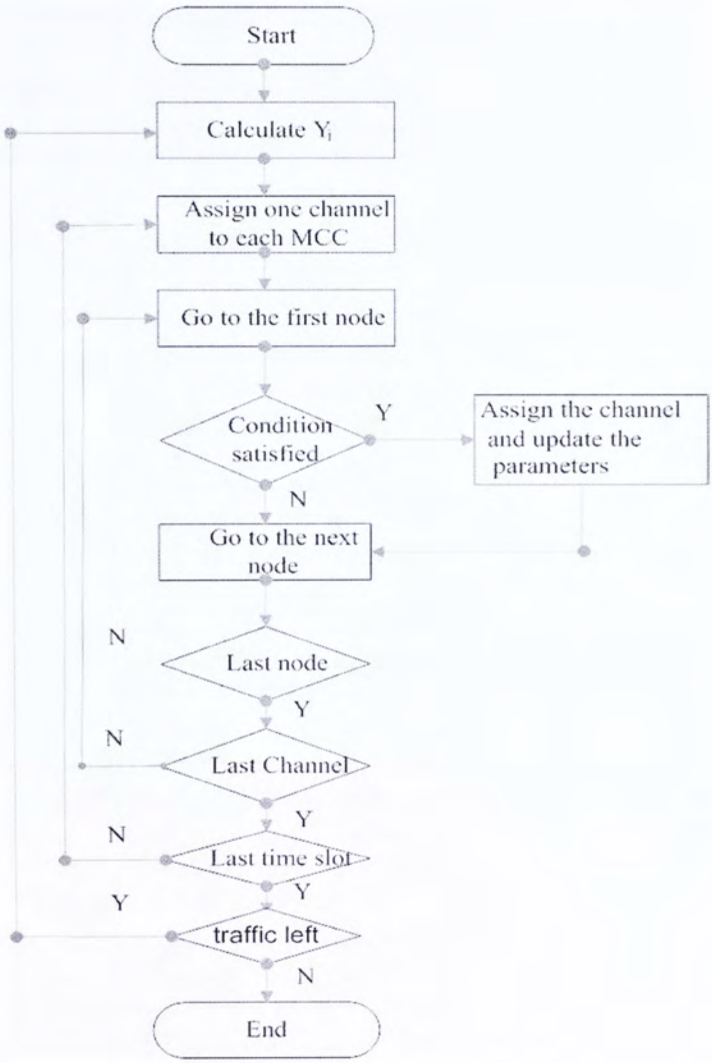

Figure 4.10: Flow Chart of the Algorithm

Both of the simulation results show that our algorithm outperforms the tradition method in a string topology and some random topologies. The whole process is summarized in Fig. 4.10.

□ **End of chapter.**

Chapter 5

Conclusion

Summary

This chapter aims to state our conclusion and to comment on some future work.

In this thesis, we look at some throughput characteristics in the multi-radio multi-channel WMNs under the realistic assumptions such as omnidirectional transmissions, multiple radio interfaces and interference effects among concurrent transmissions. We show that without network coding the maximum throughput in the m-radio n-channel case is bounded by n times the maximum throughput of the 1-radio 1-channel case. We give one concrete example to show that in the m-radio n-channel case using network coding can further increase the throughput.

In addition, we look into the resource allocation issue in the multi-radio multi-channel WMNs. We propose one algorithm to minimize the total number of radio interfaces used at each base station without affecting the maximum throughput when there is no restrictions on the number of radio interfaces used at each base station. We show by simulations that when traffic load is not balanced in the grid network, we do not need to place an equal amount of radio interfaces at each base station. When traffic load is becoming more and more balanced, the gain of the algorithm will become less and less. Finally, we generalize the basic idea in the algorithm to more general topologies.

However, there is still much work to be done. One tough problem is that although we give one example to show that in the multi-radio multi-channel case, network coding can improve the throughput and reduce the complexity of the network, how we can give a mathematical formulation is still a quite difficult issue.

Another tough problem is that whether we can make more accurate estimate about the smallest number of time slots needed in the period so that the decrease from the maximum throughput will be minimum. Besides, our algorithm in chapter 4 is a heuristic one and it does not work well where the traffic load is quite balanced in the network. We will take all these into account in our further studies on the throughput analysis and resource allocation in the multi-radio multi-channel WMNs.

□ **End of chapter.**

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