JOINT LINK/PACKET SCHEDULING, RATE ALLOCATION AND ROUTING IN STDMA BASED MULTI-CHANNEL/RADIO/RATE WIRELESS MESH NETWORKS

A THESIS

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By

Fazlı KAYBAL

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I certify that I have read this thesis and that in my opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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ABSTRACT

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In this thesis, we study the joint scheduling and routing problem in spatial reuse Time Division Multiple Access (STDMA) based multi-channel/multi-radio/multi-rate wireless mesh networks (WMNs). The main objective of the joint scheduling and routing problem addressed in thesis is to reduce the number of required TDMA time slots to deliver all packets to their destinations. Since the optimum solution to the problem is NP-hard, we propose a greedy iterative solution methodology. The problem is formulated as an integer linear program (ILP) under the physical interference model. We consider two versions of the problem in order to investigate the factors affecting the capacity of WMNs. In the first one, we perform scheduling and routing when the number of channels and number of radios are varied for multi-rate WMNs where nodes are equipped with omni-directional antennas. This analysis is done for both single-class (best-effort traffic) and two-class (best-effort and delay sensitive classes) traffic models. We then extend this analysis by adding the power control scheme which allows transmitters to change the transmitting powers slot-by-slot. Finally, joint scheduling and routing problem is extended for WMNs where nodes are equipped with multiple sectored antennas. We show that the network performance is improved with more radio resources, e.g., using multiple orthogonal channels, multiple radios per node, transmit power control scheme, and directional antennas in terms of delay and total dissipated energy. The network throughput when using 3 channels and 3 radios is increased by up to 67.2% compared to single channel WMNs and the total dissipated energy is reduced by up to 45.5% with transmit power control scheme. Finally, when directional antennas with 6 sectors are used at both transmitters and receivers, the network throughput increases by up to 72.6% compared to omni-directional antenna case.

Keywords:Wireless mesh networks, joint routing and scheduling, STDMA, multi-channel/multi-radio/multi-rate networks, transmit power control, directional antennas

ÖZET

STDMA TABANLI ÇOKLU-KANALLI/RADYOLU/HIZLI KABLOSUZ ÖRGÜ AĞLARDA BİRLEŞİK LİNK/PAKET PLANLAMASI, HIZ ATAMASI VE YÖNLENDİRME

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Bu tezde, biz STDMA tabanlı çoklu-kanallı/radyolu/hızlı kablosuz örgü ağlarda birleşik planlama ve yönlendirme problemini çalıştık. Bu tezde değinilen birleşik planlama ve yönlendirme probleminin ana hedefi, tüm paketleri hedeflerine göndermek için gerekli olan TDMA slot sayısını azaltmaktır. Bu probleme karşılık gelen en iyi çözüm NP-zor olduğu için, biz açgözlü tekrarlamalı bir çözüm yöntemi öneriyoruz. Bu problem bir tam sayı doğrusal programı şeklinde fiziksel enterferans modeli altında formülleştirilmiştir. Kablosuz örgü ağlarının kapasitesine hangi elemanların etkilediği hakkında fikir edinebilmek için problemin iki versiyonunu düşündük. İlkinde; planlama ve yönlendirmeyi, düğümlerin yönsüz antenlerle donatıldığı çoklu hızlı kablosuz örgü ağları için kanal ve radyo sayısı değişirken uyguladık. Bu analiz hem tek-tip hem de iki-tip trafik modelleri için yapıldı. Bu analizi ileticilere iletim güçlerini slottan slota değiştimesine izin veren güç kontrol planını ekleyerek genişlettik. Son olarak; birleşik yönlendirme ve planlama problemi, düğümlerin çoklu sektör antenlerle donatıldığı kablosuz örgü ağları için genişletilmiştir. Biz ağ performansının daha

fazla radyo kaynağı ile; örneğin, birçok kanal, düğüm başına birçok radyo, iletim güç kontrol planı ve yönlü anten kullanılırak, gecikme ve harcanan toplam enerji açısından geliştirildiğini gösterdik. Network işlem hacmi 3 kanal ve 3 radyo kullanıldığında tek kanallı kablosuz örgü ağlarına göre % 67.2'ye kadar artıyor ve toplam haracan enerji, iletim güç kontrol planı kullanıldığında % 45.5'e kadar azalıyor. Son olarak, alıcıların ve vericilerin 6 sektörlü antenler kullanıldığı durumda yönlü antenler kullanımı network işlem hacmini yönsüz antenlerin kullanıldığı duruma göre % 72.6'ya kadar arttırıyor.

Anahtar Kelimeler: Kablosuz Örgü Ağlar, birleşik yönlendirme ve planlama, STDMA, çoklu kanallı/çoklu radyolu/çoklu hızlı ağlar, iletim güç kontrolü, yönlü antenler

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To my parents and brothers...

Chapter 1

INTRODUCTION

Wireless mesh networks have recently attracted the attention of the researchers since mesh networks provide a more practical solution for providing the Internet service compared to wired networks. This practical solution can be achieved through easy and low-cost deployments of mesh networks since mesh routers form the backbone of mesh networks and provide services such as Internet to mesh clients through relaying traffic between them until the traffic reaches gateway mesh routers that have wired Internet connections. Mesh routers are rarely mobile and may not have power constraints. On the contrary, mesh clients can be mobile and can operate based on batteries.

One of the major problems in wireless mesh networks is the capacity reduction due to interference caused by multiple parallel transmissions [1]. Channel diversity (using multiple channels with single radio or multiple radios per node) can alleviate this problem. However, interference is still a problem in multi-channel/multi-radio wireless mesh networks due to the limited number of available orthogonal channels. Further improvements can be achieved through spatial diversity (e.g. transmit power control, multi-rate transmission and directional antennas). In addition to this, the cross-interaction between different layers of the protocol stack (cross-layer design) is viewed as a promising technique in order to increase the network throughput by jointly allocating the network resources, i.e., multiple channels, multiple radios, multi-rate transmissions, transmit power control and directional antennas, in a more efficient manner.

Joint scheduling and routing algorithms, which combines the link layer and the network layer together, are presented as cross-layer design approach in order to optimize the network performance in wireless mesh networks. These algorithms usually use Spatial-reuse Time Division Multiple Access (STDMA) schemes to allocate network resources when scheduling links. STDMA is the extended version of the TDMA scheme (which divides time into slots and lets only one link be active in each slot) such that it enables more than one link in a single TDMA slot if the receivers at all links satisfy the requirements of the interference model adapted in the physical layer.

In the literature, two mainly used interference models exist, namely: the protocol and physical interference models [1]. The protocol interference model defines the communication and interference regions to determine successful parallel transmissions. In this model, interference is assumed to be pair-wise, i.e., interference by another transmitter either corrupts a transmission if and only if it occurs inside the interference region of the intended receiver. In the physical interference model, a successful transmission depends on whether the signal-to-interference and noise ratio (SINR) is above a given threshold (depending on transmission rate) at the intended receiver. In contrast to the protocol interference model, the physical interference model takes into account the cumulative effects of all interferers. Since interference is not simply pair-wise and the cumulative effects of interference must be considered when deciding on which transmissions are successful, the physical interference model provides more accurate results.

The physical layer provides multi-rate communication under SINR constraints with adaptive modulation and coding (AMC) techniques. According to AMC, SINR thresholds are defined for each transmission rate and SINR value at a receiver must be above the defined SINR threshold corresponding to a rate in order to realize transmissions at this rate. Obviously, high transmission rates require high SINR thresholds compared to lower transmission rates and a transmitter can send multiple packets in a time slot using the AMC technique.

In addition to Internet service, wireless mesh networks offer additional services such as providing broadband home networking to mobile users. Since clients can demand good service and quality guarantees, network resources should be efficiently utilized. Besides that, wireless network capacity is reduced due to multiple parallel transmissions. Joint scheduling/routing algorithms, channel diversity, power control mechanism, multi-rate transmission and directional antennas are presented as the most effective tools to increase the network performance and provide services for providing better quality to clients.

In this thesis, we study joint packet/link scheduling, rate allocation and routing in STDMA based multi-radio/channel/rate wireless mesh networks. For a given packet traffic matrix, we define an optimization problem such that the maximum delay required in order to deliver all packets to their respective destinations is minimized. In each time slot, a set of links are selected for establishment and transmission rates are allocated to these links such that the minimum SINR constraints at all receivers are satisfied. Once the links and their rates are chosen, packets are forwarded across these links subject to the capacity constraints. This procedure continues until all packets reach their destinations. The resulting optimization problem is formulated as an integer linear programming (ILP) problem. Since the slot-duration defined by the TDMA scheme is fixed, rates can be translated into the number of packets transmitted per slot.

To get more insights into what factors affect the capacity of WMNs, we consider two versions of problem. In the first one, we perform scheduling and routing when the number of channels and number of radios are varied for multi-rate WMNs where nodes are equipped with omni-directional antennas. This analysis is done for both single-class (best-effort traffic) and two-class (best-effort and delay sensitive classes) traffic models. We extend this analysis by adding a power control scheme which allows transmitters to change transmitting powers slot-by-slot. Finally, joint scheduling and routing problem is extended for WMNs where nodes are equipped with multiple sectored antennas. The effects of parameters related with directional antennas such as beamwidth and antenna gain on the capacity are also analyzed.

It is observed that increasing number of channels (C) significantly improves network performance. The delay is reduced by 64.9% when increasing C from 1 to 3 as the number of radios per node (M) is kept fixed. On the other hand, increasing M has slight effects on the network performance. Only 7.6% improvement is achieved by increasing M from 1 to 3 when C is fixed. Increasing transmission power (P) from 10 mW to 80 mW in multi-channel/radio/rate WMNs, the delay is reduced by 40.6%. Power control scheme helps to reduce the total dissipated energy in the network by 45.5% compared to fixed power case. Using directional antennas also improves network performance significantly and the delay is reduced by 72.6% compared to omni-directional antenna cases when the number of antenna sectors (K) is 6 and directional antennas are used at both transmitters and receivers.

The main objective of the joint scheduling/routing problem addressed in this thesis is to reduce the number of required TDMA time slots to deliver all packets to their destinations (hereinafter referred to as the frame length). We do not directly seek the minimum frame length since the number of the set of feasible transmission rates on all links that can be scheduled in the same slot increases exponentially with increasing number of links, radios and channels involved [2]. In addition to this, it is pointed out in [3] that even the derivation of all feasible scheduling in a single-channel wireless network is an NP-hard problem. Instead, we resort to heuristic objectives that indirectly reduce the frame length. We investigate the proposed models in a realistic topology for different traffic entries and discuss the effects of parameters on the solution.

The remaining part of the thesis is organized as follows: In the next chapter, we provide some background information about wireless mesh networks. We also describe the previous studies related to our work and our contributions to the stated problem. In Chapter 3, we describe the proposed ILP model and our solution methodology to joint scheduling/routing problem. Then, we provide numerical results to discuss the effects of studied parameters. In Chapter 4, we adapt the ILP model such that communication between nodes is realized through using directional antennas. We also describe the effects of using directional antennas. Finally, we discuss the obtained results and conclude the thesis in Chapter 5.

Chapter 2

LITERATURE REVIEW

In this chapter, we first give information about wireless mesh networks in order to provide some background information. Next, we describe some of the previous studies that deal with multi-channel/multi-radio wireless mesh networks, the impacts of power control mechanisms and directional antennas in WMNs. Finally, we state the contributions of the thesis to the described problems.

2.1 Wireless Mesh Networks

Wireless Mesh Network (WMN) is a broadband wireless network, composed of mesh routers and mesh clients that are interconnected via wireless links to form a multi-hop network [4]. Wireless Mesh Networks provide a large coverage area through multi-hop communication among mesh routers which provide network access to mesh clients. Mesh routers aggregate traffic from mesh clients and relay these traffic to other mesh routers.

In addition to the routing functionality, mesh routers can act as a gateway since some routers can have more than one wireless network interface card or a wired Internet connection. This feature of mesh routers brings one of the most important features of wireless mesh networks that provide last-mile broadband Internet access to end-users. Wireless links can replace physical wires and an inexpensive and easy solution of Internet access is presented to clients such as in remote villages, dense business environment where the deployment of wired network is too expensive or difficult.

Mesh routers are stable and have no energy constraints since they do not operate based on batteries. On the contrary, mesh clients can be mobile and energy consumption is a crucial issue for them. Mesh clients can act as a router but gateway function is not available in these nodes.

Application areas of wireless mesh networks are not only limited to providing Internet Services to mobile clients but mesh networks can also be deemed to be used in building automation, broadband home networking, community and neighborhood networks [4], video surveillance and perimeter security, mines and industrial sites, military communication, sports events, emergency and hostility formed networks, railway and highway corridors, VoIP phone applications [5], etc.

Services such as VoIP phone applications, IPTV distribution in home networks and video surveillance can demand high bit rate, low latency and low bit error probability. However, Gupta and Kumar [1] state that capacity in multi-hop wireless network decreases due to interference caused by multiple parallel transmissions. To overcome this problem, techniques such as cross-layer design, multi-channel/multi-radio technology, directional antennas, multi-rate transmission technology and transmit power control algorithms are proposed. However, these methods are strongly coupled with the interference models adapted in the physical layer [6, 7].

One of the most widely used channel access scheme for wireless networks is Time Division Multiple Access (TDMA). Spatial TDMA is proposed for increasing the efficiency of TDMA such that radios with a sufficient spatial separation can use the same time slot for transmission. STDMA divides the time horizon into time slots and the interference models determine which transmitter-receiver pairs share the time slot. The protocol and physical interference models are proposed to describe which links can be simultaneously active in a STDMA slot [1]. The protocol model basically defines the interference and communication regions to determine active parallel links in the time slot. A receiver can only receive signals from the nodes in the communication region and no node in the interference region of the intended receiver transmits for a successfully received transmission. The physical interference model, on the other hand, states that if signal-to-interference and noise ratio (SINR) is above a given threshold (depending on transmission rate) at the intended receiver, the signal can be successfully decoded. The condition for successful concurrent transmissions is that SINR must be above the given threshold at all receivers. The physical model provides a more accurate model since it takes into account the cumulative effect of interference. On the other hand, the protocol model only considers the effects of transmissions that occur inside the interference region, i.e, it ignores the cumulative effect of interference.

Next, we introduce some techniques that are used to overcome capacity degradation in wireless mesh networks due to interference caused by multiple concurrent transmissions.

The first technique to overcome the capacity degradation problem in WMNs is multi-rate transmission technology [8, 9, 10]. Physical layer provides multiple transmission rates with adaptive modulation and coding (AMC) technique. A transmitter chooses its transmission rate depending on the transmitting power and the channel propagation conditions. To receive packets at a desired rate, a receiver has to satisfy minimum SINR value which is selected such that the packet error rate will be sufficiently low. With the AMC scheme in STDMA, the link layer (or MAC layer) can schedule several links at low-rates or fewer links at high-rates. Physical layer needs to interact with the link layer to adapt its transmission parameters such as modulation and coding schemes to the link quality in order to provide optimum network performance.

Power control scheme is also used in order to improve the network capacity since SINR value depends on transmitting power. With the power control scheme, it is possible to increase transmission rate with radiating higher power from the transmitter but this can lead to a decrease in transmission rates of nearby nodes by causing higher interference. Power control scheme can optimize the transmitting power at each transmitter such that the minimum power value satisfying the minimum SINR level is selected. This can lead to an increase in spatial reuse (i.e., multiple parallel transmissions) since transmitting power directly affect SINRs of other receivers and thus their link rates. Similarly in multi-rate communication, the link layer decides on transmitting powers to optimize the network performance.

Multi-channel networks (with single radio or multiple radios) also increase the network capacity since interference between nearby receivers can be reduced significantly. In order to eliminate interference completely, each transmission has to place in separate channels. This is usually impossible and interference still exists in multi-channel network. There is a need for an efficient channel assignment algorithm that assigns each radio to channels in order to increase capacity since the number of radios per node and the number of channels in the network are not usually equal and interference is still a major problem. Channel assignment algorithms proposed in the literature are categorized into three groups according to the frequency of assignment: Dynamic, semi-dynamic and static channel assignments. In dynamic channel assignment, each radio can switch channel per slot basis. In semi-dynamic channel assignment, channel switching interval is much longer than the slot duration, e.g., minutes, hours or even days. Static channel assignment does not make any change after assigning channels to each radio. Although dynamic channel assignment has the potential of using network resources more efficiently, there is an overhead associated with channel switching due to switching times.

A further improvement in capacity can be achieved by using the multi-radio technology where each node is equipped with multiple wireless network interface cards (NICs or radios). A node with single NIC can either receive or transmit at a given time while a node with multiple NICs can transmit to and receive from other nodes concurrently in separate channels. The main advantages of using multiple NICs over single NIC are that duplex communication is possible and channel switching cost is reduced. The number of radios has to be equal or less than the number of channels, otherwise some radios may need to be idle due to high interference. In order to efficiently utilize multi-radio/multi-channel technology, three layers (physical, link and network layer) need to be considered jointly together since channel assignment affects link bandwidth, the set of parallel links and routes.

Using directional antennas is another way to increase the network capacity when the network capacity cannot be further improved with multi-channel/multi-radio technology and power control mechanisms. The main advantage of directional antenna is the non-uniform antenna gain. This non-uniformity increases spatial reuse since it reduces the interference and increases the received signal strength at the intended receiver. In order to utilize directional antennas efficiently, cross-relation between physical and link layer is necessary.

The characteristics belonging to wireless mesh networks that were stated above such as multi-rate transmission, channel diversity, directional antennas and transmit power control schemes, make cross-interaction between different protocol layers indispensable. In addition to these, multi-hop communication among mesh routers also entails cross-interaction between different protocol layers and brings several design challenges to different layers of protocol stack since routes do not have to be fixed or single in multi-hop communication and routes can be changed with varying link capacity. Therefore, the link layer and the network layer become interdependent and the network layer needs to cooperate with the link layer so as to maximize the network capacity. This is called the joint routing and scheduling problem.

Cross-layer design which solves the joint routing and scheduling problem can significantly improve network performance. There are two ways to implement a cross-layer design, loosely-coupled and tightly-coupled architectures [11]. In the loosely coupled cross-layer design, transparency between protocol layers still exists and one layer can use some parameters from other layers in order to optimize its functions. In the tightly coupled cross-layer design, protocol layers are combined altogether to optimize the network performance and so transparency between layers disappears. Cross-layer design can be possible between multiple layers or between just two layers. For instance, physical, link and network layers may be considered as a single layer and they can be optimized jointly. The main advantage of tightly coupled schemes over loosely coupled schemes is to provide better network performance since it gathers all parameters in one layer rather than passing information from one layer to another when optimizing the network performance. However, the complexity and modularity of the overall system is adversely affected due to increased sophistication.

So far, we described the techniques to overcome capacity degradation problem in WMNs. The next sections report previous studies that mainly deal with the effects of multi-channel/multi-radio wireless mesh networks, power control schemes and directional antennas on the capacity.

2.2 Multi-Channel/Multi-Radio WMNs

Since the capacity in wireless networks is degraded due to multiple simultaneous transmissions, multi-channel/multi-radio technology is presented to overcome this problem. Co-channel interference can be eliminated considerably via using multiple orthogonal channels and this results in higher network throughput or lower system activation time. The network performance can also be improved further through using nodes with multi-radios that can switch among available channels. Despite the advantages of multi-channel/multi-radio wireless networks, this technology also provides challenges in the design of efficient routing and scheduling algorithms. We divide this section into two subsections according to the traffic types that are considered in the thesis: Single-class traffic and QoS traffic.

2.2.1 Single-Class Traffic

The studies in this section consider that only single type of traffic (best-effort or data traffic) exists in the network.

In [2], the achievable performance gain offered by multi-radio/multi-channel is investigated under varying conditions such as the number of radio at each node, the network/channel status and the traffic load. The performance is measured by minimum total time to deliver the given traffic load and the problem is formulated as an ILP for joint routing and scheduling optimization problem and solved by a column generation based approach. The system activation time in delivering given traffic matrix over multi-radio/multi-channel wireless mesh network decreases when more radios are used at each node and more orthogonal channels are provided. The comparison between joint multi-path routing and shortest path (SP) routing is also provided in this paper. The results show that the joint multi-path routing approach requires lower system time requirement than SP routing since SP routing is a subset of the joint multi-path routing and so it cannot schedule as more links as the joint multi-path routing. In this thesis, we also use joint multi-path routing due to the reasons stated in [2].

Jain et.al. [3] present a methodology to derive upper and lower bounds on the optimum throughput in a multi-hop wireless network for a given matrix and topology. They use a conflict graph to model the wireless interference and analyze their method under various conditions such as multiple channels and multiple radios. Increasing the number of channels in the network improves the maximum achievable throughput.

Li et.al. [7] consider the problem of joint dynamic channel assignment, link scheduling and routing for throughput optimization in multi-channel/multi-radio wireless mesh networks. They propose an efficient algorithm for throughput and fairness optimization by considering several interference models. They analyze the impacts of the number of channels, the number of radios per node, channel combining and interference model on the throughput and fairness in wireless mesh networks. They point out that increasing the number of channels improves the throughput and fairness, the throughput and fairness does not increase always with the increasing number of radios per node and finally, the throughput and the fairness depend on the interference models adapted in the physical layer.

Soldati and Johansson [12] study the problem of joint end-to-end rate optimization, scheduling, rate and power adaptation scheme in OFDMA based multi-channel/multi-radio WMNs. The problem is formulated as ILP model under SINR-based interference model. Since the optimal solution to this problem is hard to achieve, the authors propose two methods, namely: inner column generation and a greedy heuristic methods. These methods perform close to the optimum solution and significantly reduce the computation times required to solve the problem.

Raniwala et al. [13] propose a multi-channel wireless mesh network architecture (called Hyacinth) where each mesh network node is equipped with multiple 802.11 network interface cards. The paper presents distributed channel assignment algorithm which dynamically assign NICs to channels and routes packets by only utilizing local traffic load information. The authors point out that throughput increases when the number of non-overlapping channels increases.

Kyasanur and Vaidya [14] study the impact of number of channels and the number of radios per node on the capacity of arbitrary and random wireless networks. They show that the capacity depends on the ratio of number of channels and number of radios, which is denoted by ρ, instead of the exact values of either number of channels or number of radios. In a random network, there is no capacity degradation even with a single radio when the ratio of ρ is less than $logN$ where N denotes the network size. They also prove that in a random network with up to $O(logN)$ channels, capacity is not affected from interface switching delay cost. In a random network, there is a capacity loss by a factor of $1 - \sqrt{\rho}$ when the ratio of ρ is less than N.

Alicherry et.al. [15] present a joint channel assignment and routing algorithm for throughput optimization. Due to the fact that there is no hardware at the time of writing of the paper which allows radios to frequently change channels, static link channel assignment is proposed. The effect of multi-radio/multi-channel on the capacity is analyzed for the proposed algorithm. As the number of channel increases, throughput significantly improves. Throughput improves slightly with increasing number of radios per node since link channel assignment is static.

An integer linear programming formulation for the problem is proposed in [16] which aims to maximize the global network throughput by reducing the interference and contention. Dynamic channel assignment with static routing information is considered for multi-radio/multi-channel WMNs where nodes have multiple NICs that can switch between available channels per slot basis. The effects of the number of channels and NICs on the proposed model are analyzed. When the number of NICs on each node is fixed, the throughput improves with the increasing number of channels since interference and contention decrease and adding NICs to each node does not always increase the throughput when the number of channels is fixed.

Kodialam et.al. [17] propose joint routing, link channel assignment and scheduling algorithms in order to derive lower and upper bounds on the achievable throughput in multi-radio/multi-channel single-rate wireless mesh networks. They propose two link channel assignment schemes: namely, dynamic and static link channel assignment schemes. The dynamic link channel assignment scheme outperforms static link channel assignment scheme since dynamic link channel assignment updates itself at each slot according to link quality and traffic pattern and static link channel assignment is a special case of dynamic link channel assignment. In our thesis, we use dynamic link channel assignment scheme due to the reasons stated in [17]. The authors also analyze the effects of some parameters such as the number of radios that each node has and the number of channels in the network for two different topologies and link channel assignment algorithms. The throughput increases considerably with increasing number of channels while the number of radios is kept fixed. However, increasing number of radios per node slightly improves the throughput.

The authors of [18] consider the problem of joint optimization of power control, channel assignment and scheduling in multi-channel/multi-radio wireless mesh networks. Rather than formulating the problem jointly, they divide the problem into sub-problems each formulated as linear programming problems in order to maximize the network throughput under the fairness constraint for a given network and traffic demands. They show that under the protocol interference model, the throughput increases with increasing transmission power, the number of channels in the network, and the number of radios per node. Their suboptimum solution performs closed to the optimum solution. The authors also state that at most 3 channels can be utilized efficiently when each node is equipped with a single radio; otherwise the throughput saturates for further values of the number of channels.

An optimization model is proposed in [19] which aims to find a static channel assignment that maximize the number of simultaneous bidirectional links in the multi-channel/multi-radio wireless mesh network subject to interference constraints. It is shown that the number of parallel links increases by increasing the number of channels in the network and the number of radios per node.

2.2.2 QoS Traffic in WMNs

Since the capacity is limited in wireless networks, quality of service (QoS) guarantees are crucial for such services that demand guaranteed bandwidth, maximum packet dropping probability and maximum delay constraints. For instance, real-time streaming multimedia applications such as VoIP (voice over IP) and IP-TV over wireless LANs (WLANs) require minimum bit rate in order to function properly and these applications are also delay sensitive. Thus, wireless networks have to support the required rates to such applications. QoS provides different priorities to different applications in order to guarantee a certain level of performance to each application.

Niculescu et.al. [20] study the performance of VoIP in a 802.11 based Wireless Mesh Network. They aim to increase the number of supported calls and maintain QoS under internal and external interference using several optimization techniques such as use of multiple radios, efficient routing and use of multi-hop packet aggregation. They propose efficient routing as the most appropriate tool for carrying real-time traffic in wireless mesh networks operating in an unlicensed band. They also state that the number of calls supported increases with using multiple radios since the use of multiple radios creates channel diversity as well as path diversity.

In [21], the authors present an effective heuristic for interference-aware topology control and an optimal algorithm for QoS routing in multi-channel wireless mesh network. They formulate the Bandwidth-Aware Routing (BAR) problem which seeks routes for QoS connections with bandwidth requirements. They solve the BAR problem presenting a polynomial time optimal algorithm under the assumption that traffic demands are splittable. Besides that, they propose an effective heuristic for the minimum Interference Survivable Topology Control (INSTC) problem which seeks a static channel assignment for the given network such that the induced network topology is interference-minimum among all K-connected topologies. The blocking ratios of the proposed algorithm are compared with the blocking ratios of the existing algorithms under different resource utilizations. The proposed algorithm outperforms the existing algorithms in terms of decreasing blocking ratios of QoS packets. Quite consistent with the earlier results of multi-channel/multi-radio networks, the performance improvement becomes more noticeable when more network resources such as the number of radios in one node and the number of channels in the network become available.

2.3 Impact of Power Control in WMNs

Due to the limited number of available channels, interference cannot be eliminated further with multi-channel/multi-radio technology. Power control mechanisms are presented to solve this problem and increase the network throughput. Power control mechanisms can adjust transmission powers at each transmitter such that more parallel links can be achievable and interference among nearby nodes can be efficiently eliminated.

Scheduling using a power control mechanism in TDMA based multi-rate/single-channel WMNs is studied [10]. Three versions of the problem, namely fixed power and rate, variable power and fixed rate, and variable power and rate, are investigated. Mixed Integer Linear Programming (MILP) and Column Generation(CG) models are proposed to minimize (or provide the lower bounds for) the number of needed time slots to deliver packets to their destinations across predefined routes. CG model requires less computation time than MILP model but both models are not able to solve the problem when complexity of the problem is increased.

The study of Cruz and Santhanam [8] considers the problem of joint routing, scheduling and power control to support high data rates for broadband wireless multi-hop network. They present an algorithm to compute an optimal link scheduling and power control policy that minimizes the total average transmission power in the wireless multi-hop network, subject to given constraints regarding the minimum average data rate per link, as well as peak transmission power constraints per node and SINR constraints. In addition, they provide a joint routing, scheduling and power control algorithm using link costs obtained from the algorithm.

Bhatia and Kodialam [9] study the problem of joint routing, scheduling and power control for wireless multi-hop networks. They formulate the problem as an optimization problem with a non-linear objective function and a set of non-linear constraints such that the overall network energy consumption is minimized for a given rate. The authors provide a lower bound on total energy consumption and a feasible solution to the joint routing, scheduling and power control problem.

Kozat et.al. [22] study the joint problem of scheduling and power control for given routes in multi-hop wireless networks. They propose algorithms that minimize the total transmit power while providing end-to-end QoS for sessions in terms of their bandwidth and bit-error-rate (BER) guarantees.

The authors in [23] focus on power control algorithms in TDMA based wireless mesh networks in order to decrease radio interference between wireless links while taking the path lengths between source and destination pairs into account. They aim to improve spatial reuse in WMNs through decreasing the number of time-slots needed for all transmission on links. Their proposed method decreases the number of needed time-slots by up to 22% when all configurations are optimal.

Li and Ephremides [24] consider a centralized algorithm for joint routing, scheduling and power control in ad hoc wireless networks. They take into account energy efficiency as well as queue sizes and blocking less traffic in neighboring links when designing the algorithm. The study compares performances of scheduling with power control and without power control and shows that scheduling with power control outperforms scheduling without power control. Besides that, joint scheduling and routing scheme improves network performance in terms of delay and throughput.

The authors in [25] consider the problem of power control in multi-channel/multi-radio wireless mesh networks. They propose a heuristic algorithm to improve network performance such as decreasing the total energy consumption and increasing the spatial reuse. They use RTS/CTS mechanism to control simultaneous transmissions. The proposed power control scheme outperforms fixed power scheme in terms of less energy usage and more parallel links.

2.4 Impact of Directional Antennas in WMNs

Due to limited number of available channels, the capacity cannot be further improved with multi-channel/multi-radio technology. Directional antennas has emerged as a promising radio technology to advance the network capacity. Directional antennas increase signal quality through beamforming, reduce interference through null steering and increase spatial reuse factor through non-uniform antenna gain.

The study in [10] is extended in [26] to joint routing and scheduling optimization problem in WMNs where nodes are equipped with directional antennas. The problem formulation is based on Mixed Integer Linear Programming and it is solved using Column Generation approach. The aim is to minimize the number of required time slots to deliver packets to their destinations through multipath routing. Fixed power, power control, and power and rate control schemes are studied in TDMA based single-channel WMNs for cases where nodes are equipped with both omni-directional and directional antennas cases. With directional antennas, using power control scheme instead of fixed power scheme do not improve network capacity noticeably since interference is highly eliminated when directional antennas are used. They point out that using directional antennas can greatly increase network performance when compared to omni-directional antennas.

Blough et.al. [27] develop a scheduling algorithm to provide performance analysis under different resource utilization scenarios such as using only multiple overlapped channels and using both transmit power control and directional antennas. Shortest-path routing algorithm is used and each node has a single-radio that can switch between channels on a per packet basis. It is shown that using only power control has slight effect on the performance and using both channel diversity and directional antennas provides significant improvement on the performance.

In [28], the study of joint link scheduling and power control in wireless mesh networks with directional antennas is considered. They formulate and solve the problem as a Mixed Integer Linear Program (MILP) for switched-beam system under physical interference model. Besides that, they propose heuristic objectives in order to decrease the solution time. They analyze the impact of beamwidth, maximum transmission power on the throughput. The throughput increases with decreasing beamwidth and increasing maximum transmission power.

In [29, 30, 31], a capacity analysis for ad-hoc networks consisting of nodes that are equipped with multiple directional antennas is performed and the effects of important antenna parameters such as beamwidth and gain are analyzed. The results in [28, 29, 30] point out that throughput improves with decreasing antenna beamwidth and using directional antennas increases capacity since they reduce interference significantly and increase SINR at the intended receiver.

2.5 Contributions of the Thesis

In this thesis, we propose an Integer Linear Programming (ILP) model in order to solve joint link/packet scheduling, rate allocation and routing problem in TDMA based multi-channel/multi-radio/multi-rate wireless mesh networks. The main objective of joint scheduling/routing problem addressed in this thesis is to reduce the frame length rather than finding the minimum number of necessary time slots to deliver all traffic to their respective destinations since even the derivation of all feasible scheduling in a single channel wireless network is an NP-hard problem [3]. Therefore, we apply an iterative solution, i.e., we schedule links and packets that are transmitted across these links in each time slot. In the end of each iteration (or time slot), traffic matrix is updated and this procedure continues until all packets are transmitted to their destinations. We employ heuristic objectives that indirectly reduce the frame length. This structure allows us to reduce the computation time and quite-large problems that requires much computation time and more computer resources can be solved effectively.

The ILP model is implemented under the physical interference model (which is used in [6, 8, 10, 24, 26, 27, 28, 30]) that takes into account the cumulative effect of interference evaluating the Signal-to-Interference and Noise Ratios (SINRs) at receivers and is more realistic model than the protocol interference model (which is used in [3, 6, 7, 15, 16, 17, 19, 23, 29, 31]). Furthermore, the physical interference model determines the signal transmission rates according to SINRs at the corresponding receivers. With this structure, the implemented model also supports multi-rate communication between nodes [8, 9, 10].

In this thesis, we apply multi-path routing without defining any routes in advance. Routes are selected depending on which links are active. This multi-path routing increases the network throughput since it does not force the scheduling algorithm to activate any links [2].

We discuss the effects of number of channels (C) in the network, number of radios per node (M), power control scheme and directional antennas on the network throughput using the proposed models in the thesis.

The proposed ILP model supports multi-channel/multi-radio communication and we enable dynamic channel assignment [7, 13, 16] that assigns each radio interface to channels per slot basis. Dynamic channel assignment algorithms outperform static and semi-dynamic algorithms since they allow links to change their channels per slot basis resulting in better network performance in terms of delay and network throughput. We point out that the network throughput increases significantly with increasing number of orthogonal channels when M is constant since channel diversity increases the number of parallel links in each time slot. We also show that the throughput is improved slightly or not at all as M increases when C is kept fixed. It is also observed that increasing the transmission power also improves the throughput for all C and M values since the received signal qualities at the receivers are improved and this allows establishment of high rate links. When carrying real-time traffic (QoS), increasing C can be the most appropriate way to supply QoS traffic demands since the capacity increases as C increases.

We extend the ILP model such that the transmit power is introduced as a variable and each link can have a different transmit power in each time slot. Thus, the transmit power can change from slot to slot and node to node with this modification. The power control mechanism increases the throughput through activating more parallel links in each time slot and also decreases the total transmitted energy over the complete frame length by adjusting the transmission powers such that these power levels are selected to satisfy the minimum SINR values corresponding to the desired rates at the receivers.

Sectored antenna in conjunction with the flat-topped antenna model is also adapted to the proposed ILP model. We analyze the effects of directional antennas parameters such as beamforming types (receive, transmit and joint receive and transmit beamforming), beamwidth and sectorial points. We point out that using directional antennas has one of the most powerful way to increase the network performance since interference is eliminated through null steering and the received signal quality is improved through beamforming. Decreasing beamwidth (or increasing the number of sectors) improves the network throughput since the main lobe antenna gain is increased. We also show that beamforming types also affect the capacity and the best throughput is achieved through joint receive and transmit beamforming antennas since directional antennas are used at both receivers and transmitters. Increasing the transmit power still improves the throughput for receive and transmit beamforming cases. In addition to these, the throughput further improves with increasing number of channels and radios per node when nodes are equipped with directional antennas.

In the next chapter, we introduce the proposed ILP models and simulation results in order to explain the effects of multi-channel/multi-radio technology and power control scheme for both single-class and two-class traffic in STDMA based wireless mesh network with omni-directional antennas.

Chapter 3

JOINT SCHEDULING and ROUTING in WMNs

In this chapter, we formulate the joint scheduling/routing problem as an Integer Linear Program (ILP) in multi-channel/multi-radio/multi-rate TDMA based wireless mesh networks. We solve this problem for the following two cases: (1) the transmission power is fixed for all nodes and all time-slots, and (2) the transmission power is introduced as a variable and it can be changed from node-to-node and slot-to-slot. Numerical results are provided to get better insight of these two cases under varying conditions, i.e., the number of channels in the network and the number of radios per node. For the fixed power case, we extend this analysis such that two different traffic types (voice and data) exist together in the network.

3.1 Model Assumptions and Parameters

The following assumptions are used in the mathematical models for the joint scheduling, rate allocation and routing problem presented in Section 3.2.

- The system operates in a time-slotted mode (TDMA).
- We consider a WMN with a fixed number of nodes, N.
- Nodes are static.
- We only consider large-scale fading when modeling the path loss between nodes.
- There are K separate channels.
- Channels are orthogonal so that they do not produce any interference for other channels.
- Each node can tune its radio to any of the K channels with a negligible delay.
- Each node has M radios where $M \geq 1$ and $M \leq K$.
- The radios at the same node are connected to each other using a fully connected backplane with a negligibly small delay.

The following parameters are the inputs of our optimization problem:

The first set is used to define the nodes shown by $\mathcal{N}$. We need to assign a transmitter and a receiver for each link and these are selected from the node set. Routers are the elements of the node set.

$$\mathcal{N} := \{1,...,|\mathrm{N}|\}$$

The second set used in our problem is the channel set shown by $\mathcal{C}$. We need to assign a channel for each link in the network and assigned channel to each link is chosen from the channel set. The channel assigned to the link can vary from slot to slot.

$$\mathcal{C}:= \{1,...,|C|\}$$

The third set used in our problem is the rate (or SINR) set shown by $\mathcal{R}$. A rate is assigned to each connection in the network and each assigned rate is selected from $\mathcal{R}$ and has to satisfy corresponding SINR constraint given below.

$$\mathcal{R}:= \{1,...,|R|\}$$

The following table lists the minimum SINR (Signal-to-Interference and Noise Ratio) values corresponding to given transmission rates.

Table 3.1: *minimum SINR threshold vs. Rate for* $802.16e$ *with BER* $= 1e-4$

minimum SINR threshold (Ratio) (λ_k)	$R_k(Packets)$
63.0957	9
6.3096	4
1.9953	2

$T \equiv [\ T_{ij}\ ]$ is the traffic matrix among nodes, where T_{ij} is the number of packets destined from node i to node j, $\forall i, j \in \mathcal{N}$, and $T_{ii} = 0\ \forall i \in \mathcal{N}$.

$D \equiv [D_{ij}]$ is the distance matrix among nodes, where D_{ij} is the distance between node i and node j, $\forall i, j \in \mathcal{N}$, and $D_{ii} = 0\ \forall i \in \mathcal{N}$.

$P_{ij} \equiv$ Power is radiated from node i to node j, $\forall i, j \in \mathcal{N}$. In the first part of this chapter, we assume that P_{ij} is constant. We will then relax this assumption and make P_{ij} variable.

$L \equiv [L_{ij}]$ is the path loss matrix among nodes, where L_{ij} is the path loss between node i and node j, $\forall i, j \in \mathcal{N}$, and $L_{ii} = 1\ \forall i \in \mathcal{N}$. L_{ij} is given as:

$$L_{ij} \approx D_{ij}^{-\alpha}, \text{ where } \alpha \text{ is the path loss exponent.}$$

$N_0 \equiv$ Thermal noise at receivers

$HC \equiv [HC_{ij}]$ is the hop-count matrix among nodes, where HC_{ij} is the minimum hop-count distance between node i and node j, $\forall i, j \in \mathcal{N}$, and $HC_{ii} = 0$ $\forall i \in \mathcal{N}$.

$m_i \equiv (m_i, ..., m_{|N|})$ is the vector, where m_i is the sum of square of minimum hop-count distance from node i to all other nodes.

3.2 The Greedy Iterative Solution Methodology

In this section, we describe our greedy solution method to joint scheduling/routing problem in multi-channel/multi-radio/multi-rate TDMA based wireless mesh networks. In Figure 3.1, the flow-chart of the solution method is given. For a given traffic matrix, we schedule links and packets that are transmitted across these links in each iteration where each iteration corresponds to a slot. In the end of each iteration, the traffic matrix is updated. This process is repeated until all packets are delivered to their respective destinations. We use this greedy sub-optimal iterative solution method due to the fact that the the derivation of all feasible schedules even in a single-channel wireless networks is an NP-hard problem and the number of the set of all feasible transmission rates on all links that can be scheduled in the same slot increases exponentially with increasing number of nodes, channels and radios involved [2, 3]. We aim to provide the numerical results for multi-channel/multi-radio/multi-rate TDMA based wireless mesh network. Therefore, this methodology meets our goals.

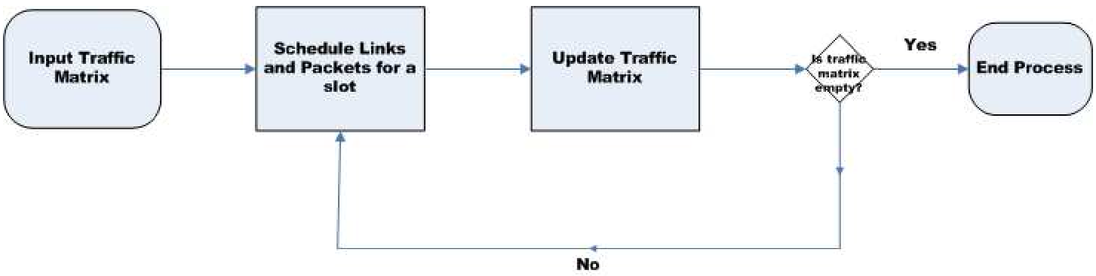


Figure 3.1: The flow-chart of the solution method

We formulate the problem of link/packet scheduling for each time slot as an integer linear program (ILP). The equations define link activation constraints, capacity constraints and update equation of traffic matrix. The equations are same for all cases, single-channel, multi-channel/single radio, and multi-channel/multi-radio cases.

Two possible interference models, namely *Protocol Interference Model* and *Physical Interference Model*, can be considered for multi-hop wireless networks when deciding on which links are active or not [1]. In our model, we employ *Physical Interference Model* since it considers the cumulative effect of interference and SINR constraints at receivers. The SINR level at receiver j when node i transmits to node j is given by:

$$SINR_j = \frac{P_{ij} \cdot L_{ij}}{N_0 + \sum_{(m,n)\neq(i,j)} P_{mn} \cdot L_{mj}} \tag{3.1}$$

where P_{ij} is the power radiated from node i to node j ($P_{ij} = 0$ when node i does not make a transmission to node j) and L_{ij} is the path loss from node i to node j. When multiple data transmission rates are considered; for a given transmission rate, a receiving node must satisfy minimum SINR value corresponding to this rate so as to send packets at this rate. That is, $SINR_j \geq \lambda_k$, where λ_k is the minimum SINR threshold when R_k is assigned.

Link Activation Constraints define a set of active links and rates are allocated to these links such that minimum SINR (Signal-to-Interference and Noise Ratio) of all receivers are satisfied. We define the following decision variables.

$$x_{ijkc} = \begin{cases} 1 & \text{if } \textit{node } i \textit{ transmits to node } j \textit{ with rate } k \textit{ on channel } c \\ 0 & \text{otherwise} \end{cases} \tag{3.2}$$

Due to SINR constraints, we can write that

$$x_{ijkc} \leq \begin{cases} 1 & \text{if } \dfrac{P_{ij} \cdot L_{ij}}{N_0 + \sum_{\substack{(m,n) \neq (i,j) \\ m,n,r}} x_{mnrc} P_{mn} L_{mj}} \geqslant SINR_k \\ 0 & \text{otherwise} \end{cases} \tag{3.3}$$

Equation(3.3) can be linearized as follows:

$$x_{ijkc} P_{ij} \cdot L_{ij} \geq N_0 SINR_k + SINR_k \sum_{m,n,r:(m,n) \neq (i,j)} x_{mnrc} P_{mn} L_{mj} - bigM(1 - x_{ijkc}) \tag{3.4}$$

where $bigM$ is a sufficiently large integer.

With the above equations, multi-rate communication is adapted through assigning rates to links such that minimum SINR constraints at all receivers are satisfied. In our scheme, we also employ multi-channel communication which provides reducing the interference between nodes in multi-hop networks. According to this, a node can choose a channel among multiple channels in order to communicate with other nodes and can tune its radio to different channels when passing through slots. Two communicating nodes tune their radios to the same channel to initiate communication. If a single-radio communication is adapted, a node can only receive or transmit at once on all channels in a slot. If a node can have more than one radio;

$$\sum_{j,k,c} (x_{ijkc} + x_{jikc}) \leq M \tag{3.5}$$

since possible total number of transmissions and receptions of the node on all channels is limited by the number of radios that the node has. Since when a radio at a node transmits at channel c in a slot, no other radio at the same node can receive at channel c (due to large interference), we have

$$\sum_{j,k} x_{jikc} \leq 1 - \frac{1}{M} \sum_{j,k} x_{ijkc} \tag{3.6}$$

After the set of links are chosen, the following capacity constraints (Equation (3.7-3.10)) define how many packets are forwarded across these links. The following decision variable corresponds to the number of packets transmitted over each link, i.e.,

$z_{ijm} \equiv$ indicates the number of packets destined from node i to node m forwarded over link $i \rightarrow j \; \forall \; i, j, m \in \mathcal{N}$.

On which links a packet destined from node i to node m can be transmitted is determined by δ_{ijm}. We do not define any specific route between node i to node m and we only determine all possible routes which satisfy the condition in (3.8). We eliminate the routes that forward packets farther nodes to the destinations instead of closer ones and cause possible loops. Equation (3.7) states that the number of sent packets destined from node i to node m over link $i \rightarrow j$ is limited by T_{im} and whether these packets can use link $i \rightarrow j$.

$$z_{ijm} \leq T_{im} \delta_{ijm} \tag{3.7}$$

where

$$\delta_{ijm} = \begin{cases} 1 & \text{if } ((D_{im} > D_{jm}) \wedge (D_{im} > D_{ij})) \vee (j = m) \\ 0 & \text{otherwise} \end{cases} \tag{3.8}$$

In equation (3.9), the number of transmitted packets destined from node i to node m over all links is limited by T_{im}.

$$\sum_{j} z_{ijm} \leq T_{im} \tag{3.9}$$

In equation (3.10), the number of packets destined from node i to all other nodes transmitted over link $i \rightarrow j$ is limited by the total capacity of link $i \rightarrow j$.

$$\sum_{m} z_{ijm} \leq \sum_{k,c} x_{ijkc} R_k \tag{3.10}$$

Finally, at the end of each iteration, the traffic matrix is updated taking into account packets forwarded in the previous time slot.

$$T'_{im} = T_{im} - \sum_{j} z_{ijm} + \sum_{j:i \neq m} z_{jim} \tag{3.11}$$

This iterative procedure is continued until all packets reach their respective destinations.

In the next section, we describe heuristic objectives that are used for each iteration as an objective function of our ILP model.

3.2.1 Heuristic Objectives

We do not find optimum number of required slots to send all packets to their destinations since the derivation of all feasible scheduling algorithms in a single channel is an NP-hard problem [3]. Instead, we use some heuristic objectives in each iteration in order to minimize number of required slots. In this section, we describe the heuristic objectives used in this thesis. These heuristic objectives are applied in each slot in order to select a set of links and routes for packets and to minimize the number of required slots to deliver all packets.

1. Maximizing total number of transmitted packets:

   $$\boldsymbol{max} \quad \sum_{i,j,m \,:\, i \neq m} z_{ijm}$$

2. Maximizing total number of transmitted packets weighted by hop-distance between the destination and the transmitter:

   $$\boldsymbol{max} \quad \sum_{i,j,m \,:\, i \neq m} z_{ijm} * HC_{im}$$

3. Maximizing total number of transmitted packets divided by hop-distance between the destination and the transmitter:

   $$\boldsymbol{max} \quad \sum_{i,j,m \,:\, i \neq m} z_{ijm} / HC_{im}$$

4. Maximizing total number of transmitted packets with weighted reception preferences of nodes in the corners:

   $$\boldsymbol{max} \quad \sum_{i,j,m \,:\, i \neq m} z_{ijm}(1 + 0.25 * m_j)$$

5. Maximizing total number of transmitted packets with weighted transmission preferences of nodes in the corners:

   $$\boldsymbol{max} \quad \sum_{i,j,m \,:\, i \neq m} z_{ijm}(1 + 0.25 * m_i)$$

6. Maximizing total number of transmitted packets with weighted reception preferences of nodes in the center:

   $$\boldsymbol{max} \quad \sum_{i,j,m \,:\, i \neq m} z_{ijm}(1 - 0.25 * m_j)$$

7. Maximizing total number of transmitted packets with a weighted preference of multi-hops destined packets:

   $$\boldsymbol{max} \quad \sum_{i,j,m \,:\, i \neq m} z_{ijm}(1 + 0.25 * HC_{im})$$

8. Maximizing total number of transmitted packets with a weighted preference of single-hop destined packets:

$$\boldsymbol{max} \quad \sum_{i,j,m\ :\ i \neq m} z_{ijm}(1 - 0.25 * HC_{im})$$

Applying different heuristic objectives helps us reduce the number of required slots and get better insight on the effects of multi-channel/multi-radio schemes on the network throughput.

3.2.2 Simulation Results for Fixed Power Case

In this section, we consider the fixed power case such that $P_{ij} = P$ for all i,j and for all time slots. ILP formulation presented above has been modeled using GAMS and solved by CPLEX. We have solved the problem using the 8 different heuristic objectives presented in Section 3.2.1. Simulation parameters are stated in Table 3.2. We use three different traffic matrices for the network topology given in Figure 3.2.2.

Traffic Matrix-1 :

We design a scenario where traffic among mesh routers are uniform such that the traffic between each source-destination pair is 2 packets.

Traffic Matrix-2 :

Some mesh routers are assumed to be gateway routers in this scenario. Traffic Matrix-2 is non-uniform and only nodes 1, 2, 3 and 4 in the corners have 7-packets to each destination.

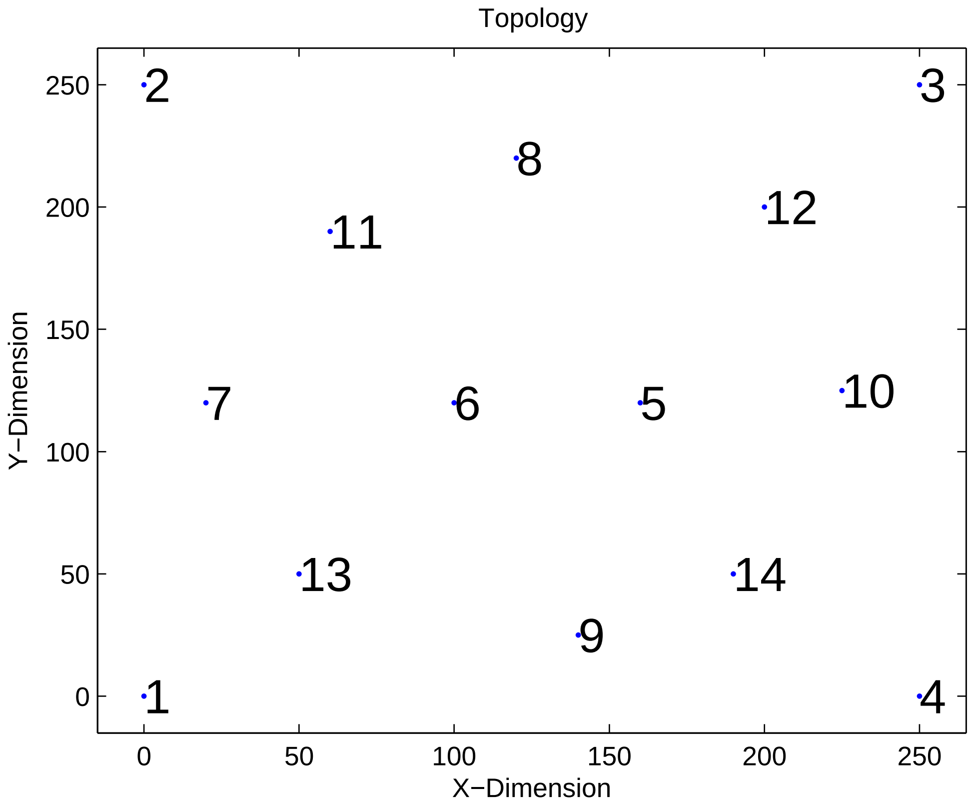


Figure 3.2: 14-nodes Topology

Traffic Matrix-3 :

Traffic Matrix-3 is also non-uniform and node 5 has 15 packets to each destination and other nodes have 1 packet to each destination. We draw a scenario such that node 5 serves as a gateway which connects the WMN with the wired network and other nodes demand Internet access from this gateway.

Note that the total number of the packets in all these traffic matrices are the same.

Figure 3.3 shows the total number of slots necessary to carry the whole traffic as a function of the fixed transmit power for the three traffic matrices as C and R change. In the number of necessary time slots, the minimum slot count achieved among all heuristic objective functions is reported in Figure 3.3. In Figure 3.3,

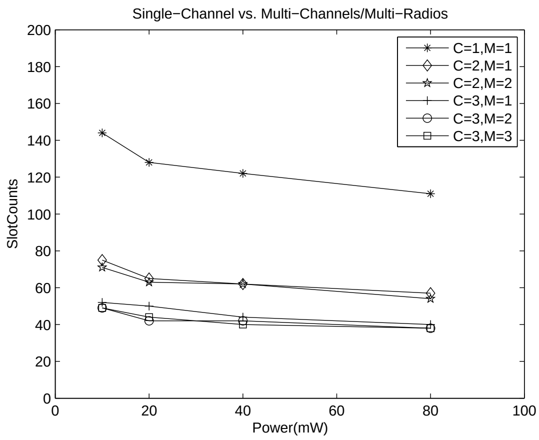
Table 3.2: *Simulation Parameters used for Performance Evaluation*

Parameters	***Values***
Traffic Matrix	1,2,3
Number of Nodes	14
Transmitting Power	10, 20, 40, 80 mW
path-loss exponent	3
N_0	10^{-6} mW
Number of Channels (C)	1,2,3
Number of Radios (M)	1,2,3
Rate vs. SINR Table	Table-3.1

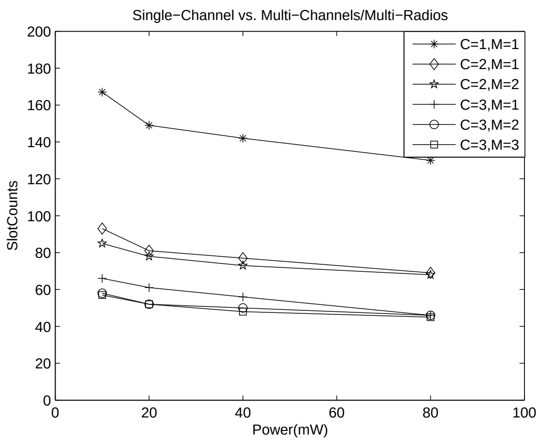
it is observed that as we increase transmitted power for any given number of channels and radios, the number of required slots to send all packets to their destinations decreases since increase in power enables establishment of high rate links. It is also observed that when we increase the number of channels, the number of required slots also decreases for any given power level. Increasing number of channels results in reducing interference among nodes that are close to each other and this provides the network to establish more simultaneous links.

Slight improvements in capacity are observed when the number of radios is increased for the given number of channels and increasing number of radios does not improve the capacity in some cases. The reasons for this problem can be that the solutions can get closer to the lower bounds for necessary number of time slots to transmit all packets or it is hard to increase capacity (or decrease slot-counts) by using heuristic objectives near the optimum solution.

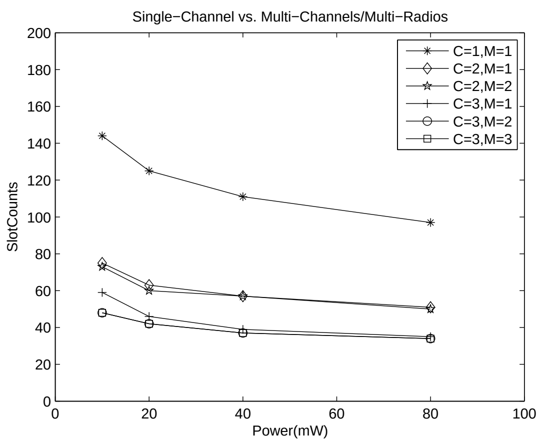
Three traffic matrices provide similar results and this supports the ideas stated above. The number of required slots to transmit all packets are not same among these traffic matrixes for the same number of channels and radios and power level despite the fact that they have the same number of packets. The reason can be that cumulative hop-distance for transmitting all packets are different and the distribution of packets affects the set of possible parallel links that can be established in each slot.



(a) Traffic Matrix - 1



(b) Traffic Matrix - 2



(c) Traffic Matrix - 3

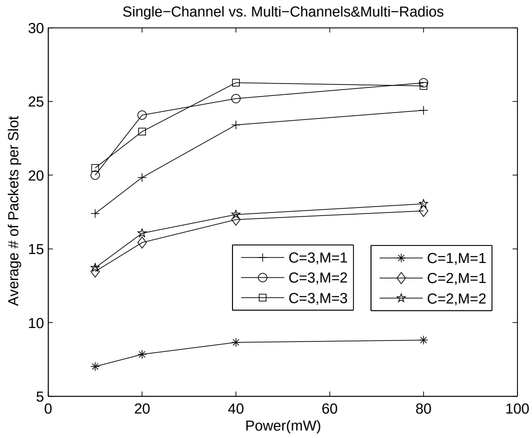
Figure 3.3: Frame lengths for different power levels, number of channels and number of radios

The average number of packets transmitted in a slot is plotted in Figure 3.4 for different traffic matrices and network parameters. The average number of packets transmitted per slot increases as the transmit power, number of radios and number of channels increase. It can be observed that the capacity improves when power, number of channels and number of radios are increased.

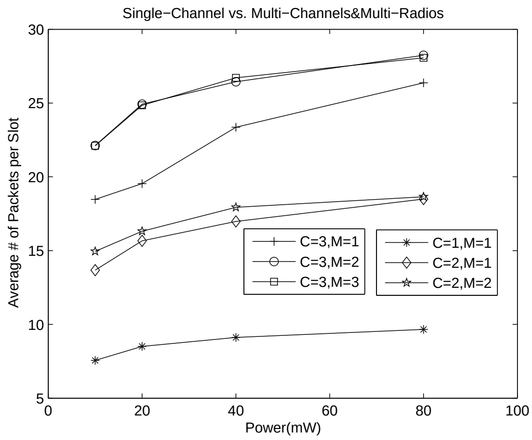
In Figure 3.5, the average number of links per slot decreases when we increase the transmission power. The reasons can be that interference among nodes that are close to each other is increased with increasing power and this leads to reduction in the number of simultaneous links per slot. As the number of channels is increased, the average number of links per slot increases because dividing channels into sub-channels helps to reduce the interference and this leads to an increase in the number of parallel links.

In Figure 3.6, the average number of packets per link increases when transmitting power increases. Higher transmission power allows radios to transmit at higher rates although it can reduce the number of parallel transmissions. This leads to an increase in the average number of transmitted packets per link.

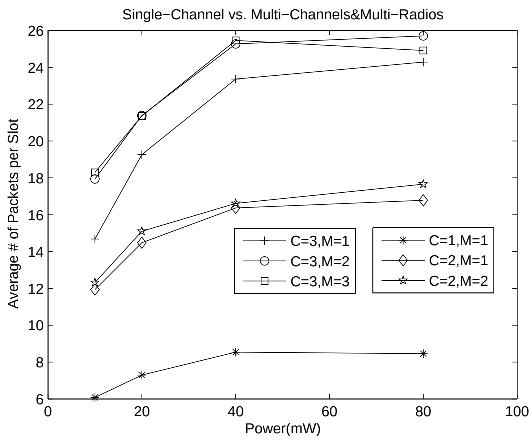
Figure 3.7 shows the total number of necessary time-slots to deliver all traffic as a function of the fixed transmit power for two cases (($C = 1$, $M = 1$) and ($C = 3$, $M = 3$)) as heuristic objective changes. Any of these heuristic objectives does not always outperform other heuristic objectives for varying conditions, i.e, the number of channels, the number of radios per node and transmission power levels. We choose Heuristic-1 as the objective function when analyzing the effects of the power control scheme since hop-counts for every source-destination pair are 1 when transmission power is 200 mW. In directional antennas case, we also use Heuristic-1 since hop-counts between every two nodes are 1 due to high antenna gains and all heuristic objectives become identical to each other.



(a) Traffic Matrix - 1

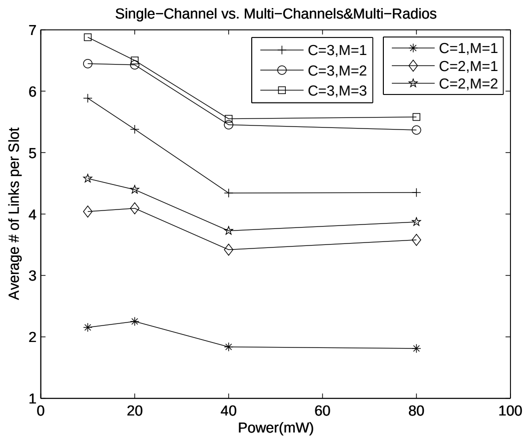


(b) Traffic Matrix - 2

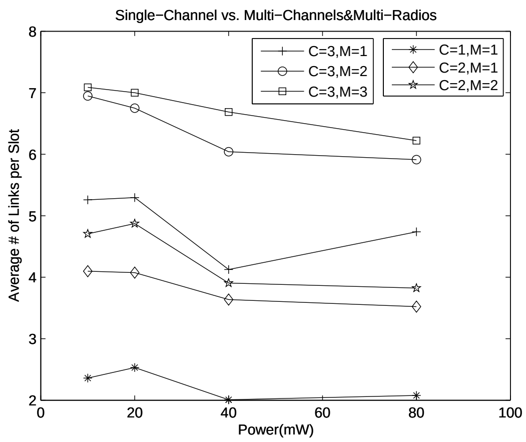


(c) Traffic Matrix - 3

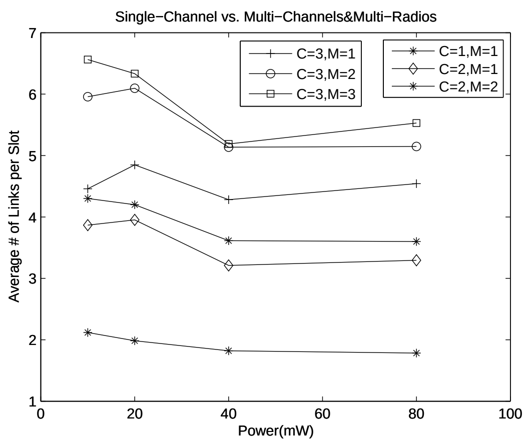
Figure 3.4: Number of Packet per slot for different power levels, number of channels and number of radios



(a) Traffic Matrix - 1

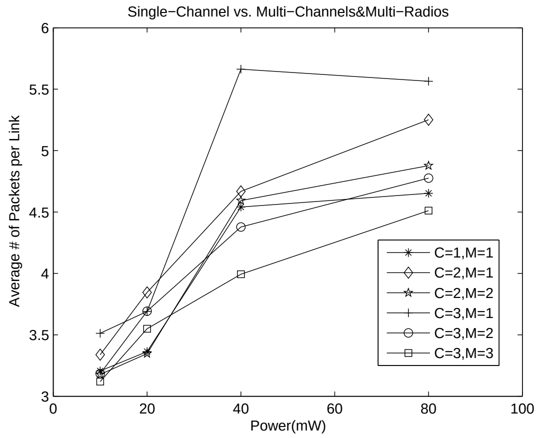


(b) Traffic Matrix - 2

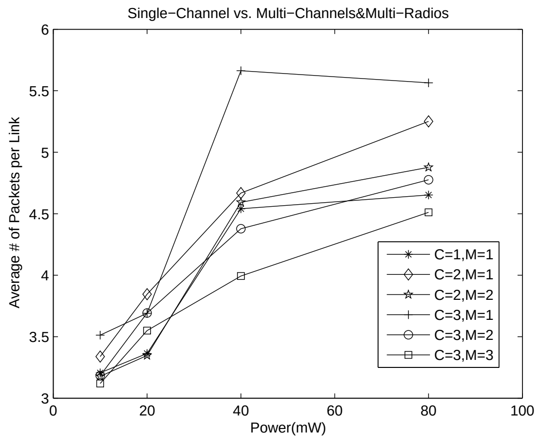


(c) Traffic Matrix - 3

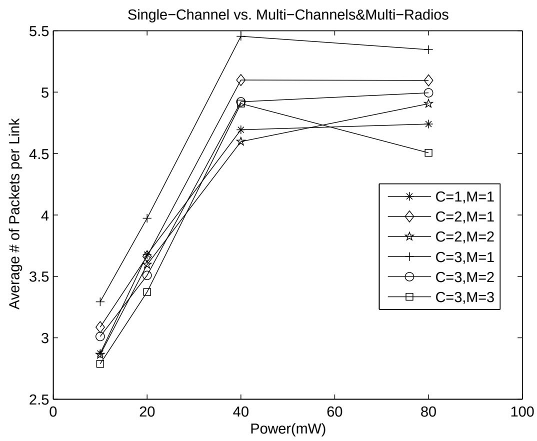
Figure 3.5: Average number of links per slot for different power levels, number of channels and number of radios



(a) Traffic Matrix - 1

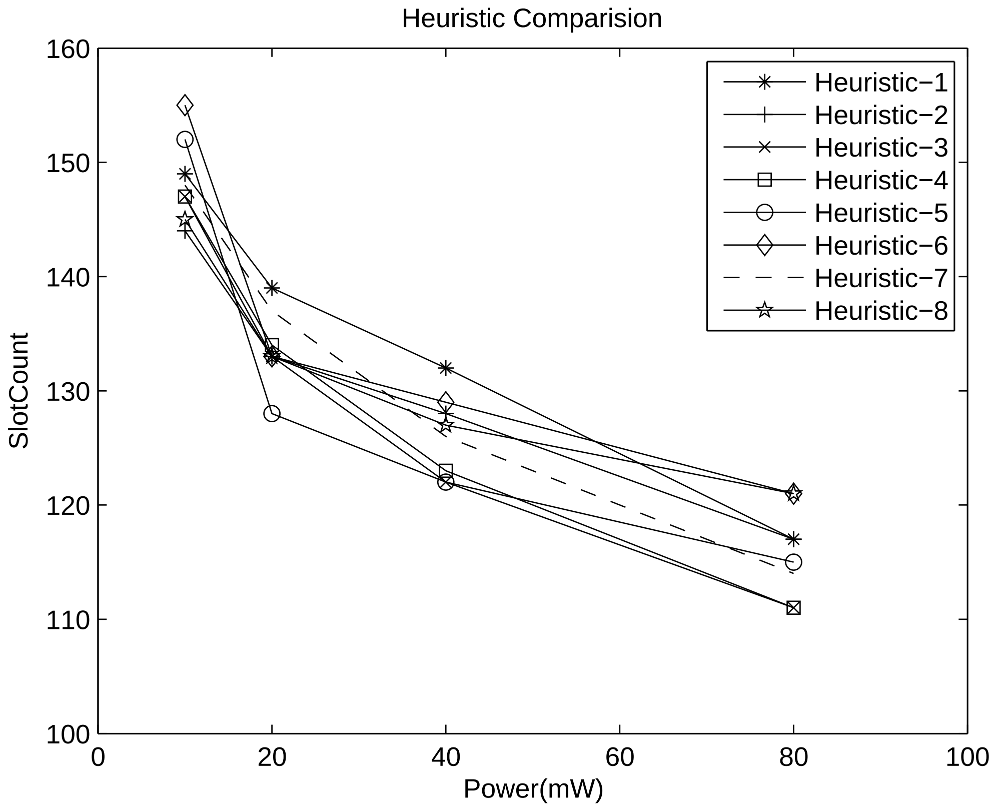


(b) Traffic Matrix - 2

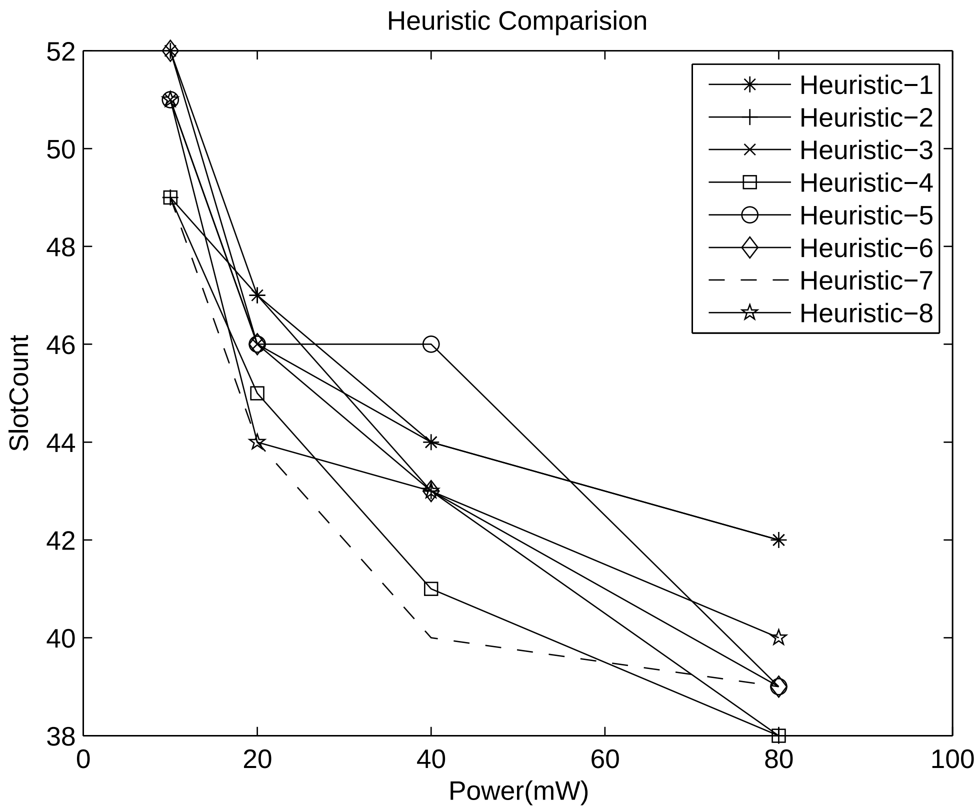


(c) Traffic Matrix - 3

Figure 3.6: Average number of packets per link for different power levels, number of channels and number of radios



(a) $C = 1, M = 1$



(b) $C = 3, M = 3$

Figure 3.7: Heuristic Comparison-(Traffic Matrix-1)

3.2.3 Multi-hop Communication vs. Single-hop Communication

According to the ILP formulations, packets are sent to their destinations through multi-hop communication. In this section, we compare multi-hop communication to single-hop communication where direct-links are established between every source and destination node to carry traffic.

Transmission power is set to 200 mW for both cases and thus, direct-links can be established between all source and destination pairs. Simulations are done using Heuristic-1 for multi-hop communication case and we allow only one node to transmit on a channel for single-hop communication.

The total numbers of deliver all packets to their destinations are given in Table 3.3 for $C = M = 1, 2, 3$ and Traffic Matrix-1,3. We observe that multi-hop communication performs better compared to single-hop communication for two different traffic matrices.

Table 3.3: *Slot-Counts Comparison between Multi-hop Communication and Single-hop Communication*

Traffic Matrix	C	M	Multi-hop Comm.	Single-Hop Comm.
Traffic Matrix-1	1	1	107	182
	2	2	55	91
	3	3	38	61
Traffic Matrix-3	1	1	98	203
	2	2	50	102
	3	3	33	68

3.3 Power Control Case Model

The assumption that the transmit power does not vary between nodes and is fixed for all slots is relaxed in this section so that each link can have a different transmit power in each slot, independent of other links. Thus, in the power control case model, transmitted power can change from slot to slot and node to node. Formulations are adapted such that the transmit power is introduced in the ILP formulations as a variable that can take 5 different values.

The transmit power is assigned to each link and is chosen from the power set, $\mathcal{W}$.

$$\mathcal{W} := \{1,...,|W|\}$$

$P \equiv [P_w]$ is the power vector where $w \in \mathcal{W}$.

We assume that a node can change its transmit power immediately when passing through a new time slot. We modify the decision variable defined in (3.2) such that the transmit power can also be a variable:

$$x_{ijkcp} = \begin{cases} 1 & \text{if } \textit{node i transmits to node j with a rate k on channel c at power p} \\ 0 & \text{otherwise} \end{cases} \tag{3.12}$$

$\forall\ i, j \in \mathcal{N},\ k \in \mathcal{R},\ c \in C,\ p \in \mathcal{W}$

Link activation still depends on SINR constraints and transmitting power is selected from the power vector, P.

$$x_{ijkcw} \leq \begin{cases} 1 & \text{if } \dfrac{P_w L_{ij}}{N_0 + \sum_{\substack{(m,n)\neq(i,j) \\ m,n,r,t}} P_t L_{mj} x_{mnrct}} \geqslant SINR_k \\ 0 & \text{otherwise} \end{cases} \tag{3.13}$$

$\forall\ i, j, m, n \in \mathcal{N},\ k, r \in \mathcal{R},\ c \in \mathcal{C},\ w, t \in \mathcal{W}$

The equation (3.13) is linearized similar to (3.3) as follows:

$$x_{ijkcw} P_w L_{ij} \geq N_0 SINR_k + SINR_k \sum_{m,n,r,t:(m,n)\neq(i,j)} x_{mnrct} P_t L_{mj} - bigM(1 - x_{ijkcw}) \tag{3.14}$$

The physical limitations due to limited number of radios are formulated through equations (3.15) and (3.16). The number of possible transmissions and receptions is limited by the number of radios that the node has and a node cannot receive and transmit in the same channel in the same time slot. These constraints are given as:

$$\sum_{j,k,c,p} (x_{ijkcp} + x_{jikcp}) \leq M \tag{3.15}$$

$$\sum_{j,k,p} x_{jikcp} \leq 1 - \frac{1}{M} \sum_{j,k,p} x_{ijkcp} \tag{3.16}$$

After the set of links are chosen, the capacity constraints defines how many packets are forwarded across these links. Capacity equations remain similar to (3.7)-(3.10) with a slight modification.

$$\sum_{j} z_{ijm} \leq T_{im} \tag{3.17}$$

$$\sum_{m} z_{ijm} \leq \sum_{k,c,p} x_{ijkcp} R_k \tag{3.18}$$

$$z_{ijm} \leq T_{im} \delta_{ijm} \tag{3.19}$$

Traffic update equation is same as (3.11).

3.3.1 Numerical Results for Power Control Case

In the numerical results for the power control case, the power vector is selected as: $P = [3\ 10\ 40\ 100\ 200]\ mW$.

Simulations are done using the Heuristic-1 for Traffic Matrix-1. Since the complexity of the problem increases when transmit power levels are introduced, we performed numerical studies only for the case of single radio per node, i.e., $M = 1$. In Table 3.4, the number of necessary time slots are shown as the number of channels change. It is observed from the results that the power control case improves the throughput compared to the fixed power case for all cases considered.

Table 3.4: *Slot-Counts Comparison when Power Control Case and Fixed Power Case*

Number of Channels(C)	Fixed Power Case	Power Control Case
1	107	100
2	55	53
3	36	35

The total transmitted energies over the complete frame length are given in Table 3.5 assuming that each time slot 1 ms. We observe that, in addition to reducing the delay, the power control mechanism significantly reduces the total dissipated energy.

Table 3.5: *Dissipated Energy Comparison when Power Control Case and Fixed Power Case*

Number of Channels(C)	Fixed Power Case(mJ)	Power Control Case(mJ)
1	38.8	23.1
2	38	20.7
3	34	20.5

3.4 QoS Model

In Section 3.2, we only considered the case of single type of traffic (best-effort or data traffic). We extend this model in this section such that two different traffic types (voice and data) exist together in the network. In order to formulate this problem, we need to do some necessary changes in the previous model since voice packets have maximum delay constraints. The decision variables used in QoS Model are stated below:

$v_{ijm} \equiv$ a variable indicating the number of voice packets destined from node i to node m over link $i \rightarrow j$

$z_{ijm} \equiv$ a variable indicating the number of data (best-effort) packets destined from node i to node m over link $i \rightarrow j$

$T^V = [T^V_{ij}] \equiv$ Voice Traffic Matrix

$T^D = [T^D_{ij}] \equiv$ Data Traffic Matrix

Link activation Constraints are the same as the equations (3.2)-(3.6) given in Section 3.2. Capacity constraints are modified as stated below:

$$\sum_j z_{ijm} \leq T^D_{im} \tag{3.20}$$

$$\sum_j v_{ijm} \leq T^V_{im} \tag{3.21}$$

$$z_{ijm} \leq T^D_{im}\delta_{ijm} \tag{3.22}$$

$$v_{ijm} \leq T^V_{im}\delta_{ijm} \tag{3.23}$$

$$\sum_m (z_{ijm} + v_{ijm}) \leq \sum_{k,c} x_{ijkc}R_k \tag{3.24}$$

Both traffic matrices are updated at the end of each iteration.

$$T'^D_{im} = T^D_{im} - \sum_j z_{ijm} + \sum_j{}_{i \neq m} z_{jim} \tag{3.25}$$

$$T'^D_{im} = T^V_{im} - \sum_j v_{ijm} + \sum_j{}_{i \neq m} v_{jim} \tag{3.26}$$

The objective function used at each iteration is given by:

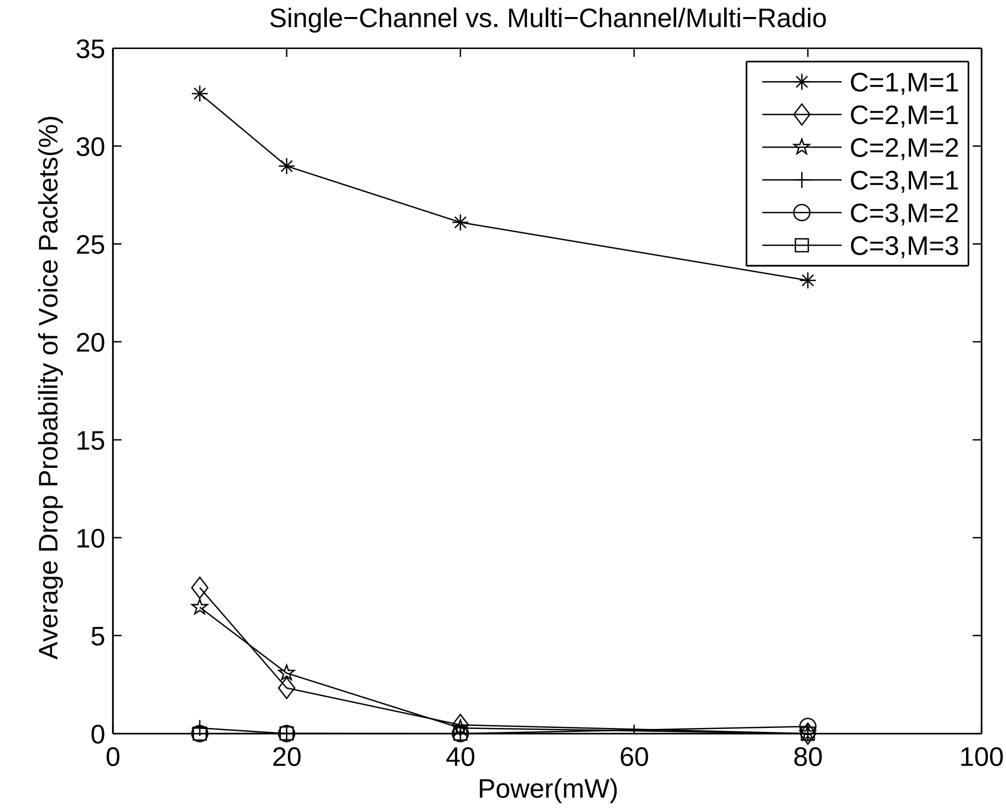
$$\boldsymbol{minimize} \quad \sum_{i,m} T_{im}^{\prime V} - \epsilon \sum_{i,j,m} (v_{ijm} + 0.1 * z_{ijm}) \tag{3.27}$$

In (3.27), we try to minimize the total number of voice packets at the end of each slot as the primary objective and maximize the number of transmitted voice packets with higher preference than the number of transmitted data packets as the secondary objective. The constant parameter $\epsilon \ll 1$ is chosen such that the second term in (3.27) never exceeds 1.

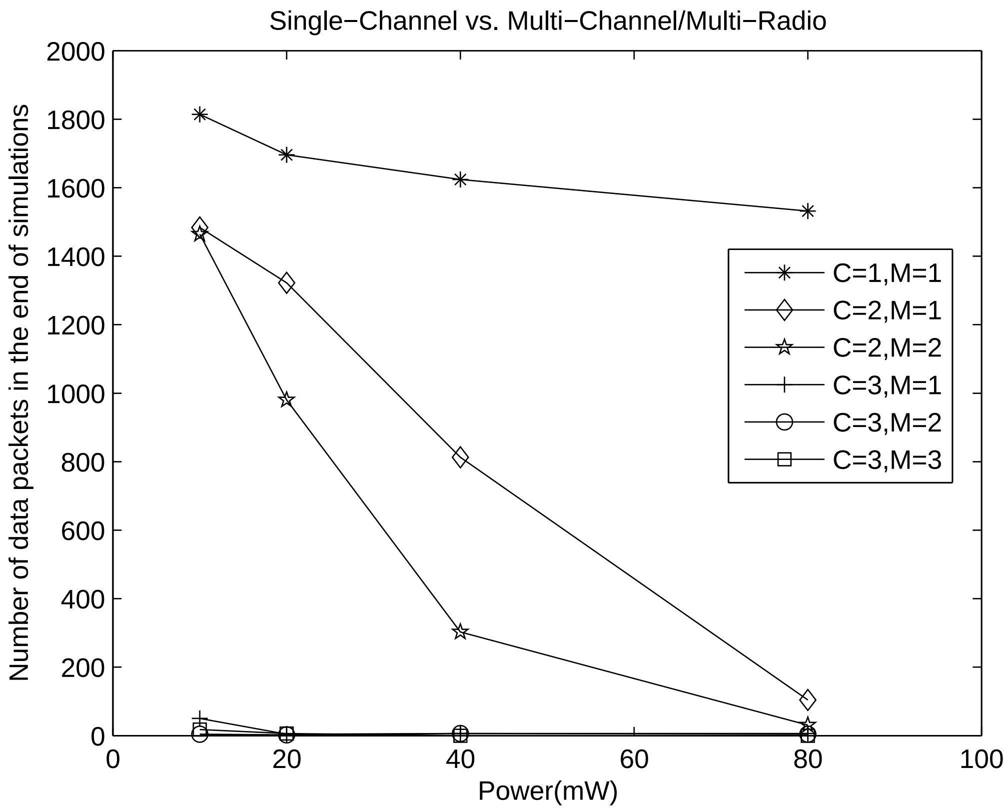
3.4.1 Simulation Results for QoS Model

We provide the simulation results for the QoS Model in this section. In these simulations, we generate a new voice traffic matrix at every 20^{th} slot and we drop voice packets if they are not transmitted to their respective destinations within 20 slots (which is assumed to be maximum delay constraint for voice packets). A newly generated voice traffic matrix is dependent on the previous voice traffic matrix and the total number of voice packets generated every 20 slots is 80. This process is repeated until voice traffic matrix is generated 50 times. We also generate two data packets in each time slot. The main objective is to minimize the total number of dropped voice packets at the end of every 20^{th} slot together with minimizing the total number of data packets not transmitted in the end of the simulation. Simulations are only done using the Heuristic Objective stated in (3.27) for Traffic Matrix-1.

In Figure 3.8(a), the average drop probabilities of voice packets are shown. Drop probabilities decreases as the number of channels and radios increase. In Figure 3.8(b), the total number of remaining data packets in the end of simulations are shown. The total numbers of data packets that are not transmitted to their destinations decreases as the number of channels and radios increase.



(a) Average drop probability of voice packets



(b) The number of remaining data packets in the end of simulation

Figure 3.8: QoS Simulations for multi-radio/multi-channel network

We can conclude that it is necessary to divide channels into sub-channels and increase the number of radios per node in order to provide better service quality. We observe that most of the improvement can be achieved by using a multi-channel ($C = 3$) and single radio ($M = 1$). There is negligible improvement between $C = 3$, $M = 1$ and $C = 3$, $M = 3$.

Chapter 4

DIRECTIONAL/SECTORED ANTENNAS

We showed in Section 3.2.2 that the capacity improves in WMNs as the number of channels and the number of radios per node are increased. Due to the limited number of available channels, interference between nearby nodes cannot be eliminated further and this limits the gain in the capacity. Therefore, power control schemes and using directional antennas are proposed to solve this problem. We observed in Section 3.3.1 that the power control scheme provides slight improvement on the network performance. In this chapter, we will introduce directional/sectored antennas and we will analyze the effects of using directional antennas on the capacity.

4.1 Technical Background

Directional antennas are categorized into two groups [32]: Switched antenna (or Sectored antennas) [26, 29, 30, 31] and steered antennas (or adaptive antennas) [31]. A switched antenna has identical K sectors where each sector covers $360/K$

degrees. If a node U intends to transmit signal to a node V, U selects the sector that encloses V and sets this sector as the main radiation lobe of the antenna. On the other hand, a steered antenna points its main beam toward the direction such that the main beam covers the intended receiver.

Sectored antennas are more suitable for TDMA systems since switching between antennas can be done much faster than mechanically steering the antenna. An antenna model is characterized by the associated antenna gain pattern. The commonly used antenna models are idealized antenna model, flat-topped antenna model [26, 29, 30, 31], sinc-function antenna model and adaptive antenna model. Idealized antenna model assumes a constant antenna gain within beamwidth that is independent of beamwidth and zero outside the beamwidth. Flat-topped antenna model has a constant antenna gain within beamwidth and smaller antenna gain outside the beamwidth. These models are widely used since their adaptation to proposed algorithms are simpler when compared to other models. In our design, we use sectored antennas in conjunction with the flat-topped antenna model.

A sectored antenna covers all regions with M sectors and $\theta_B = \frac{2\pi}{M}$ is the beamwidth. The flat-topped antenna gain pattern $G(\theta, s)$ for each sector s is identical and stated in (4.1). The antenna gain outside the beamwidth is assumed to be at least $10dB$ less than the antenna gain within beamwidth [26, 31, 33].

$$G(\theta, s) = \begin{cases} \frac{2\pi}{\theta_B} & ;(s-1)\theta_B \leq \theta \leq s\theta_B \\ \frac{2\pi}{10\theta_B} & ;\text{otherwise} \end{cases} \tag{4.1}$$

$s = 1, 2, ..., K$.

Directional antennas can also be categorized into three groups according to implementation points. Transmission with directional antennas and receptions with omni-directional antennas, transmission with omni-directional antennas and receptions with directional antennas, and both transmission and receptions with directional antennas are called transmit beamforming, receive beamforming and joint transmit and receive beamforming, respectively. We implement all versions in our design.

4.2 Model Modifications

In the previous chapter, we assume that the antenna gains at both transmitters and receivers are 1 and so only the path loss forms the channel gain between communicating nodes. Now, we introduce g_m and g_s that are the main lobe and side lobe antenna gains, respectively. The channel gain also depends on the antenna implementation points. For instance, if directional antenna is implemented only at the receiver, then the transmitter and receiver antenna gains are assumed to be 1 and g_m, respectively. The channel gain between receiver j and transmitter i due to using directional antennas can be classified into three groups: namely, transmit, receive and joint transmit and receive beamforming. The channel gain G_{ij} between transmitter i and receiver j is given in (4.2) for these three cases.

$$G_{ij} = \begin{cases} g_m^2 & \text{if joint transmit and receive beamforming} \\ g_m & \text{if transmit beamforming} \\ g_m & \text{if receive beamforming} \end{cases} \tag{4.2}$$

We need to know relative positions of interfering nodes with respect to the receiver and the transmitter when calculating SINR at the receiver. For joint transmit and receive beamforming, we have following 3 cases: (1) both transmitter m and i are inside beamwidth of receiver j (*condition-1*) and both receiver j and n are inside beamwidth of transmitter m (*condition-2*), (2) only one of two conditions is true, (3) none of two conditions is true. The channel gain G_{mn}^{ij} between m and j when i and m transmits to j and n, respectively, is given in (4.3).

$$G_{mn}^{ij} = \begin{cases} g_m^2 & \text{if case(1) occurs} \\ g_m g_s & \text{if case(2) occurs} \\ g_s^2 & \text{if case(3) occurs} \end{cases} \tag{4.3}$$

For receive or transmit beamforming antenna, channel gain G_{mn}^{ij} between m and j is stated in (4.4) when i and m transmits to j and n, respectively. We have the following two conditions: (1) If receiver j (or transmitter i) is in the main lobe of transmitter m (or receiver n) for receive(transmit) beamforming, (2) otherwise. The channel gain is given by:

$$G_{mn}^{ij} = \begin{cases} g_m & \text{if case(1) occurs} \\ g_s & \text{if case(2) occurs} \end{cases} \tag{4.4}$$

We only introduce the antenna gain between the transmitter and the receiver (G_{ij}) and the antenna gain between interfering nodes and the receiver (G_{mn}^{ij}) in (3.4) and the remaining formulations are similar to those in Section 3.2.

$$x_{ijkc} P G_{ij} L_{ij} \geq N_0 SINR_k + SINR_k \sum_{m,n,r:(m,n)\neq(i,j)} x_{mnrc} P G_{mn}^{ij} L_{mj} - bigM(1 - x_{ijkc}) \tag{4.5}$$

4.3 Simulation Results

In this section, we present the computational results obtained in the topology stated in Section 3.2.2 to have some insight on which directional antennas parameters affect network performance. We provide the number of necessary time slots to deliver all packets to their destinations to understand the effects of directional antennas parameters such as beamwidth, transmit or receive or joint transmit and receive beamforming. The simulation parameters are summarized in Table-4.1.

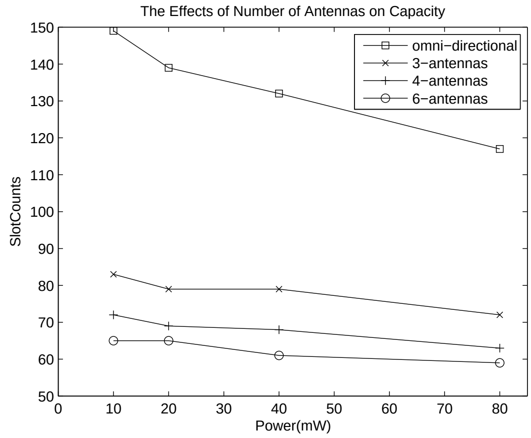
Table 4.1: *Simulation Parameters used for Performance Evaluation*

Parameters	***Value***
Traffic Matrix	1
path-loss exponent	3
N_0	10^{-6} mW
K (Number of Sectors)	2,3,4,6
Transmitting Power	10, 20, 40, 80 mW
Heuristic Objective	1, 2
Rate vs. SINR Table	Table-3.1

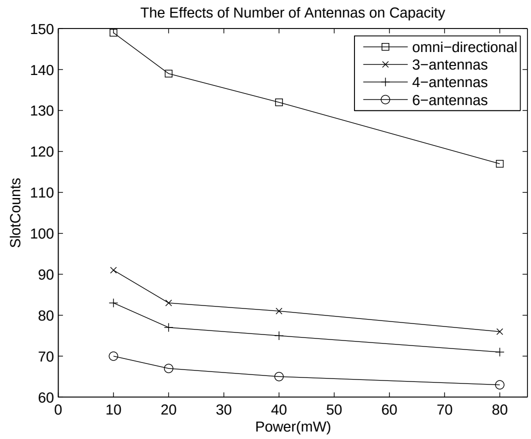
In Figure 4.1, we analyze the effects of the number of sectors (or beamwidth) on the capacity for 3 cases: receive, transmit and joint transmit and receive beamforming. We point out that the capacity improves when beamwidth decreases for all cases [29, 31] since antenna gain within beamwidth increases with the reduced beamwidth. Increasing the transmit power does not improve the network performance in the case where both transmissions and receptions are realized using directional antennas since the channel gain is 36 (for 6-sectored antennas) times of the case that both transmissions and receptions with omni-directional antennas and this high channel gain already generates high-rate links. Increasing the transmit power only causes more interference to other receiving nodes.

In Figure 4.2, we show the effect of sectorial points on the capacity for the case where the sector divides the area horizontally and vertically. It can be observed that sectorial points can also change the capacity.

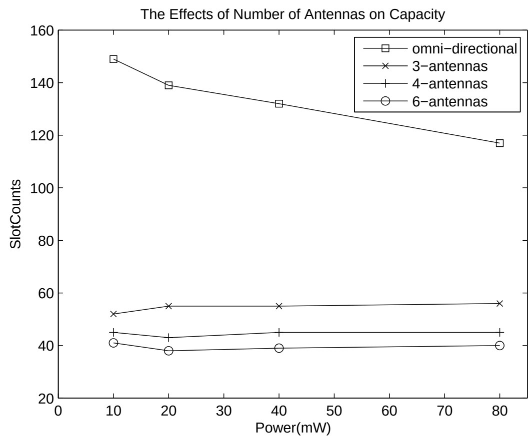
In Figure 4.3, we simulate the effects of number of radios and channels on the capacity when nodes are equipped with 3-sectored directional antennas at both transmitters and receivers. We point out that the capacity also improves as the number of radios and channels increases in WMNs where nodes are equipped



(a) Transmit Beamforming



(b) Receive Beamforming



(c) Joint Transmit and Receive Beamforming

Figure 4.1: The effects of the number of sectors on capacity-($C = 1$, $M = 1$)

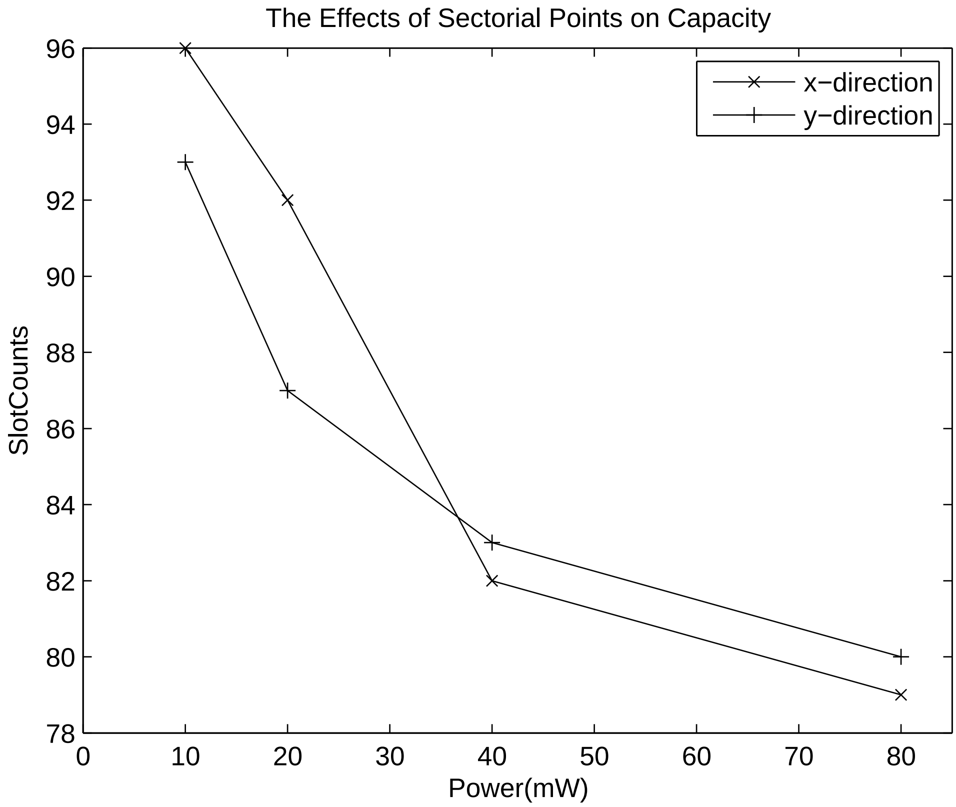


Figure 4.2: The effects of sectorial points on capacity-($C = 1$, $M = 1$, $K = 2$, Transmit Beamforming)

with directional antennas. The effect of increasing the number of radios per node is more prominent than the case when nodes are equipped with omni-directional antennas.

In Figure 4.4, the effects of 3 cases ((1) omni-reception and directional transmission (2) directional reception and omni-transmission (3) directional reception and directional transmission) on the throughput are analyzed. Using directional antennas at both transmitters and receivers give by far the best result since interference is highly eliminated and received signal strength is increased.

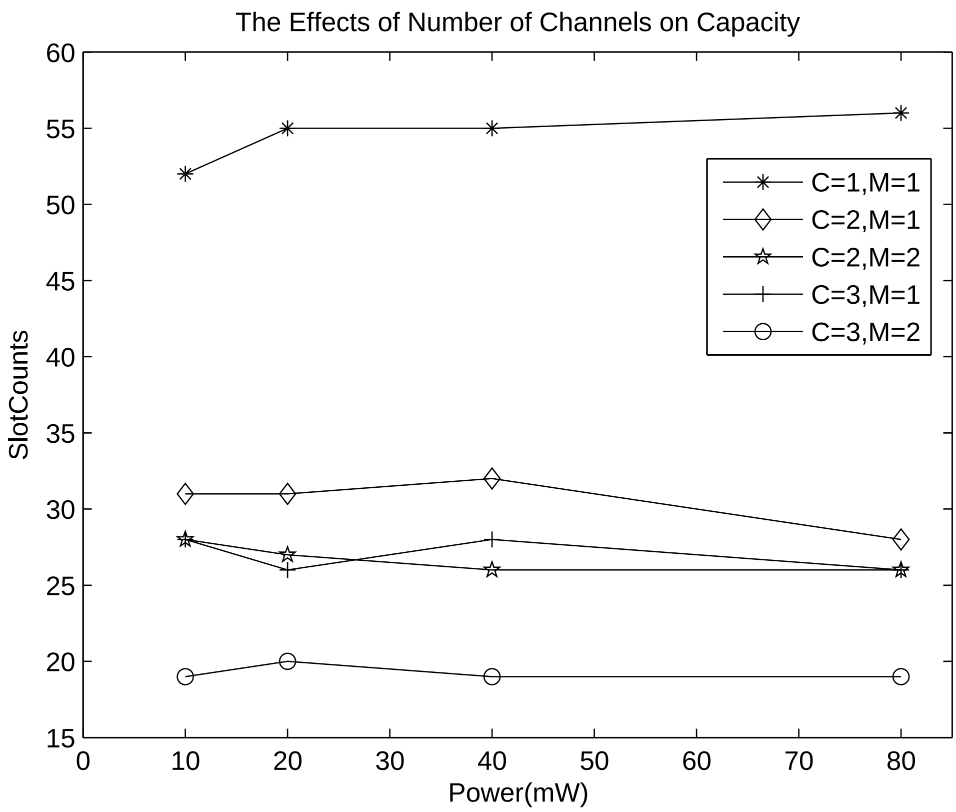


Figure 4.3: The effects of number of channels and radios on the capacity-(Joint transmit and receive beamforming, $K = 3$)

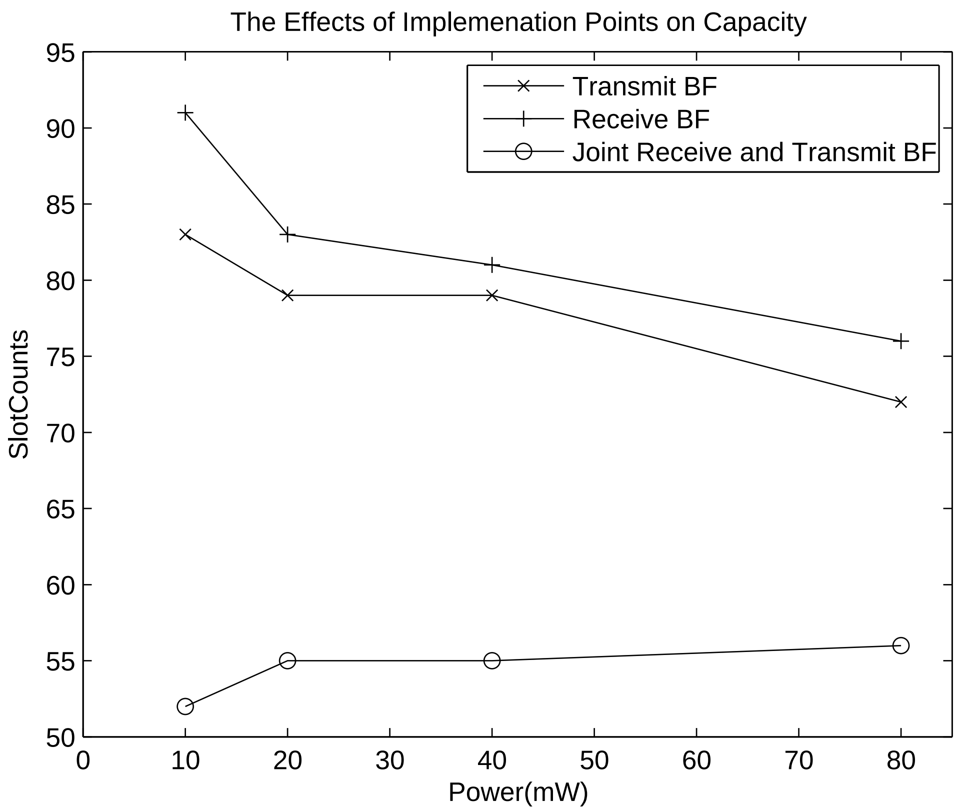


Figure 4.4: The effects of implementation points-($C = 1$, $M = 1$, $K = 3$)

Chapter 5

CONCLUSIONS

In this thesis, we proposed an Integer Linear Programming (ILP) Model to solve the joint link/packet scheduling, routing and rate allocation problem in STDMA based multi-channel/multi-radio/multi-rate wireless mesh networks. The proposed ILP model combines the link layer and the network layer to optimize the network performance under the physical interference model. The main objective of the joint scheduling/routing problem addressed in this thesis is to reduce the number of necessary TDMA time slots to deliver all packets to their respective destinations (referred to to as the frame length). We did not directly seek the minimum frame length since even the scheduling problem is often NP-hard. Instead, we resort to heuristic objectives that indirectly reduce the frame length.

We discussed the effects of multi-channel/multi-radio technology, power control scheme and directional antennas in this thesis. Firstly, we discussed multi-channel/multi-radio technology and it is observed that the frame length decreases as the number of channels in the network (C), the number of radios per node (M), and the transmit power (P) increases. For multi-channel/multi-radio/multi-rate wireless mesh networks, the maximum reduction in frame length is 40.6% when we increase the transmit power from $P = 10$ mW to $P = 80$ mW for all C and

M values (C and M values are fixed while increasing P from 10 mW to 80 mW). Increasing C has also a great impact on decreasing the frame lengths and the maximum improvement between $C = 3$, $M = 3$ and $C = 1$, $M = 1$ is 67.2% and between $C = 2$, $M = 2$ and $C = 1$, $M = 1$ is 52.0% for all P values (P is fixed as we increase C and M). That is, the frame length for the case ($C = 1$, $M = 1$) is three times of the case ($C = 3$, $M = 3$) and the frame length for the case ($C = 2$, $M = 2$) is half of that for the case ($C = 1$, $M = 1$). We point out that increasing M has a slight effect on the capacity and the average and maximum decay in the frame lengths between $C = 3$, $M = 3$ and $C = 3$, $M = 1$ is 3.6% and 7.6%, respectively for all P values. We can conclude that the maximum improvement can be achieved by increasing P, C and M values.

Secondly, it is observed that the power control mechanism has slight effects on improving the capacity compared to increasing C and P but it significantly reduces the total transmitted energy over the complete frame length. The power control scheme reduces the frame length by 6.5% compared to the fixed power case (where maximum transmission power is same for both cases) for $C = 1$, $M = 1$. For further C values, the effect of power control mechanism becomes less noticeable. On the other hand, the total dissipated energy is reduced by 45.5% compared to the fixed power case for $C = 2$, $M = 1$.

Finally, the effects of directional antenna parameters such as beamforming types (receive, transmit and joint receive and transmit beamforming) and beamwidth on the capacity are investigated. The directional antennas provide significant improvements in the capacity compared to omni-directional antennas and decreasing beamwidth (or increasing the number of sector (K)) improves capacity further. For joint transmit and beamforming sector antennas, the frame length is reduced by 65.1%, 69.8%, 72.6% with respect to omni-directional antennas for the cases $K = 3$, $K = 4$ and $K = 6$, respectively when $C = 1$, $M = 1$ and $P = 10$ mW. When analyzing the types of beamforming, it is observed that the maximum capacity is achieved through joint transmit and receive beamforming antennas. The frame lengths for joint transmit and receive beamforming cases ($K = 3$, $K = 4$, $K = 6$) are reduced by 37.3%, 37.5%, 36.9% with respect to transmit beamforming cases ($K = 3$, $K = 4$, $K = 6$) respectively when $C = 1$, $M = 1$ and $P = 10$ mW. The effect of increasing M on the throughput is more prominent when directional antennas are used. The throughput (when $C = 3$, $M = 2$ and $P = 10$ mW) is improved by 32% the case ($C = 3$, $M = 1$ and $P = 10$ mW). 87.3% improvement is achieved by the case ($C = 3$, $M = 1$, $P = 10$ and $K = 3$) compared to the case ($C = 1$, $M = 1$, $P = 10$, and $K = 1$) when sector antennas are used at both the transmitters and the receivers.

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