

SEAMLESS SUPPORT FOR LONG-LIVED MULTI-GIGABIT FLOWS IN  
WIRELESS NETWORKS

By

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A dissertation submitted in partial fulfillment of  
the requirements for the degree of

Doctor of Philosophy

(Electrical and Computer Engineering)

at the

UNIVERSITY OF WISCONSIN-MADISON

2012

Date of final oral examination: 03/06/12

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To my beloved family, for their love, faith, and support.

## ACKNOWLEDGMENTS

In these five years, I walk in a long and black shoal-shell and look for the exit. After several turns, the sunshine outside the shoal-shell brightens the path in front of me.

I would first and foremost like to thank my advisor, Prof. Parmesh Ramanathan, for giving me the opportunity to work with him, and for the invaluable guiding light that he has been for me all along this path. As I write this acknowledgement, I realize that I will never be able to find enough words to express how much he means to me. His comments and observations help me construct a concrete research framework and resolve the obstacles in establishing it. His warmth, wisdom, knowledge and commitment to the highest standards have always been a great motivation to me. What I have learned from him within these years fulfills my own strengths and encouragement not only in finishing academic works but also in facing all challenges in the life.

I would like to thank and acknowledge the members of my Ph.D Thesis committee Prof. Kweal Saluja, Prof. Mikko Lipasti, Prof. Yu Hen Hu, and Prof. Mark Hill for their time and constructive feedback. I would especially like to thank Prof. Saluja for being a big source of inspiration and for giving me constant advice all through my years of graduate school. I would like to thank the ECE dept. for providing the resources to enable me to successfully complete my Ph.D.

All of my fellow WANDER Lab team members have undoubtedly made an unforgettable experience to me. The countless hours spent working on projects, sharing knowledge and discussing interesting ideas with Niv, Kamal, Yen-Ting, Chao, KC, Sreejith, Nikhill, Nairan, Pregro, Luyu, and Areazoue have been an enriching and fun experience at the same time. I would like to express my sincere thanks to all my friends, Hsiao-Wei, EmmaX, Kate, Basil, Ivy, Belinda, Yunju, Sunday, Iris, Chia-chen, Hsun-yu, Betsy, Elise, Kent, Yanzan, etc., for generously spending their time

in finding and shipping stuffs from Taiwan to Madison, in discussing life issues with me, and in feeding me a lot of yummy foods.

Last, but not least, I would like to dedicate this dissertation to my family for their love, patience, and understanding-they support me to spend most of time on accomplishing this journey. My grand parents always give me encouragement to overcome all challenges. My father e-mail me all foods I should not miss on every single festival and my mother keeps me posted the latest news at home to let me feel they are always with me. My brother shares his thoughts with me and inspires me to enjoy handling all kind of possible research challenges. My thanks and love for all of them.

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## NOMENCLATURE

|          |                                             |
|----------|---------------------------------------------|
| WMN      | Wireless Mesh Network                       |
| AP       | Access Point                                |
| MN       | Mesh Node                                   |
| WSP      | Wireless Service Provider                   |
| WU       | Wireless User                               |
| CR       | Cognitive Radio                             |
| CR-WMN   | Cognitive Radio based Wireless Mesh Network |
| C-MVNO   | Cognitive Mobile Virtual Network Operator   |
| MRSA     | Joint Multipath Routing and Spectrum Access |
| OMNC     | Optimized Multipath Network Coding          |
| ANC      | Analog Network Coding                       |
| IETF     | Internet Engineering Task Force             |
| IntServ  | Integrated Services                         |
| DiffServ | Differentiated Services                     |
| RSSI     | Received Signal Strength Indicator          |
| WCDMA    | Wideband Code Division Multiple Access      |

|      |                                              |
|------|----------------------------------------------|
| VCG  | Vickrey-Clarke-Groves                        |
| TCP  | Transmission Control Protocol                |
| CTCP | Compound TCP                                 |
| UDP  | User Datagram Protocol                       |
| BDP  | Bandwidth Delay Product                      |
| RTT  | Round Trip Time                              |
| SRNC | Spare-bandwidth Rate-adaptive Network Coding |
| DAG  | Directed Acyclic Graph                       |
| SINR | Signal to Interference plus Noise Ratio      |
| QoS  | Quality of Service                           |
| ARP  | Adaptive Rate Purchase                       |
| CV   | Coefficient of Variation                     |
| RTP  | Real-time Transport Protocol                 |
| RE   | Redundancy Elimination                       |

## ABSTRACT

Wireless networks in the near future must be able to support seamless mobility for multi-gigabit flows due to growing popularity of smart mobile devices and due to growing demand for applications such as media streaming, video conferencing, and high-definition television. The challenge, however, is that factors such as packet losses, handoff delays, and re-routing delays have more severe performance impact when the data rate increases. Mesh networking is a promising approach to support such high data rates to mobile users in malls, homes, business enterprises, public transport, and personal vehicles. However, to support these multi-gigabit data rates, the wireless mesh networks need access to a large amount of frequency spectrum. Unfortunately, in the current static licensing approach used by spectrum regulatory bodies, unfettered access to a large amount of frequency spectrum is not possible. As a result, spectrum regulatory bodies such as Federal Communication Commission (FCC) are considering a new dynamic frequency allocation approach enabled by recent technological advances called cognitive radios. This dissertation addresses the challenges of multi-gigabit communication in cognitive radio based wireless mesh networks.

To address these challenges, the dissertation envisions a network in which multiple service providers deploy their own infrastructure and compete with each other to provide gigabit communication services to mobile users. In order to compete with others, a service provider deploys a set of wireless access points which communicate with each other to form a mesh network over the geographic area of interest. The transmission power of each such access point determines its coverage area such that mobile users within this area can potentially associate with it. Larger the transmission power, the larger coverage area and hence potentially more users. However, since the mobile users associated to an access point must share its wireless bandwidth, more users often results in lower link layer throughput for each user. As a result, mobile users selfishly switch their

association between access points, both within the same service provider and also across service providers, in order to increase their individual link layer throughput. This dissertation formulates the problem of configuring the transmission powers of access points of a single provider as a cooperative game between the access points and between the mobile users and the access points of a provider. The game results in a joint optimization of the transmission power selection and user association. The dissertation describes a solution to this optimization problem which in turn results in a method for a single service provider to deploy a wireless mesh network covering the entire geographic area of interest and thereby providing basic wireless access service to the mobile users.

In order to further increase the data rate provided to a mobile user, the service providers lease frequency spectrum from nearby licensed users and resell the spectrum to mobile users. Since larger spectrum means higher data rate but at larger cost, mobile users individually optimize their spectrum purchasing strategy based on the needs of their application and the prices set by the service providers for reselling their individual spectrum. This dissertation proposes a dynamic spectrum pricing strategy for the service providers and a dynamic spectrum purchase strategy for the mobile user in order to collectively increase the data rate supported to the users while individually increasing the revenue for each service provider. Unfortunately, such a spectrum leasing and purchasing strategy results in considerable fluctuations in the wireless data rates within the mesh network of a single provider. Simulation results presented in the dissertation show that these fluctuations cause a disproportionate degradation in the end-to-end performance of Transmission Control Protocol (TCP) based traffic flows to mobile users as data rates increase multi-megabit to multi-gigabit. This dissertation also proposes a novel approach called Spare-bandwidth Rate-based Network Coding (SRNC) to alleviate the performance degradation problems caused by link bandwidth fluctuations. Simulation results presented in the dissertation show that, using SRNC, a single service provider can support multi-gigabit end-to-end data rates to mobile users despite the bandwidth fluctuations caused by the leasing and re-leasing of frequency spectrum from nearby licensed users. Consequently, an integrated approach involving SRNC, joint power and user association strategy, dynamic spectrum pricing strategy, and dynamic spectrum purchase strategy

results in a seamless support for multi-gigabit data rates to mobile users in cognitive radio based wireless networks.

# Chapter 1

## Introduction

The number of people with mobile devices is growing exponentially. For instance, on the average, there are over 48 mobiles per 100 people in the United States of America (USA). In countries like Taiwan, there are more mobile devices than people. In addition, there is a rapidly growing interest in high bandwidth applications such as High Definition TV (HDTV), high-definition video conferencing, and high-speed data access. In the near future, the bandwidth requirements of these applications are expected to exceed 1 Gigabits per second (Gbps). As a result, next generation wireless networks must be designed to support a very large number of users, each with highly-demanding applications. Moreover, most of these applications are long-lived, and are commonly referred to as elephants. They are amenable to certain solutions, which are not appropriate for short-lived (or mice) applications.

In major metropolitan areas and in hotspots such as coffee shops, airports, and bookstores, mesh infrastructure networks are deployed to support seamless high data rate access to the Internet. In a mesh network, a set of low-cost routers (henceforth called *mesh nodes*) are deployed in selected locations to provide a multihop interconnection between a mobile user and a large scale infrastructure node such as a cellular basestation or an Internet gateway (see Figure 1.1 [1]). In Figure 1.1, mesh routers are deployed at homes, and end users, pedestrians, or vehicles access the Internet by associating with a nearby mesh router. More specifically, packets sent to/from the Internet are forwarded by the gateway put on the roof of the gas station. Although the geographic extent covered by a mesh node is fairly small, the nodes together can support users in a large area. Moreover, since the distance between the mobile user and a mesh node is much smaller as compared to that in a traditional cellular system, the achieved data rates can be much larger. As a

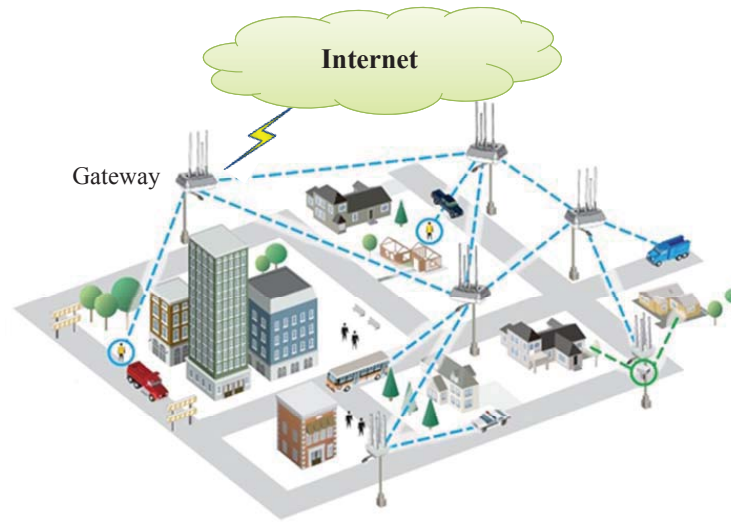


Figure 1.1 Wireless mesh network.

result, mesh networks are a very promising approach for next generation multi-gigabit communication. Hence, the focus of this thesis is on designing protocols for multi-gigabit mesh networks (henceforth, referred to as *gigameshes*).

To support the high data rates, gigameshes need access to a large amount of frequency spectrum. Unfortunately, unfettered access to a large amount frequency spectrum is almost impossible because they have already been allocated to some users. Under the current static licensing approach used by spectrum regulatory bodies, interference between different wireless systems is avoided through assignment of exclusive usage licenses to different users. It has led to acute bandwidth shortages in spectrums used for wireless communication, even though studies have shown that there is a widespread under utilization in the overall frequency space [2]. As a result, Federal Communications Commission in United States of America and other world regulatory bodies have indicated their willingness to consider a more dynamic frequency allocation approach enabled by new technological advances called *cognitive radios* (CR).

With CR, each wireless device can sense and operate over a wide range of frequencies. As a result, a wireless device can opportunistically explore and make use of unused bandwidth among a broad frequency spectrum. Such an approach requires temporary leasing or purchasing of the unused spectrum from the corresponding licensed users. Through such purchases, nodes in a

gigamesh can acquire sufficient frequency spectrum to support the gigabit data rates. Unfortunately, since the mesh nodes do not have long-term access to this spectrum, the mesh nodes may lose their ability to support high data rates when the licensed user stops leasing the spectrum. This creates large bandwidth fluctuations in the cognitive radio based wireless mesh networks (CR-WMN) which in turn creates significant problems for wireless users. Addressing this problem is one of the main contributions of this thesis.

## 1.1 Envisioned Network Architecture

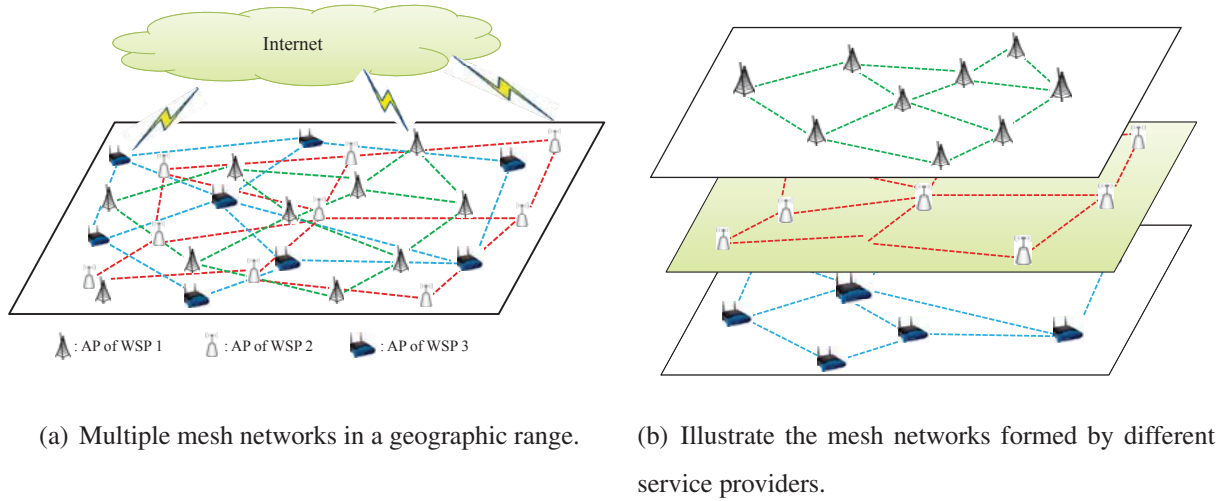


Figure 1.2 Example of multiple mesh networks in a geographic range.

A large number of wireless network users are present in a geographic area of interest. Many of these users are stationary such as in home, office, shops, enterprises, etc.. However, a significant fraction of these users are also mobile. Multiple wireless service providers (WSP) compete to serve these users. Each provider deploys a mesh of access points (APs). The APs of a single service provider typically form a multihop wireless network. For example, in Figure 1.2(a), mesh networks from three service providers cover a certain geographic area; the three meshes are shown separately in Figure 1.2(b). Note that, some of the mesh nodes in each provider's network have

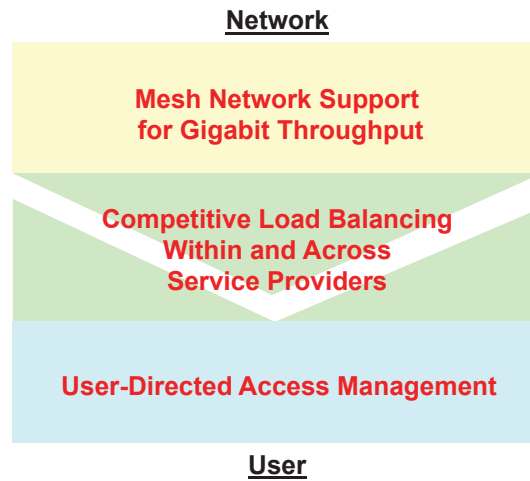


Figure 1.3 Challenges supporting long-lived multi-gigabit flows.

direct connection to the Internet (henceforth called *gateway* nodes). Packets from/to Internet enter/leave the provider's mesh through one of the gateway nodes and are then are forwarded from/to the wireless users through the mesh nodes.

The geographic region will typically contain other users who hold exclusive licenses to a part of the frequency spectrum. In the envisioned network architecture, these users are allowed to and willing to lease short-term access rights to other service providers, who in turn, may re-lease these rights to individual wireless users. It is assumed that significant data rate increases can be achieved by purchasing access rights to these secondary spectrum.

To achieve gigabit data rates in this network architecture, there are three key challenges (see Figure 1.3) which need to be addressed. Section 1.1.1, 1.1.2, and 1.1.3 describe these challenges in more detail. Chapter 3, 4, 5, and 6 collectively describe a comprehensive approach for addressing these challenges.

### 1.1.1 Mesh network support for gigabit traffic flows

One of the major drawbacks of leasing and relinquishing spectrum from licensed users is that it causes considerable fluctuations in the link bandwidths. These fluctuations occur in timescales much larger than typical wireless channel quality fluctuations and hence are not adequately handled

by conventional physical and link layer solutions. Furthermore, the fluctuations caused by leasing and relinquishing of spectrum have spatial and temporal correlations not commonly present in typical wireless channel quality fluctuations. For instance, when a license holder decides not to renew a lease, multiple nearby mesh nodes will simultaneously lose part of the frequency spectrum, which in turn, reduces the link data rates they can support. Such spatial-temporal correlation in bandwidth fluctuations cause a burst of packet losses in the network, which substantially degrades the end-to-end throughput of traffic flows. In particular, one can show that the end-to-end throughput of Transmission Control Protocol (TCP) based traffic flows are much smaller than desired due to the bandwidth fluctuations caused by these cognitive radio effects, i.e., caused by short-term leasing and relinquishing of frequency spectrum from nearby licensed users.

For instance, simulation results show that TCP-based long-lived traffic flows experience considerable throughput degradation due to the bandwidth fluctuations caused by short-term leasing and relinquishing of frequency spectrum (see Chapter 3). The simulation results further show that the degradation becomes more severe as data rate increases. For example, when the maximum possible sustainable data rates exceed 1 Gbps, the TCP-based flows achieve end-to-end throughput of less than 600 Mbps (i.e., 60% of maximum possible throughput) as compared to 70 Mbps (i.e., 70% of maximum possible throughput) when the maximum possible sustainable data rates are 100 Mbps. To alleviate these degradation, this thesis describes a set of network layer strategy which can be collectively implemented by the mesh nodes in each service provider's network. This strategy integrates techniques such as diagraph routing, inter-flow network coding, forward error correction, and buffer management.

### **1.1.2 Competitive Load Balancing Within and Across Service Providers**

Once deployed, the mesh nodes must compete with each other for the wireless users. For the mesh nodes belonging to the same service provider, this is a “friendly” competition to divide the entire geographic area into individual coverage areas for each mesh node so that the wireless users connected to the provider can get high data rates. Specifically, the coverage area of a mesh node depends on its transmit power. If the transmit powers are too small, then there may be coverage

holes where the wireless users do not have sufficient signal-to-noise ratio to be able to connect any mesh node from the provider. On the other hand, if the transmit powers are too large, then the coverage areas of multiple mesh nodes will overlap and the wireless users in the overlapping region may receive low data rates due to signal interference from other mesh nodes. Since the “optimal” values of parameters such as transmit power may change over time with changes in user density (due to mobility) and with changes in availability of frequency spectrum, friendly competition is a way for the mesh nodes to dynamically adapt their parameters to the changing conditions in a decentralized fashion.

Clearly, the competition for wireless users is even more intense across the service providers. Service providers are in the connectivity business and their revenue depends directly on the number of wireless users who get Internet connectivity through their mesh nodes. The number of wireless users connected to a particular mesh node also determines the data rate received by a wireless user because its resources (e.g., its frequency spectrum) is shared among the the wireless users connected to that node. Therefore, the wireless users have selfish interest in not only switching between providers but also between mesh nodes of the same provider in order to increase their individual rates.

To address these challenges, Chapter 4 describes a joint power and user association strategy for the friendly competition among the mesh nodes within the same provider network. This joint strategy integrates a distributed transmission power adaptation scheme for the mesh nodes with a decentralized association scheme through which stationary wireless users select a mesh node to obtain their network connectivity. Chapter 5 of the thesis describes a dynamic strategy for pricing wireless channels so that a service provider can sell them to stationary and mobile users. The prices vary with time and are a function of demand, supply, and competition from other providers.

### **1.1.3 User-directed Mobility Management**

Mobile users have additional difficulty maintaining their access to the network. As they move, a mobile user must connect to a different mesh node. The delays involved in “mobility management” have considerably more detrimental effects at gigabit data rates than at lower data rates.

Traditionally, resource allocation decisions to cope with mobility related issues are handled by the network as opposed to the user. This is because the network traditionally has information from a large number of users and can hence make a “better” decision. However, in such approach, it is more difficult to tailor the decision to the needs of each individual user. In addition, with the growing popularity of smart devices, each individual user has considerable information on their needs. For example, individual users can now easily predict their “near-future” locations using context, Global Position Systems information, etc. There is also a wide variation in the nature of the requirements among the users. User-directed strategies are better suited than network-directed strategies to the emerging reasons.

Chapter 6 describes a channel purchasing strategy for the users. In this strategy, a wireless user can purchase channels to meet its bandwidth needs from one or more of the service providers. If the price is “right”, the user perceives a demand for bandwidth based on a monitoring of its applications, a wireless user may also purchase bandwidth from a service provider at a mesh node near a predicted location some time in the future. Through this active purchase strategy, a wireless user can optimize the cost needed to assure QoS needs of its applications. Such strategy also creates the competitively market through which multiple service providers compete for the “business” from a wireless user (i.e., the channel pricing strategy of Chapter 6).

## **1.2 Thesis Organization**

The thesis is structured as follows. In Chapter 2, we review related research in the areas of cognitive radio, multipath routing, network coding, QoS management and resource allocation, and mobility management. Chapter 3 presents the spare-bandwidth rate-adaptive network coding scheme to route TCP flows in the cognitive radio wireless mesh networks. Through this scheme, each mesh node distributedly utilizes the spare bandwidth on its outgoing links to reliably forward packets in the network. The effectiveness of the scheme is evaluated using the network simulator ns-2 [3]. Chapter 4 presents the joint user association and power adaption scheme. The enhancement of the network performance is evaluated at the end of the Chapter. Chapter 5 and 6 form the wireless channels supply and demand market. In Chapter 5, we present the dynamic pricing

strategy for mesh nodes to sell the channels. Evaluation results show the service provider maximizes its revenue under different scenarios. In Chapter 6, we present the channel purchase strategy for the users to maintain the QoS of their applications. The effectiveness for supporting QoS is evaluated in the simulation section. Specifically, the mesh nodes price their channels following the pricing strategy in Chapter 5. The thesis is summarized in Chapter 7 with some future directions for research.

## Chapter 2

### Related Research

Many researchers have investigated different approaches to improve network performance. To enhance network performance, one often needs to properly combine several approaches aimed at different components of a network. In this chapter, several ideas from the system point of view for supporting multi-gigabit networks are reviewed.

#### 2.1 Cognitive Radio

Recent studies have shown that the usage of the frequency spectrum for wireless communication is very inefficient [2]. This inefficiency stems from the static licensing approach to spectrum regulation traditionally taken by regulatory bodies worldwide. Under this approach, interference between different wireless systems is avoided through assignment of exclusive usage licenses to different users. It has led to acute bandwidth shortages in certain spectrums used for wireless communication even though there is a widespread under utilization of the overall frequency space. As a result, the Federal Communications Commission of the United States of America and other regulatory bodies have indicated their willingness to consider a more dynamic frequency allocation approach enabled by new technological advances called *cognitive radios* (CR).

With CR, each wireless device can sense and operate over a wide range of frequencies. As a result, a wireless device can opportunistically explore and make use of unused bandwidth among a broad frequency spectrum. Such an approach requires temporary leasing of the unused frequency bands from the corresponding licensed users. More specifically, a “secondary” wireless user may request and lease an unused frequency band from the “primary” user of that band. The usual

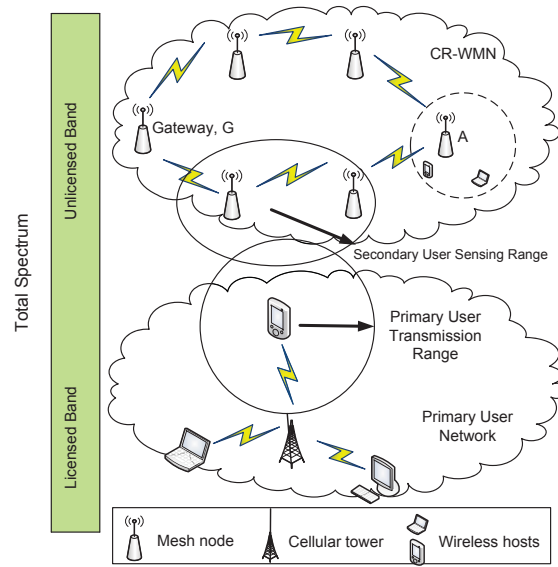


Figure 2.1 Example of cognitive radio wireless mesh network.

agreement is that the secondary user will stop using the spectrum whenever it senses that the primary user needs it.

For example, consider a *cognitive radio based wireless mesh* (CR-WMN) in which the CR utilizes the spare spectrum for providing larger bandwidth for wireless communication. In which the wireless users access to the Internet infrastructure over a fixed multihop wireless network of “mesh nodes” (see Figure 2.1). Each wireless user is associated with one of the mesh nodes and some of the mesh nodes have direct connection to the Internet.

The CR-WMN lies within the communication range of certain portions of the white space spectrum available to the CR-WMN nodes. Consequently, in addition to the bandwidth permanently available to the CR-WMN, the communication between the mesh nodes also occurs over bandwidth temporarily leased from free spectrum after sensing. The leased bandwidth can of course be withdrawn by the primary user with little or no notice.

A majority of work in CR focuses either on spectrum sensing to identify available primary user channels or on the physical layer design needed for wireless communication over a wide range of the frequency spectrum. For example, cooperative sensing is analyzed in [4, 5] to show the benefit of cooperation. Security is further considered for spectrum sensing in white space access in [6].

In this section, we will base on the network environment to introduce related researches of the applications of cognitive radios.

### 2.1.1 Cognitive Radio in Spectrum Pricing Markets

Economic approaches offer a variety of services and provide opportunities of utilizing the spectrum. Economic approaches are summarized and introduced in [7, 8, 9, 10] to picture the pricing or game theoretic approaches in order to effectively access and share the free spectrum. Liu *et. al* propose spectrum auction games for multimedia streaming over CR networks [11]. Three distributed auction based spectrum access schemes are proposed aimed to maximize the proposed utility function. Furthermore, Liu *et. al* also investigate game theoretic spectrum approaches in other works [12, 13]. Furthermore, Niyato *et. al* work on spectrum pricing from several viewpoints to investigate and address the issues in spectrum trading, pricing model, pricing setup, price game, etc. under different network infrastructures in [14, 15, 16, 17, 15]. Authors in [18] explore dynamic competitive market from both price and quality sensitivity to develop an optimal strategy to ensure QoS for wireless communication.

In addition to Liu and Niyato, an economic framework for dynamic spectrum access and service pricing is addressed in [19, 20, 21, 22, 23, 24, 25] in order to dynamically access to free spectrum. Specifically, in [19], a dynamic pricing strategy is introduced in consideration of knapsack based auction. The result shows the optimal use of spectrum. An auction based bandwidth allocation is formulated for secondary users to bid free spectrum for communication in [20, 21]. Specifically, a dynamic updating algorithm is presented for secondary users to bid spectrum in order to effectively and fairly access the free spectrum in [20]. SATYA (Sanskrit for "truth") [21] is proposed for spectrum auction in heterogeneous wireless systems. In addition to access spectrum, fair share of the free spectrum is considered in [22, 23] through properly spectrum pricing strategies. Also, to improve QoS the WSPs sell their channels to optimize spectrum lease and service for WiFi-2.0 in [24], and the power control is jointly considered and combined with the Stackelberg game model in [25].

According to the contract theory, in [26], a market-driven spectrum trading is proposed to design a monopolist-dominated quality-price contract. Users purchase spectrum with quality-price intended for their type, and under this condition, primary users are able to maximize their utilities. Furthermore, considering short-term spectrum contract, authors in [27] propose and analyze a cognitive mobile virtual network operator (C-MVNO) to sense the free spectrum flexibly and dynamically. Further, depending on the estimation of secondary user requirement, the C-MVNO invests and prices spectrums to improve the expected profit. In addition, in [28], primary users allow overbooking for spectrum reservations of secondary users to further utilize the available free spectrum. An algorithm based on Cox-Ross-Rubinstein approach is designed to price reservation for overbooking for performance analysis. Moreover, to better reflect the bursty nature of packet-based communication and to effectively allocate resources, the proposed auction scheme announces not only the spectrum price but also the spectrum leasing time period in [29].

### **2.1.2 Cognitive Radio in Routing**

There are several papers that integrate network layer issues such as routing with link and physical layer issues in cognitive radio networks. This body of work is more relevant to our paper. Some of these papers focus on traditional single path routing with, if needed, re-routing based on the feedback from the nodes in the network [30, 31, 32, 33]. Others, such as [34], rely on multiple path routing to combat the effects of bandwidth fluctuations caused by leasing and relinquishment of primary user channels. In addition, the authors analyze the multihop delay and connectivity to fully utilize the free spectrum in the network [35]. However, they require feedback information from the intermediate nodes to packet senders and/or any other node in the network.

### **2.1.3 Cognitive Radio for Transmission Control Protocol (TCP)**

Three recent cognitive radio papers, also focusing on TCP performance are [36, 37, 38]. In [36], the authors consider the challenges, which TCP faces are due to the dynamic spectrum access in CR networks and develop an analytic model to incorporate cognitive radio effects on TCP performance. The work in [36] considers a single hop TCP flow from a cellular basestation to a

wireless host. However, [36] does not propose any scheme to improve TCP's performance. In [37], the authors extend the common network simulator ns-2 to study the effects of cognitive radio effects on TCP performance. In particular, they model the impact of stoppage in packet forwarding during spectrum sensing and spectrum handoff and the impact of the differences in the data rate and delay characteristics of primary user channels. Through simulation they study the effect of these cognitive radio effects on different versions of TCP.

In [38], the authors propose a modification to the state transition diagram of TCP sender to incorporate cognitive radio effects. Feedback from the intermediate nodes indicating their non-availability for packet forwarding due to spectrum sensing and spectrum handoff is used to change the state of TCP sender so as to avoid unnecessary timeouts and reductions in sending rates.

## 2.2 Multipath Routing

Packets from a traffic flow are usually forwarded by multiple intermediate nodes in the network from its source to its corresponding destination. During transmission, the packets may experience loss, error, or disordering which prevent them from being successfully delivered to the destination, and the destination obtains low end-to-end throughput. Many routing algorithms are designed to enhance the reliability for packet forwarding/routing in the network. Several routing issues [39, 34, 32, 30, 31, 40, 33, 41] have been investigated in wireless networks. Many researches, for example [30, 31, 40, 33], focus on single path routing because of its low cost and low computation complexity. Unlike single path routing, packets are forwarded through multiple paths to the destinations. Multipath routing improves the network performance from the perspective of better balancing traffic loads, fewer burst losses, more tolerance to congestion. [39]. Wang *et. al* [34] propose the joint multipath routing and spectrum access (MRSA) to achieve better end-to-end throughput and traffic load balancing in mesh networks. In MRSA, all available paths are used for sending packets, but MRSA requires source routing to maintain routes, which limits the packet rates because the source node cannot instantly figure out the channel condition. Optimized Multipath Network Coding (OMNC) [41] combines multi-path routing and network coding to improve

the throughput of unicast sessions in lossy wireless networks in a distributed manner. However, the proposed rate control algorithm requires each node to update information periodically.

## **2.3 Network Coding**

In the network, multiple packets are linearly combined at a node, and sent the combined packets to another node. Further, a node decodes and reconstructs linear combined packets when it receives enough number of linearly independent packets. The linear combining and reconstructing process in the network are named as network encoding and network decoding, respectively. In [42], the authors proved that network coding using alpha codes can be used to deliver minimum of the max flow rate from the source to each receiver in a multicast. After this work, a large body of researches on network coding are proposed and network coding has been proven to be one of the viable approaches to reach maximum flow rate and has been applied to many different issues to improve network performance.

### **2.3.1 Network Coding for Multicast Transmission**

Among the existing work, some focus on the theory of multicast transmission, and some apply network coding to improve the video streaming performance through multicast [43, 44, 45, 46, 47, 48]. As addressed in [42], the minimum of max flow rate is achieved by network coding for multicast, in [47], the usage of network coding increases the data rate for multicast, therefore the performance of video streaming is improved. In addition, through the assistance of network coding, authors in [48] proposed a bandwidth partition algorithm to share bandwidth for multicast applications. Specifically,

### **2.3.2 Network Coding for Unicast Transmission**

Among the existing network coding based designs for unicast, most of the work, such as [49] network encode packets among the same flows. Furthermore, there are about four papers, which deal with both network coding and TCP [49, 50, 51, 52]. In [49], the authors propose a modification to protocol stack at the TCP sender and receiver to introduce a new network coding sublayer

between the transport and network layers. The new sublayer encodes/decodes segments transmitted/received by TCP sender/receiver. As mentioned above, modification of protocol stack at the sender and receiver of a TCP flow is not desirable. Further, other nodes in the mesh network also perform inter-flow network coding to improve TCP performance. In [49], redundancy management is done at the TCP sender. It requires the sender to collect information and estimate the spare bandwidth available in the route to determine how many redundant packets can be transmitted. The authors of [50] propose an indirect way to manage redundancy at the sender using the feedback (i.e., acknowledgments) inherent in some protocols (e.g. TCP), although the scheme in [50] is described for a single hop broadcast scenario with multiple receivers. In addition to the inter-flow network coding, this is another major advantage of our approach as compared to the one in [49].

The schemes in [53, 54] are also targeted towards wireless mesh networks. Multipath routing and network coding are used as well in order to increase throughput. Specifically, both schemes take advantage of opportunistic routing for throughput improvement. Further, the proposed method in [53] focuses on IEEE 802.11 medium access control scheduling, and the mechanism in [54] controls number of packets for transmission with the assistance of feedback information. However, they do not focus on TCP issues, although TCP flows can benefit from the techniques in [54, 53]. Moreover, the works in [54, 53] are at different abstraction levels than our scheme. The papers [51, 52] also use network coding for enhancing TCP throughput in multihop wireless networks based on the IEEE 802.11. The focus of these papers is also on the optimal use of the IEEE 802.11 medium access protocol, hence they are also at a different layer of abstraction than our scheme.

There are several recent papers [55, 56, 57, 58, 59] which use inter-flow network coding for packet combination. They rely on solving an optimization problem to do rate control.

### **2.3.3 Network Coding for Wireless Communication**

Simple XOR's of broadcast packets for a practical network coding scheme is proposed in [60] for a 802.11 based network. Using the broadcast capability of wireless networks to exploit the opportunity increasing the throughput across multiple unicast transmission. [61] utilizes the broadcast nature of wireless networks for analog network coding (ANC)-based mechanism. Authors in

[62] design a heuristic joint link scheduling, channel assignment and routing algorithm with network coding for multi-channel and multi-radio environment. In addition, in [41], network coding is applied to recover packet errors/losses in lossy wireless networks through combining multipath routing.

## 2.4 QoS Management and Resource Allocation

Multiple traffic types are sent to the network simultaneously. All of them have different QoS constraints. To effectively supporting different requirements of each traffic, network resources have to be properly allocated. Over the past two decades, there has been extensive research on QoS architectures for the Internet. This has resulted in the standardization of many associated protocols by the Internet Engineering Task Force (IETF). For example, the IETF has standardized several protocols for QoS architectures such as Integrated Services (IntServ) [63] and Differentiated Services (DiffServ) [64]. To improve QoS, network resources have to be managed and allocated properly to each entity in the network aimed to fully utilize the available resources in the network as well as improve QoS assurances for each traffic flow. Spectrum access/allocation has been described previously, and in this section, we will introduce the rest of the directions for QoS management.

### 2.4.1 Power Control

In [65, 66, 67, 68], strategies for power control are presented in the context of IEEE 802.11 networks. For example, in [65], Akella *et al.* propose a power control scheme, PERF, to reduce the interference among access points. Their scheme adjusts the transmission power of the access points according to the feedback about the measured interference from the users. Game-theoretic approaches for power control are proposed in [66, 67]. Furthermore, some works combine power control and other resource allocation mechanisms to improve the network performance [69, 70, 71, 72]. A joint power and channel allocation mechanism is developed in [69] to provide capacity fairness of all links in the mesh networks while a joint scheduling, power control and rate adaption is proposed in [70] to maximize the minimum throughput among all flows in the

network. In addition, authors in [71] combine power control and scheduling together for resource allocation, and authors in [72] propose synchronized two phase rate-power control to improve the network performance in the 802.11 environment. Moreover, in [73], for supporting diverse QoS and utilizing available spectrum, users adjust their transmission power to minimize interference and optimize their utilities.

### 2.4.2 Association

Association strategies for the IEEE 802.11 networks are proposed in [74, 75]. In both schemes, the access points broadcast Received Signal Strength Indicator (RSSI) density table to help users estimate the interference levels for uplink transmissions. They do not consider downlink transmissions in making association decisions. If, as expected, most of the traffic is downlink, then the resulting association solution may not be good. In [76], base stations in a Wideband Code Division Multiple Access (WCDMA) networks broadcast the number of user associated with them. A user selects a base station to associate with based on the received signal to noise and interference ratio and the number of associated users with that base station. However, due to the differences in the medium access control scheme, the results in [76] do not directly translate to IEEE 802.11 networks. Furthermore, cell-breathing optimizes the association through adjusting the cell size of each access point in the WLANs in [77]. Specifically, this combining power control and user association framework mainly operates by the access points in response to the dynamic change of traffic loads in the network. Furthermore, the handoff cost is also taken into account for the access points to dynamic adjust their transmission power which in turn reflects their wireless connectivity coverage and incur user re-association to keep wireless connectivity. Moreover, a decentralized mechanism is developed to first optimize node (i.e., AP) selection and transmission strategy for wireless users, and then these selected nodes further optimize their transmission power to maximize the data rate across all sources in [78]. In order to focus on QoS or performance improvement, in [79], proportional fairness is taken into consideration for a centralized user association algorithm.

### 2.4.3 General Resource Allocation

A centralized radio resource management in [80] is designed, and each node in the mesh networks reaches fair throughput through efficiently managing and minimizing the energy and spectrum usage. Authors in [81] formulate a convex optimization problem for admission control to meet the requirement of QoS and fairness. Furthermore, in [82], the authors formulate the power control problem as a dynamic programming to minimize the power consumption as well as maximize user QoS. Specifically, this power control mechanism is designed to improve the QoS for streaming. In addition, cross-layer approaches have been intensively investigated for many years aimed to optimize the resource allocation for QoS performance enhancement. For example, in [83] utility based resource allocation is applied to combine routing (i.e., following the idea of shortest path routing), bandwidth allocation, and admission control for maximizing QoS. Some works consider the node placement in [84, 85] to effectively utilize available resources aimed to improve network performance. Due to the dramatically increasing demands of the video streaming application, the importance of addressing the multimedia oriented QoS guarantee has increased for next five to ten years. In [86], spectrum is allocated for multimedia transmission. Specifically, users are charged based on the resource usage, and the users request resources according to their transmission strategy aimed to maximize the system utility. Furthermore, in [87], the authors consider caching in resource auction in order to guarantee the QoS of video streaming. Furthermore, a collaborative approach is proposed for the applied Vickrey-Clarke-Groves (VCG) auction aim to effectively allocate bandwidth and maximize the social welfare while the QoS of video streaming is also satisfied.

## 2.5 Mobility Management

Seamless wireless communication is a critical concern while the wireless network is designed. Researchers have investigated mobility management for more than 10 years to support seamless

wireless communication in networks [88, 89, 90]. Generally, six research issues, packet processing, signaling load, route optimization, resource management, evaluation of algorithms, and service guarantees are addressed. Resource (bandwidth, channel, spectrum, etc.) reservation is one possible direction to support packet transmission performance for wireless users. For example, MRSVP is proposed to reserve paths and resources for packet forwarding in response to the movement of a wireless user [91]. Further, MRPEC provides all possible locations that the wireless user may visit for resource reservation, and the resources are reserved when resources are available along the paths. Similarly, the effect of predictability of mobility for bandwidth provisioning is investigated in [92], and the results show the improvement of voice call dropping rate benefited by intelligent prediction. However, the focus of the above two works is on supporting the mobility, and they need modifications for further supporting QoS of the real-time bandwidth demanding applications. Some works like [93] consider the QoS constraints for real-time periodic streams for bandwidth allocation in order to minimize the bandwidth reservation and the energy consumption. Specifically, a bandwidth reservation model is formulated and a reservation based channel access algorithm in WLAN is proposed based on the generic algorithm. Furthermore, the impact of the traffic scheduling policies in the formulated model is well studied to illustrate the effectiveness of bandwidth usage and QoS maintenance.

Moverover, handoff management is the main feature for supporting mobility. Two approaches, multicasting and re-routing are addressed most often. Several schemes are proposed in order to provide mobility management for 802.11 infrastructure based mesh networks [94, 95, 96]. Authors propose a fast handoff scheme, called SyncScan [96], for the 802.11 infrastructure based networks, where the nodes constantly track nearby access points by synchronizing their listening periods with the transmissions from the access point and choose the best one for the handoff. By modifying drivers at the mobile user end, the system achieves a handoff latency of 5 milliseconds. In [95], SMesh, a multicast based approach is proposed to support seamless handoff by using a combination of DHCP and gratuitous address resolution protocol messages between the access point and the mobile users. Specifically, in SMesh, the latency for handoff is around 50 milliseconds. To efficiently reduce the handoff delay, a cross layer approach is developed in [97] for mobility

management. Specifically, the proposed algorithm considers link and network layer routing for managing mobility. In addition, mobility prediction is applied for mobility management to reduce the handoff delay and enhance the handoff performance in [98, 99, 100]. Specifically, the mobile host actively adapts its mobility for handoff prediction/awareness aimed to reduce the handoff delay. Moreover, due to the security concern for user authentication while associating with an access point, a secure fast handoff algorithm in the mesh network is proposed in [101] specifically for 802.11 based deployments. From the perspective of packet synchronization, authors in [102] propose an IP based network layer soft handoff to improve the common issues of synchronization among nodes involving packet forwarding and bandwidth wastage in software handoff. Also, considering IP based handoff and mobility management, HAWAII [103] is proposed to manage micro-mobility through domain-based approach. Specifically, intra-domain and mobile IP are considered for the development.

In addition to general infrastructure based network mobility management, some works focus on the mobility performance enhancement in swarm mobility, group mobility, or delay tolerant networks, etc., such as [104, 105, 106]. However, it is less relevant to our work, and we will not specifically introduce them in further detail.

## Chapter 3

### Routing TCP Flows in Cognitive Radio Wireless Mesh Networks

Cognitive radio based wireless mesh networks (CR-WMNs) are designed to provide better performance than other existing personal, local, and metropolitan wireless networks, such as Wireless Local Area Networks and WiFi. In CR-WMNs, each link has different number of channels belonging either to primary users or to secondary users. Primary users release and take away their channels dynamically. Secondary users share unlicensed channels and borrow channels from primary users when primary users do not use their authorized channels. When the number of available channels for secondary users fluctuates, Transmission Control Protocol (TCP) flows experience packet losses, packet re-ordering, and timeouts, resulting in low end-to-end throughput.

To alleviate the problem of low TCP throughput, in this Chapter, we propose a *Spare-bandwidth Rate-adaptive Network Coding* (SRNC) scheme. In SRNC scheme, each gateway node forwards packets after network coding. Each intermediate node also adaptively uses network coding before forwarding the packets to the outgoing links. Each mesh access node decodes the network coded packets before forwarding them to the destinations. The key feature of SRNC is that each node adapts its network coding rate based on the available channels on the outgoing links, such that the access nodes can decode the packets with higher probability without significantly affecting the cross-traffic. Effectiveness of the proposed scheme is evaluated using simulation. The simulation results show that the proposed scheme uses the available channels on each link efficiently and it significantly improves end-to-end throughput of TCP flows.

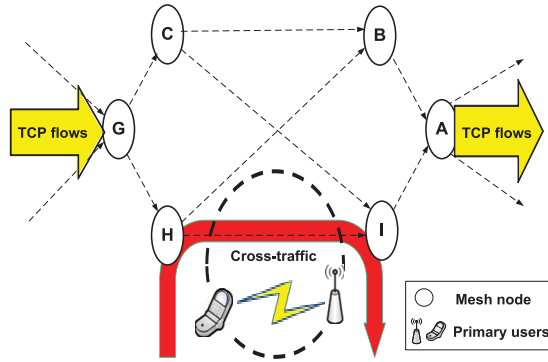


Figure 3.1 Simple wireless mesh network topology

### 3.1 Motivation

The main advantage of CR is that the secondary user gets access to large wireless bandwidth when the primary user releases it. The problem, however, is that the large bandwidth may be taken away from the secondary user under fairly short notice. The resulting large variation in bandwidth availability creates problems in the underlying information exchange among the secondary users.

More specifically, as a result of this frequent leasing and relinquishment of primary user bandwidth, there is considerable spatial and temporal variations in the bandwidth available to the mesh nodes. These variations create some problems for the mesh nodes in the CR-WMN. In particular, this variability in bandwidth available for communication creates performance problems to the TCP based packet flows. For instance, when the bandwidth is withdrawn in the CR-WMN, TCP flows passing through those nodes experience packet re-ordering, packet losses, and timeouts. In response, the corresponding TCP sources reduce their sending rates and re-transmit the lost packets. Meanwhile, the CR-WMN routing algorithms may also attempt to re-route the TCP flows away from the congested nodes. While these adaptations to bandwidth reductions are taking place and/or after these adaptations have occurred, the primary user may relinquish the bandwidth back to the CR-WMN nodes and the CR-WMN must begin another round of adaptation to exploit the availability of additional bandwidth.

For example, consider a wireless mesh network as Figure 3.1.

The mesh has six nodes labeled A, B, C, G, H, and I. Node G is the gateway to the Internet.

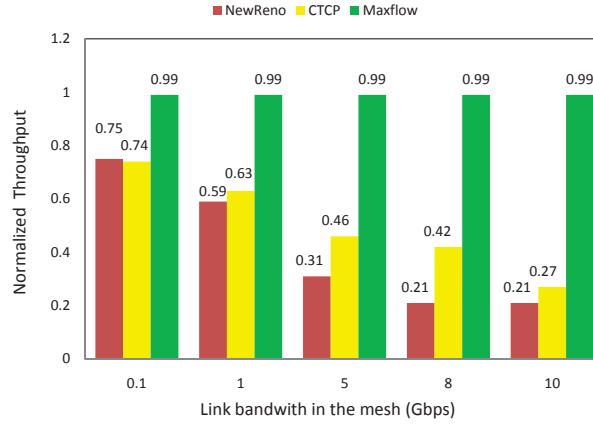


Figure 3.2 Evaluate TCP throughput of NewReno and Compound TCP under different link bandwidth scale

Wireless hosts associate themselves with one of the nodes in the mesh. In this example, we focus on wireless hosts associated to node A. We assume that there are ten such hosts and each host has a TCP-based downlink streaming from the Internet. Other relevant characteristics of the network are:

- The RTT of each of the ten TCP flows is 12 ms.
- The bandwidth of each link in the mesh fluctuates between  $x$  and  $2x$ ; we include results of several different values of  $x$ .

Figure 3.2 shows the average normalized end-to-end throughput of the ten TCP flows for  $x = 0.1, 1, 5, 8, 10$  (Gbps). The figure compares the performance of two different TCP versions: NewReno[107] and Compound TCP (CTCP)[108]. Note that, CTCP is specifically designed for network with large BDP. However, as evident in Figure 3.2, both versions do not perform well as data rate increases. In particular, when  $x = 5, 8, 10$ , the maxflow rate between G and A is at least 99% of the link bandwidth. But, the normalized end-to-end TCP throughput of both versions are below 0.5.

Since the RTT is kept unchanged for different values of  $x$ , the BDP increases in proportion to  $x$ . When link bandwidth fluctuations occur due to leasing and relinquishing of free spectrum, TCP flows experience some packet losses. As BDP increases, TCP congestion control scheme takes

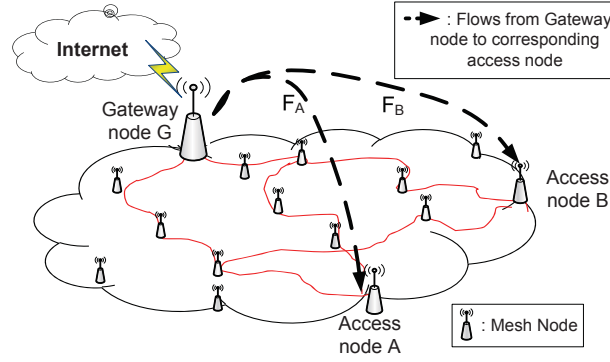


Figure 3.3 Cognitive radio wireless mesh network.

more time to adapt. Even CTCP, which is specifically designed to respond faster to congestion in high bandwidth-delay situations, does not seem to do well in the presence of congested link related bandwidth fluctuations. The spatial and temporal correlations in CR-related bandwidth fluctuations and the time scales of these fluctuations cause both NewReno and CTCP to substantially underperform as data rate increases.

### 3.2 Network Environment Overview

Consider a cognitive radio enabled wireless mesh network (CR-WMN) with Internet gateway node G as shown in Figure 3.3. The other mesh nodes serve as access points to the wireless hosts. Therefore, downlink traffic from the Internet to a particular wireless host enters the mesh network through node G, traverses one or more hops in the mesh network to the corresponding access node (say node A) and then goes over the wireless link to the receiving host. In this paper, we describe the idea in terms of the actions taken by the mesh nodes in forwarding TCP packets to the wireless hosts connected to the access node A. For clarity of presentation, we refer to this set of downlink TCP flows as  $F_A$ .

Further, we assume that each mesh node has access to a set of channels to communicate with neighboring mesh nodes. Some of these channels are permanently licensed to the mesh network while other channels are temporarily leased from certain primary users in the neighborhood. The

temporarily leased channels must be instantly relinquished by a mesh node when the primary user needs the channel for its use.

### 3.3 Components of Spare-bandwidth Rate-adaptive Network Coding (SRNC) Scheme

To effectively utilize the available bandwidth in repose to the dynamic changes of primary user activities, we develop a methodology, SRNC which integrates with existing communication network stacks. Specifically, it is implemented between link and network layers. The SRNC consists of four key components, digraph routing, network coding, exploiting available bandwidth, and buffer management.

#### 3.3.1 Digraph Routing

Traditionally, packets of  $F_A$  are forwarded in the CR-WMN over a single route. Instead, in SRNC, the routing algorithm finds a directed acyclic graphic (DAG),  $G_A$  rooted at node  $G$  and ending at node  $A$ . Packets of  $F_A$  are routed from  $G$  to  $A$  over all paths in  $G_A$ . Only the sub-graph  $G_A$  of the CR-WMN is relevant to flows in  $F_A$ .

#### 3.3.2 Network Coding

In traditional routing, a node simply forwards a received packet along one of its outgoing links in the routing DAG. Instead, in SRNC, each node computes a linear combination of packets in  $F_A$  and forwards the resulting packets on one of the outgoing links in the DAG. Specifically, packets are network encoded across multiple flows (i.e. inter-session network coding) in contrast to commonly used intra-session network coding. In addition, we suggest systematic codes for encoding other than random linear combinations. As a consequence, not all network encoded packets are lost when a set of network encoded packets are undecodable.

### 3.3.3 Exploiting Available Bandwidth

In a basic plus network coding scheme, a node forwards only as many packets in  $F_A$  as it receives. Instead, in SRNC, a node forwards as many combination of packets it possibly can, subject to certain constraints described later.

### 3.3.4 Buffer Management

If a node  $i$  forwards as many packets as possible on its outgoing link to node  $j$ , then the buffer at node  $j$  may get filled up by packets from node  $i$ . A full buffer will cause packet losses to flows in  $F_A$ , thereby decreasing the performance of flows in  $F_A$ . Also, it is unfair to other flows in the CR-WMN. Therefore, each node implements a buffer management strategy which ensures that no particular set of flows can overly dominate the buffer space at any node in the CR-WMN.

In the rest of this section, we elaborate on the four notions described above. In this elaboration, we present SRNC from the perspective of three different types of nodes: gateway node G, intermediate node  $i$ , and mesh access node A.

## 3.4 Description of SRNC

### 3.4.1 SRNC at gateway node

Figure 3.4 describes the steps taken by node G during the time interval  $[kT, (k+1)T)$ , where  $T$  is a pre-determined design parameter. At the start of the interval, G discards all packets in  $F_A$  which arrived in the interval  $[(k-2)T, (k-1)T)$ . During the interval  $[kT, (k+1)T)$ , node G transmits linear combined packets in  $F_A$  arrived during the interval  $[(k-1)T, kT)$ . Further, packets in  $F_A$  arrived during the interval  $[kT, (k+1)T)$  are simply buffered for later transmission. Moreover, all packets transmitted during this interval  $[kT, (k+1)T)$  has a special *label* with value  $k$ . The other nodes can identify packets that are linear combination of the same set of packets using this label. Let  $n_{A,k}$  be the total number of packets in  $F_A$  which arrived during  $[(k-1)T, kT)$ . In order to assist buffer management policy, the first  $n_{A,k}$  packets transmitted by G during this interval

are marked as “High priority”. The others are marked as “Low priority”. As described later, other nodes will give preferential treatment to “High priority” packets if their buffer is full.

Example: Consider a gateway node  $G$  shown in the Figure 3.5. Node  $G$  has two outgoing links into the mesh. Assume that the packets can be routed on both of these links to reach access nodes  $A$  and  $B$  in the mesh. Several wireless hosts are connected to the access nodes  $A$  and  $B$  and they are receiving downlink traffic from the Internet through the gateway node  $G$ .

As described in Figure 3.4, node  $G$  buffers the packets which arrive in the time interval  $[(k - 1)T, kT)$  for forwarding in the time interval  $[kT, (k + 1)T)$ . Suppose that node  $G$  received only five packets identified as  $a_1, a_2, a_3, b_1$  and  $b_2$  during the interval  $[(k - 1)T, kT)$ . Packets  $a_1, a_2$  and  $a_3$  are destined for wireless hosts connected to access node  $A$ . Likewise, packets  $b_1$  and  $b_2$  are destined for wireless hosts connected to access node  $B$ . Then, the actions taken by node  $G$  in  $[kT, (k + 1)T)$  in forwarding these packets can be explained as follows.

Suppose that the order in which the scheduler at node  $G$  considers these packets for forwarding is as shown in Figure 3.5. In the traditional approach, the scheduler will forward these packets in this order when the outgoing links are free. In contrast, in SRNC, node  $G$  forwards linear combination of appropriate packets. More specifically, the first packet considered by the scheduler is  $a_1$ . Therefore, at time  $t_0$ , when an outgoing link is free to transmit a new packet, node  $G$  forwards a linear combination,  $f_1$ , of  $a_1, a_2$ , and  $a_3$ , i.e., packets which are destined for the access node  $A$ . Next, at time  $t_1$ , the scheduler considers packet  $b_1$ . Therefore, node  $G$  forwards a linear combination,  $g_1$ , of  $b_1$  and  $b_2$ , i.e., packets which are destined for the access node  $B$ . Similarly, at times  $t_2, t_3$ , and  $t_4$ , the scheduler considers packets  $b_2, a_2$ , and  $a_3$  and thus forwards three packets, first a linear combination,  $g_2$ , of  $b_1$  and  $b_2$  followed by linear combinations,  $f_2$  and  $f_3$ , of  $a_1, a_2$ , and  $a_3$ .

Further, in the traditional approach, the scheduler will be done after transmitting the five packets. In contrast, in SRNC, node  $G$  continues to forward packets derived from these packets until time  $(k + 1)T$ . For instance, at time  $t_5$ , node  $G$  goes back to the first packet considered by the scheduler, namely  $a_1$ , and forwards a linear combination,  $f_4$ , of  $a_1, a_2$ , and  $a_3$ . Thus, in this example, node  $G$  has forwarded four packets which are linear combination of  $a_1, a_2$ , and  $a_3$ . At most

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**Algorithm Gateway**


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**In time interval  $[kT, (k+1)T)$** 


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1. Discard all packets in  $F_A$  which arrived in  $[(k-2)T, (k-1)T)$ .
  2. Buffer all incoming packets in  $F_A$ .
  3. At  $kT$  :
  4. Let  $n_{A,k}$  be the total number of packets in  $F_A$  which arrived in  $[(k-1)T, kT)$ .
  5. Create  $n_{A,k}$  network encoded packets with linear combination in  $F_A$  which arrives in  $[(k-1)T, kT)$ .
  6. Attach a label  $k$  to each of these packets.
  7. Mark these network encoded packets as “High priority”.
  8. On each outgoing link, transmit (as permitted by the packet scheduler) network encoded packets :
  9. If the total number of transmitted packets of all outgoing links is less than  $n_{A,k}$ ,
  10. Forward the “High priority” network encoded packets.
  11. Else,
  12. Generate a random linear combined packet of packets in  $F_A$ .
  13. Attach a label  $k$ , mark it as “Low priority”, and forward it.
- 

Figure 3.4 Algorithm executed by the gateway node in SRNC.

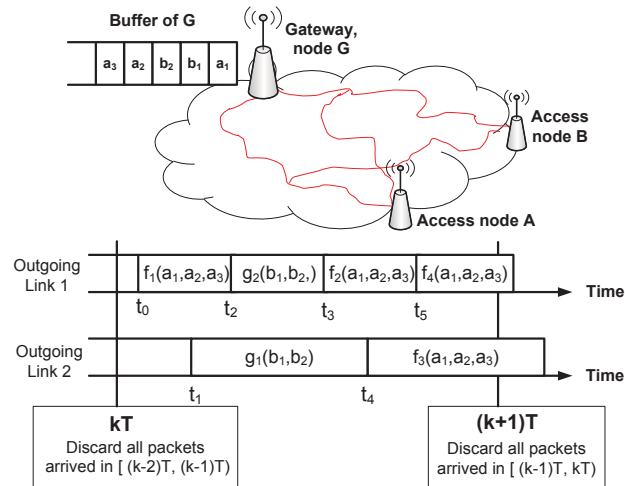


Figure 3.5 Illustration of SRNC at gateway node.

three of these packets are linearly independent and with high probability, any of three of these four packets are linearly independent. Forwarding of redundant packet helps the mesh cope with fluctuations in available bandwidths due to leasing and relinquishing of primary user channels. At time  $(k + 1)T$ , node G will delete packets  $a_1, a_2, a_3, b_1$ , and  $b_2$  from its buffer and switch to forwarding packets which arrived in the interval  $[kT, (k + 1)T)$ .

Note that, all the packets forwarded by node G in the interval  $[kT, (k + 1)T)$ , will have a label  $k$  so that the mesh nodes can identify the packets which can be network coded.

### 3.4.2 SRNC at intermediate node

Figure 3.6 describes steps taken by an intermediate node  $i$  with respect to packets in  $F_A$ . It includes two parts. The first part describes the actions taken when a new packet in  $F_A$  arrives. The other part describes the strategy used for transmitting packets on the outgoing links.

The process relies on a self-clocking scheme with respect to labels. For intermediate node  $i$ , packets in  $F_A$  arrive on each incoming link in non-decreasing order of label values. Specifically, when a packet of label  $k + 1$  arrives on an incoming link  $l$ , node  $i$  knows that it will not receive any packet with label value less than  $k + 1$  on that incoming link. Furthermore, when node  $i$  has received packets with label  $k + 1$  from each incoming link it will not expect to receive packets with label value less than  $k + 1$  in the future. Then, node  $i$  starts processing label  $k$ .

In addition, Node  $i$  implements a buffer management strategy. In this strategy, preference is given to “High priority” packets if the buffer is full.

Moreover, the transmission strategy at an intermediate node is similar to that at gateway node, except that the packets in  $F_A$  with the current label are used for linear combination. If node  $i$  receives a certain number of “High priority” packets in  $F_A$ , it transmits at most that many “High priority” on its outgoing links.

*Example:* Consider a typical node  $i$  in the mesh which is on the routing DAG for all downlink traffic to wireless hosts connected through access nodes A. Node  $i$  receives packets with label  $k$  destined for wireless hosts connected to access node A. As shown in Figure 3.7, node  $i$  keeps buffering these packets until it has received a packet with label  $(k + 1)$  on each of its incoming

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**Algorithm Intermediate**


---

**When a packet in  $F_A$  arrives on incoming link  $l$ :**

1. If buffer is full;
2. If incoming packet is marked as “Low priority”,
3. Discard the incoming packet.
4. Else,
5. If all packets in buffer are marked as “High priority”,
6. Discard incoming packet.
7. Else,
8. Find the most recent “Low priority” packet in buffer and discard it.
9. Enqueue incoming packet.
10. Let  $L_l$  be the largest label of all  $F_A$  packets received on incoming link  $l$ .
11. Let  $k = \min\{L_l : \text{incoming } l\} - 1$ .
12. When  $k$  is updated :
13. Discard all packets in  $F_A$  in buffer with label smaller than  $k$ .
14. Let  $n$  be the total number of packets in  $F_A$  in buffer and  $n_h$  be the total number of “High priority” packets in buffer.

**On each outgoing link :**

15. Transmit (as permitted by packet scheduler) linear combined packets in  $F_A$  with label  $k$  in buffer no more than number of received packets of label  $k$ .
  16. If the sum number of packets sent by all outgoing links is less than  $n_h$ ,
  17. Duplicate an unsent “High priority” packet with label  $k$  and forward it.
  18. Else,
  19. Create a random linear combined packet of packets in  $F_A$  in buffer
  20. Attach a label  $k$ , mark it as “Low priority”, and forward it.
- 

Figure 3.6 Algorithm executed by the intermediate node in SRNC.

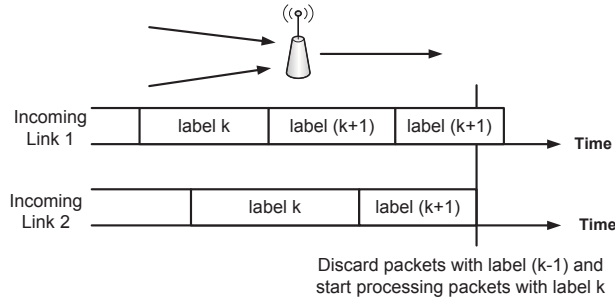


Figure 3.7 Illustration of SRNC at intermediate node.

links in the corresponding DAG. When node  $i$  has received a packet with label  $(k + 1)$  on each of its incoming links, it discards all packets with label  $k - 1$  from its buffer. This is because it now knows that it will not receive any packet with label  $k$  destined for wireless hosts connected to node A.

Traditionally, node  $i$  simply forwards one copy of the packet it has received on an outgoing link in the routing DAG. In contrast, in SRNC, node  $i$  linearly combines all packets with label  $k$  before forwarding it on an outgoing link. Suppose node  $i$  has received  $p$  packets with label  $k$  destined towards node A. Node  $i$ , traditionally, will forward exactly  $p$  packets on its outgoing links. In contrast, node  $i$ , in SRNC, forwards as many linearly combined copies as possible until it is time to switch to label  $(k + 1)$ . Each of these forward copies will also have label  $k$ . If the available bandwidth on its outgoing links does not allow node  $i$  to transmit  $p$  copies, node  $i$  forwards fewer than  $p$ . On the other hand, if the available bandwidth on its outgoing links allows node  $i$  to transmit more than  $p$  copies, node  $i$  forwards more than  $p$  copies, even though some of them are redundant. If node  $i$  has  $h$  high priority packets among packets with label  $k$  (destined towards node A), it forwards at most  $h$  high priority packets with label  $k$  (destined towards node A). If node  $i$  gets an opportunity to forward more than  $h$  packets, the remaining packets will be tagged as low priority.

In SRNC, mesh nodes such as node  $i$  must also perform buffer management. If a low priority packet arrives on an incoming link of node  $i$  whose buffer is full, the packet is discarded. However, if a high priority packet arrives on an incoming link of node  $i$  whose buffer is full, node  $i$  drops the

most recently arrived low priority packet from its buffer to make space for incoming high priority packet.

### 3.4.3 SRNC at access node

Figure 3.8 describes the steps taken by mesh access node A. Node A also implements a buffer management strategy similar to intermediate node  $i$ . Similarly, node A also uses a self-clocking algorithm to determine which packets to decode. If decoding is successful, the unencoded packets are forwarded to wireless hosts. Otherwise, undecoded packets are discarded.

*Example:* Consider a typical access node A which is receiving network coded packets destined for wireless hosts connected to it. Similar to Figure 3.7, node A buffers all packets with label  $k$  until it has received at least one packet with label  $(k + 1)$  on each of its incoming links. When it has received at least one packet with label  $(k + 1)$  on each of its incoming links, node A checks whether sufficient number of linearly independent packets with label  $k$  are present in its buffer in order to successfully recover the original packets. If original packets are recoverable, node A performs necessary decoding, reconstructs the original packets, and forwards them to the corresponding wireless hosts. If original packets are unrecoverable, all undecoded packets with label  $k$  are discarded, which in turn, will result in loss of corresponding original packets on the wireless hosts.

## 3.5 Evaluation

### 3.5.1 Overview

In this section, we present results of our experimental evaluation. The goals of this evaluation are two-fold. The first goal is to compare the performance of the proposed SRNC scheme to that of other schemes in literature under different scenarios. The second goal is to explore the effectiveness and fairness of SRNC. To meet the first goal, we compare SRNC's performance to the following three schemes from literature. Note that packets are sent through multipath routing in all schemes. These three schemes also demonstrate the necessity of integrating the four components of SRNC,

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**Algorithm Access**


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**When a packet in  $F_A$  arrives on incoming link  $l$ :**

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1. If buffer is full,
  2. If incoming packet is marked as “Low priority”,
  2. Discard the incoming packet.
  3. Else,
  4. If all packets in buffer are marked as “High priority”,
  5. Discard incoming packet.
  6. Else,
  7. Find the most recent “Low priority” packet in buffer and discard.
  8. Enqueue incoming packet.
  9. Let  $L_l$  be the largest label of all packets in  $F_A$  received on incoming link  $l$ .
  10. Let  $k = \min\{L_l : \text{incoming } l\} - 1$ .
  11. When  $k$  is updated :
  12. Discard all packets in  $F_A$  in buffer with label smaller than  $k$ .
  13. Apply decoding algorithm on packets in  $F_A$  with label  $k$ .
  14. If the decoding algorithm succeeds,
  15. Transmit the recovered unencoded packets on the outgoing links as per routing algorithm.
  16. Else,
  17. Discard undecoded  $F_A$  packets with label  $k$ .
- 

Figure 3.8 Algorithm executed by the access node in SRNC.

diagraph diversity, network coding, exploiting available bandwidth, and buffer management in order to route packets in the mesh efficiently.

- **Multipath Routing (MR) [34]:** Packets from the gateway are routed to the respective access node along the multiple edges of a DAG. Since multipath routing can exploit the bandwidth available on more than one route, it is not likely to be as susceptible to performance degradation as traditional single path routing when bandwidth reductions occur due to relinquishment of primary user channels. However, multipath routing is more prone to packet re-ordering, especially when there are fluctuating and unequal available bandwidths along different routes. These packet re-orderings often result in Fast Retransmits from the TCP sender, which in turn reduces the TCP throughput.
- **Packet Re-ordering (PRO) [109]:** Packet re-ordering occurs when packets experience different link delay through different routing path. Although multipath routing balances traffic loads in the network, packet re-ordering still decreases TCP throughput. To solve this problems, packets are re-ordered before sent to transport layer of a receiver. When transport layer receives consecutive packets, it increases congestion window, and then TCP throughput is increased. However, packet losses causing packet retransmission still reduce TCP throughput.
- **Network Coding on TCP (JK2009) [49]:** Sundararajan et. al propose network coding based mechanism aimed to improve TCP throughput by sending appropriate number of redundant packets to the network. Specifically, the number of redundant packets are sent according to the measured packet loss probability in the network. Therefore, lost packets could be recovered with higher probability by redundant packets, and TCP throughput could be improved.

The performance evaluations of MR, PRO, and JK2009 are done using simulations in ns-2 [3]. Further, CTCP [108] is applied as TCP congestion control protocol. In this paper, we only include results for one mesh topology shown in Figure 3.9. We have conducted simulations for other topologies and the qualitative results and conclusions are similar.

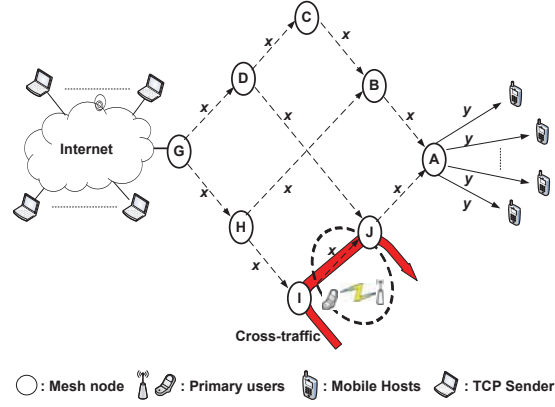


Figure 3.9 Evaluation mesh topology.

### 3.5.2 Experimental Setup

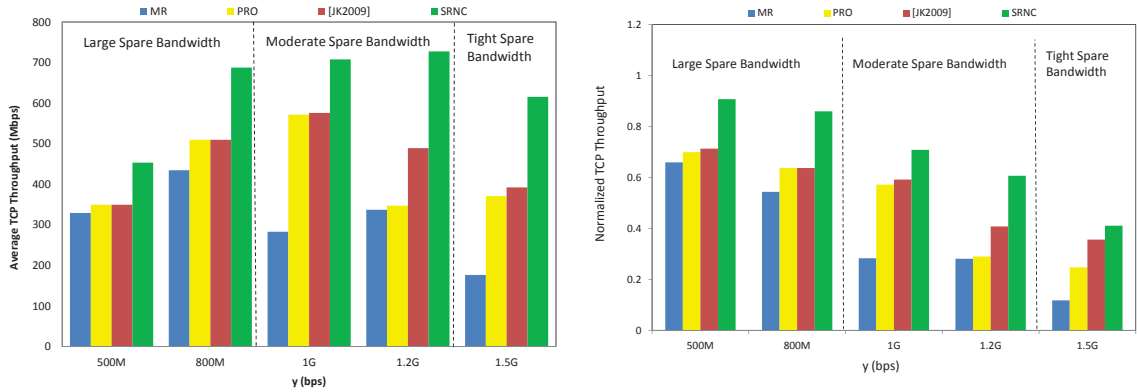
In Figure 3.9, ten TCP flows are sent from their TCP senders, through Internet to their destinations (i.e., wireless users) in the mesh network. In the mesh network, the link bandwidth between two mesh nodes is  $x$ . Due to the spectrum leasing and relinquishing from each mesh node's neighboring primary users, the link bandwidth fluctuates between  $x$  and  $2x$ . Further, the link bandwidth between the access node A and each wireless user is  $y$ . Denote  $\bar{x}$  as the average bandwidth on each link, the maxflow rate in the mesh network is  $\min\{2\bar{x}, 10y\}$ . In addition, cross-traffic shares the link bandwidth between mesh node  $I$  and  $J$  when it is active.

More specifically,  $x$  is set to be 5 Gbps, link delay from Internet to the gateway is set to be 6 ms, and RTT between a TCP sender-receiver pair is 12 ms. Additionally, on average, the borrowed channels from primary users fluctuate spatially every 1 sec and fluctuate temporally every 5 sec. The long term measured maxflow rate from G to A is 14 Gbps while the bandwidth varies within 5-10 Gbps on each link. Moreover, 3 Gbps cross-traffic is sent through the mesh when the cross-traffic is active. The cross-traffic is modeled as two state ON/OFF Markov chain with Pareto distribution.

### 3.5.3 Evaluation Results

#### 3.5.3.1 Explore the effect of spare bandwidth

The goal of this experiment is to explore end-to-end network performance in response to different amount of spare bandwidth in the mesh. Three cases, large spare bandwidth, moderate spare bandwidth, and tight spare bandwidth are considered. To evaluate the impact of different spare bandwidth situations on end-to-end TCP throughput, different TCP traffic loads are sent to the mesh network in the presence of cross-traffic. Specifically, let  $y = 0.5$  and  $0.8$  Gbps in large spare bandwidth case (i.e.,  $2\bar{x} \gg 10y$ ), let  $y = 1.0$  and  $1.2$  Gbps in moderate spare bandwidth case (i.e.,  $2\bar{x} > 10y$ ), and let  $y = 1.5$  Gbps in tight spare bandwidth case (i.e.,  $2\bar{x} \sim 10y$ ).



(a) Average TCP throughput over different link bandwidth between wireless users and egress node (bps). (b) Normalized TCP throughput over different link bandwidth between wireless users and egress node (bps).

Figure 3.10 TCP throughput over different link bandwidth between wireless users and egress node (bps).

- Performance Evaluation

Figure 3.10(a) and 3.10(b) show the results for the four schemes in five different scenarios. In each figure, x-axis shows the link bandwidth between A and each wireless user. Further, y-axis shows the average TCP throughput and the normalized TCP throughput in Figure 3.10(a)

and 3.10(b), respectively under different link bandwidth between A and each wireless user. Obviously, SRNC outperforms in all cases by adaptively exploiting spare bandwidth in the network. It is because SRNC adaptively utilize available bandwidth to send redundant packets in the mesh, packet losses can be recovered with high probability. Further, in SRNC, each mesh node adjusts number of packets forwarded to its next hop base on the availability of link bandwidth aimed to control the redundancy introduced to the network. JK2008 also sends redundant packets, but the TCP sender requires feedback information from the network to control number of redundancy. Due to the delays involved in this feedback, the effectiveness of these adaptations is reduced. PRO and MR do not send redundant packets even if sufficient bandwidth is available in some links. However, since PRO resolves packet re-ordering caused by multipath routing, it performs better than MR.

*When mesh has large spare bandwidth,  $2\bar{x} \gg 10y$ ,* SRNC reaches approximately 0.9 normalized TCP throughput while the rest schemes only reach 0.7. SRNC utilizes spare bandwidth to recover lost packets resulting from cross-traffic. Although JK2009 also sends extra packets to recover packet losses during transmission, the improvement in end-to-end throughput is limited. In JK2009, redundant packets are sent from TCP source nodes. Since the link bandwidth from TCP sources nodes to the mesh is much smaller than the link bandwidth in the mesh, the best TCP throughput JK2009 can reach is lower than SRNC.

*When mesh has moderate spare bandwidth,  $2\bar{x} > 10y$ ,* SRNC and JK2009 obtain much higher TCP throughput than PRO and MR do because redundant packets sent by SRNC and JK2009 recover some lost packets. However, due to the fluctuation of link bandwidth as well as high traffic loads in the network, the throughput enhancements of SRNC and JK2009 are limited. Specifically, moderate spare bandwidth only allows certain number of extra packets sent on each outgoing link, and then packet losses are not completely recovered. As a consequence, SRNC obtains 0.7 normalized TCP throughput by effectively utilizing spare bandwidth. JK2009 also adaptively sends redundant packets to recover packet losses. However, the number of redundant packets are adjusted by feedback information. Since network environment changes dynamically, relying on feedback

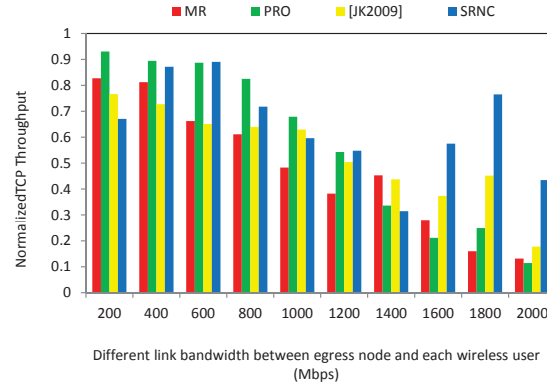


Figure 3.11 Impact of diversity among the flows on the normalized TCP throughput.

information still limits throughput enhancement, and JK2009 obtains 0.5 normalized TCP throughput.

When mesh has tight spare bandwidth,  $2\bar{x} \sim 10y$ , the mesh network becomes bottleneck for packet transmission, and the normalized TCP throughput of each scheme is below 0.5. In SRNC, each mesh node still forwards some extra packets on its outgoing links when spare bandwidth is available, therefore SRNC reaches higher end-to-end throughput than other schemes. As for JK2009, the sending of redundant packets also improves TCP throughput. However, the number of redundant packets in JK2009 cannot be controlled as well as in SRNC. The normalized TCP throughput of JK2009 is about 0.4. PRO and MR do not have any adaption scheme in response to the change of network condition, and they even do not obtain 0.3 normalized TCP throughput.

### 3.5.3.2 Explore the impact of diversity among all TCP flows

The goal of this experiment is to evaluate the TCP throughput among different TCP flow rates. Specifically, the link bandwidth between A and each wireless user varies from 0.2 Gbps to 2.0 Gbps, and thus, each TCP flow reaches different levels of TCP throughput. Further, rest network setup is the same as that in Section 3.5.2.

- Performance Evaluation

Figure 3.11 illustrates the normalized TCP throughput of each TCP flow. x-axis is the link bandwidth between A and the destination of a specific TCP flow, and y-axis is the normalized TCP

throughput by the measured TCP throughput over  $x$ . For the results shown in Figure 3.11, the normalized TCP throughput of each flow, in SRNC, is almost above 0.5 while other schemes have large variations on the normalized TCP throughput among all flows. Specifically, when the link bandwidth of a flow is greater than 1600 Mbps, the normalized TCP throughput in MR, PRO and JK2009 are much lower than those in the rest flows. When packet losses result in timeout, TCP enters slow start and the end-to-end throughput drops significantly. To reach TCP throughput back to that before drops takes time, especially when the flow initially obtains high throughput (e.g. 1600 Mbps). Under this condition, the overall throughput of these flows are lower. However, SRNC does not suffer from this drawback because it adaptively sends redundant packets to recover most of the losses. Furthermore, on average, the normalized network throughput of MR, PRO, JK2009 and SRNC is 0.36, 0.41, 0.46, 0.59, respectively. SRNC and JK2009 send additional packets to recover packet loss in advance, and thus they have better throughput than PRO and MR have. Also, SRNC effectively utilizes available bandwidth in the network so that the network deliver the highest TCP throughput to wireless users.

### 3.5.3.3 Explore fairness among different network encoded TCP flow sets

In this experiment, we explore the sharing of spare bandwidth among multiple independent groups of TCP flows in SRNC. We assume that among ten TCP flows sent from the Internet, five of them send TCP packets through G to the corresponding destinations connected to A. The other five TCP flows send their packets to their destinations associated with another access node in the mesh network. TCP flows destined towards access node A are not linearly combined with TCP flows destined towards the other access node. These two groups of encoded flows share the link bandwidths in the mesh network.

- Performance Evaluation

Figure 3.12 shows the corresponding results. The y-axis is the average end-to-end throughput of each TCP flow set as a function of time. For these results, the spatial correlation in bandwidth fluctuations occur dynamically over time while the temporally correlated fluctuations occur in the

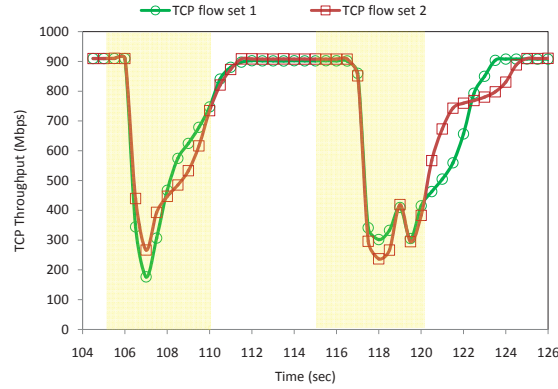


Figure 3.12 Bandwidth fair share among different TCP flow sets.

time instance in the shaded region. Clearly, both sets of flows have approximately the same TCP throughput, and these two set of flows share the network bandwidth equally between them. This further validates the claim that SRNC allows multiple competing TCP flows to co-exist in the network without adversely affecting their performances.

### 3.5.3.4 Explore the impact of wireless packet loss

The goal of this experiment is to investigate the effect of unrecoverable packet errors resulting from wireless packet loss in the mesh. Three schemes, PRO, JK2009, and SRNC are evaluated. Note that in all previous experiments, we consider the ideal case, in which the medium access protocol perfectly recovers all packet errors which occur in an wireless link.

Since MR and PRO do not send any redundant packets to recover lost packets during transmission, they reach similar throughput. Further, MR is unable to handle packet re-ordering, and it achieves lower throughput than that of PRO. As a result, in the experiments we only show the results of PRO, JK2009, and SRNC. In this experiment, the link bandwidth in the mesh as well as the link bandwidth between the egress node A and each wireless user are 1 Gbps, and the rest of the setup in the mesh is as described in Section 3.5.2. Further, denote packet loss probability on each link in the mesh as  $p$ , and  $p$  is independent and identically distributed (i.i.d). Then, the average packet loss rate in the mesh is  $p_{mesh} = 1 - (1 - p)^4 \sim 4p$ . We evaluate the performance when  $p$  from 0 to 2.5% (i.e.,  $p_{mesh}$  from 0 to 10%).

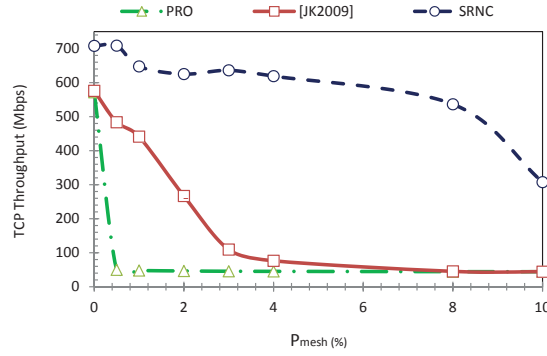


Figure 3.13 TCP throughput under different wireless packet loss rate in the network.

- Performance Evaluation

Figure 3.13 shows the TCP throughput as a function of packet loss probability. PRO has low end-to-end TCP throughput even under small packet loss probability. PRO does not send any redundant packets to recover from the packet losses, and consequently, the TCP throughput drops significantly.

SRNC and JK2009 benefit from sending extra packets especially when the loss probability is low (i.e.,  $p_{mesh} \leq 1\%$ ). In addition, each mesh node, in SRNC, appropriately forwards redundant packets on its outgoing links, and as a result, most lost packets are recovered successfully at the egress node A. Hence, the throughput of SRNC is not as sensitive to packet loss probability as compared with PRO and JK2009. When  $1\% \leq p_{mesh} \leq 8\%$  (i.e.,  $0.25\% \leq p \leq 2\%$ ), the TCP throughput of JK2009 drops more significant than that of SRNC. In JK2009, the amount of redundancy is not sufficient to recover all lost packets since the redundant packets are only created at TCP sources. However, in SRNC, redundant packets are introduced and forwarded on each outgoing when bandwidth is available. Therefore, SRNC obtains about 600-700 Mbps throughput which is much higher than that of JK2009.

### 3.6 Conclusions

Cognitive radio based wireless mesh networks are designed in such a way that each node can temporarily lease unused channels from nearby licensed users in order to increase the aggregate

bandwidth of the mesh. If the licensed users need to access to the leased channels, the mesh nodes must immediately relinquish them. Thus, the aggregate bandwidth in the mesh can vary significantly over the lifetime of a typical traffic flow. Due to certain inherent protocol characteristics, these fluctuations in bandwidth significantly lower end-to-end throughput of TCP flows especially for gigabit TCP flows. In this paper, we propose a novel approach called SRNC to address this problem of low end-to-end throughput for downlink TCP flows due to the effects of cognitive radio. The proposed scheme incorporates several ideas including inter-flow network coding, multiple path routing, and distributed redundancy management.

The proposed scheme is implemented in the network simulator ns-2 and its performance under different scenarios is compared against three conventional schemes from literature. More specifically, SRNC is executed in a distributed fashion at each mesh node without any feedback information for decision making. Simulation results show that the improvement in the end-to-end throughput of TCP flows is significant as compared to that of the three schemes in literature. The results also show that the performance of the proposed scheme is robust to the variations in bandwidth caused by leasing and relinquishment of channels in CR-WMNs.

## Chapter 4

### Coverage Management in Wireless Mesh Networks

Packets are directly delivered to users at the last hop transmission, and the performance may decrease when the resource of last hop is not allocated properly. In traditional mesh networks, the mesh nodes coordinates with each other to provide ubiquitous wireless access to all wireless users. However, in such dynamic changed wireless environments, once there is a new arrival of wireless users, the steady state of the network would break, which results in the decrease of the network throughput. Specifically, network resource, such as bandwidth is shared by all users associated with the same mesh node in the mesh networks.

To overcome the aforementioned problems, in this Chapter, we introduce our proposed distributed User Association and Power Adaptation scheme to maximize the throughput of entire network. First, we define different utility functions for wireless users, mesh nodes, and the network, which can reflect users' satisfactory to their throughput. Then, each wireless user selects candidates from their neighboring mesh nodes based on the estimated utility. Meanwhile, the mesh nodes adaptively adjust power to maximize their utility or to minimize the interference with their neighbors according to the change of the network. To validate the performance of our proposed scheme, we consider different network conditions, and simulation results show that the average utility of the network using our scheme can greatly increase throughput than the existing work.

#### 4.1 System Model

Before the discussion of our system model, we first define some notations which are used throughout this Chapter. We use  $MN_i$  to represent the mesh node  $i$  and  $WU_j$  for wireless user  $j$ .

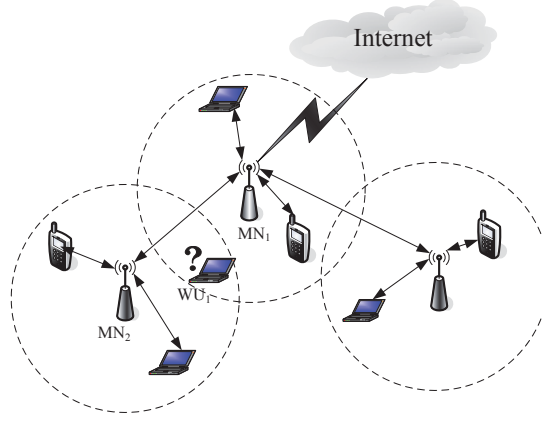


Figure 4.1 Illustration of interference between WU and MNs

We denote the packet transmission power and the link layer rate of  $MN_i$  as  $p_i$  and  $\Phi_i$ , respectively. If  $WU_j$  is associated with  $MN_i$ , we denote the physical layer rate of  $WU_j$  associated with  $MN_i$  as  $\phi_{ij}$ , and the Signal to Interference plus Noise Ratio (SINR) at  $WU_j$  as  $\gamma_{ij}$ .

Consider a geographic area with  $N$  MNs and  $M$  WUs, which is illustrated in Figure 4.1. To simplify the problem, we focus on the MNs are deployed by the same service provider through certain planning for deployment. Further, we assume that the traffic of each WU is with the same priority, and the WU purchase the same amount of the network resources to maintain wireless connectivity. Then, the bandwidth is shared evenly among the flows access to the same MN. After association, the WU primarily receives traffic from the network, i.e., traffic is mostly downlink. The transmission from a MN may cause interference at a WU associated with another MN. For example, as shown in Figure 4.1, we assume that  $WU_1$  is associated with  $MN_1$ . Since  $MN_2$  is very close to  $WU_1$ , the transmission from  $MN_2$  would cause high interference at  $WU_1$ . Even if the MNs are operating on different channels, the signals from multiple MNs at a WU will not completely orthogonal. To combat this interference and noise, MN adapts the physical layer data rate. In addition, the multiple WUs associated to an MN must share the transmissions from the MN. Thus, the link layer data rate delivered to a WU depends not only on its physical layer rate but also the number of WUs associated with that MN and their respective physical layer rates. The

goal is to devise a power control strategy for the MN and an association strategy for the WUs so that total utility of WUs due to their link layer data rate is as large as possible.

More specifically, we let  $P_1 < P_2 < \dots < P_L$  be  $L$  permitted transmission powers at each MN, which indicates that  $p_i \in \{P_1, P_2, \dots, P_L\}$  for  $i = 1, 2, \dots, N$ . If  $MN_i$  associates with  $WU_j$ , we denote the interference between them as  $r_{ij}$ , and therefore can express the SINR at  $WU_j$  as

$$\gamma_{ij} = \frac{p_i/d_{ij}^2}{\sigma^2 + r_{ij}}$$

where  $d_{ij}$  is the distance between  $MN_i$  and  $WU_j$ , and  $\sigma^2$  is the power of the noises.

Shannon Theory proves that for the  $WU_j$  associated with  $MN_i$ , its physical layer rate,  $\phi_{ij}$ , is in proportion to  $\gamma_{ij}$  and thus to  $p_i$ . Let us define  $I_{ij}$  to represent the association between  $MN_i$  and  $WU_j$ :

$$I_{ij} = \begin{cases} 1, & \text{if } WU_j \text{ is associated with } MN_i \\ 0, & \text{otherwise} \end{cases}$$

We can thus conclude that  $\phi_{ij}$  is a function of both  $p_i$  and  $I_{ij}$ . For brevity, we use  $\phi_{ij}(p_i, I_{ij})$  to represent their relationship.

Assume that  $\gamma_{ij}$  imposes a certain physical layer rate  $\phi_{ij}$  at WU  $j$  when connected to  $MN_i$ . Assume that an AP users FIFO scheduling to transmit packets to its WUs. Further assume that the WUs desire as much traffic as can be delivered. If all packets are of length  $B$  bits, then resulting link layer data rate for  $WU_j$  associated with  $MN_i$  is

$$\Phi_{ij} = \frac{B}{\sum_{j \in S_i} \frac{B}{\phi_{ij}}} = \left( \sum_{j \in S_i} \frac{1}{\phi_{ij}} \right)^{-1}, \quad (4.1)$$

where  $S_i$  is the set of WUs associated with  $MN_i$ . That is, the link layer rate of a WU connected to a MN is the harmonic mean of the physical layer rates of all the WUs connected to that MN. Since the harmonic mean is smaller than the smallest value, the link layer rate delivered by a MN to a WU is smaller than the smallest physical layer rate. In particular, even the WU that is connected to the MN with the highest physical layer rate will receive data rate comparable to that of the WU with the slowest physical layer rate. This is an artifact of IEEE 802.11 medium access protocol

where access is resolved at the end of each packet transmission. This characteristic of IEEE 802.11 has a considerable impact on the transmission power selection and WU-MN association. Since the link layer rate delivered to all WUs connected to an MN are all the same, we also use the notation  $\Phi_i$  to denote the link layer data rate delivered by  $MN_i$  to all its WUs.

The problem addressed in this paper can be formulated as

$$\begin{aligned}
& \max_{I_{ij}, p_i, n_i} \quad \sum_{i=1}^N n_i U(\Phi_i) \\
& s.t. \quad \Phi_i = \left( \sum_{j=1}^{n_i} \frac{1}{\phi_{ij}(p_i, I_{ij})} \right)^{-1} \\
& \quad \sum_{i=1}^N I_{ij} = 1, \quad \forall j = 1, 2, \dots, M \\
& \quad \sum_{j=1}^M I_{ij} = n_i, \quad \forall i = 1, 2, \dots, N \\
& \quad p_i \in \{P_1, P_2, \dots, P_L\} \\
& \quad I_{ij} \in \{0, 1\}
\end{aligned}$$

where  $U(\Phi_i)$  is the utility of WUs associated with  $MN_i$ .

## 4.2 Joint User Association and Power Adaptation Scheme

To maximize the utility of the entire network, we propose a joint association and power adaptation scheme. Since we define the utility of each MN as a function of its association and the transmission power, we can consider association and power adaption separately, and then *dynamically adjust the status of all WUs and MNs in the network*. However, we cannot employ any existing algorithms to solve the association and power adaption problems, such as [74, 75, 76, 65, 66]. The reason is that none of the existing algorithms described above consider association and power control together, since [74, 75, 76] does not consider downlink transmission, and [65, 66] requires information other than throughput.

Figure 4.2 illustrates the flow of our proposed scheme. Once network condition changes, for example, a WU alternates its associated MN or an MN selects another transmission power level,

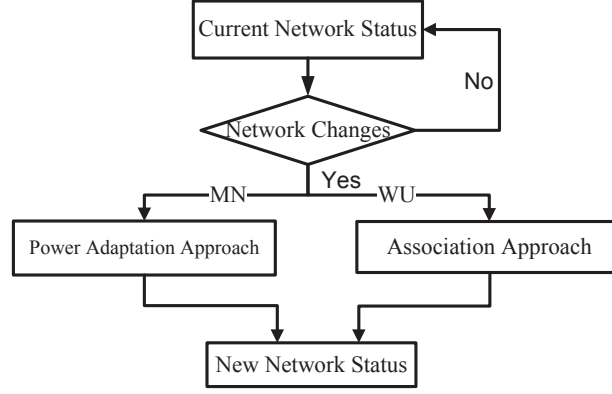


Figure 4.2 The flow of our proposed joint association and power adaptation scheme

the original utilities of the remaining WUs and MNs would change correspondingly. Therefore, we need to trigger our association and power adaption scheme again. Specifically, each WU executes its association approach to maximize its utility. Meanwhile, all MNs adapt their transmission power to achieve their maximum utility. Note that we can separately consider association and power adaption due to our utility function definitions.

#### 4.2.1 Association Approach

In this Subsection, we introduce our proposed association approach, which is enumerated in Algorithm 1. Specifically, for each  $WU_j$ ,  $j = 1, 2, \dots, M$ , we consider two different cases, which are Initialization and Reassociation.

The Initialization denotes the case when  $WU_j$  enters the network. In this case,  $WU_j$  selects the  $MN_i$  with the highest SINR for association.

After  $STA_j$  enters the network, it needs to dynamically update its association. We denote this case as Reassociation. In this case, let us first define  $\mathcal{A}_j$  as a set of MNs satisfying  $\gamma_{kj} > \gamma^*$ , where  $k$  is the index of MN and  $\gamma^*$  is the pre-specified SINR threshold. If the cardinality of  $\mathcal{A}_j$ ,  $|\mathcal{A}_j|$ , is zero,  $WU_j$  cannot associate with any MN. Otherwise, for each  $MN_k \in \mathcal{A}_j$ ,  $WU_j$  first estimates the new link and physical layer rate if it moves to associate with  $MN_k$ . This estimation is based on the current  $n_k$  and  $\Phi_k$ . We denote the estimated link layer rate and the new number of connections

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**Algorithm 1: Association Approach for  $WU_j$** 


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- Initialization
    1. Select the  $MN_i$  with the highest  $\gamma_{i,j}$  for association;
  - Reassociation (Current Status:  $WU_j$  is associated with  $MN_i$ )
    1.  $\mathcal{A}_j \triangleq \{MN_k | \gamma_{k,j} > \gamma^*, \forall k = 1, 2, \dots, N\}$ ;
    2. If  $|\mathcal{A}_j| = 0$ , disconnect;
    3. Else
    4.   For each  $MN_k \in \mathcal{A}_j$  :
      5.       If  $k \neq i$ , then  $\frac{1}{\Phi'_k} = \frac{1}{\Phi_k} + \frac{1}{\phi_{k,j}}, n'_k = n_k + 1$ ;
      6.       If  $k = i$ , then  $\Phi'_k = \Phi_i, n'_k = n_k$ ;
    7.   End for
    8.   Associate with  $\arg \max_k \{n'_k \Phi'_k - n_k \Phi_k | MN_k \in \mathcal{A}_j\}$ ;
    9. End if
-

of  $MN_k$  after associating  $WU_j$  with  $AP_k$ , as  $\Phi'_k$  and  $n'_k$ , respectively. Finally,  $WU_j$  re-associates with the  $MN_k$  which has the largest improvement of  $n'_k \Phi'_k > n_k \Phi_k$  in  $\mathcal{A}_j$ .

It is obvious that our proposed association approach is greedy. With the proposed approach, each WU associates with the MN which is expected to maximize utility function. Further, from the perspective of other WUs, they execute Reassociation in order to increase the utility again if possible.

## 4.2.2 Power Adaptation Approach

In this Subsection, we introduce our proposed power adaption approach, which is enumerated in Algorithm 2. Specifically, for each  $MN_i$ ,  $i = 1, 2, \dots, N$ , we also consider two cases, which are Initialization and Adaption.

The Initialization denotes the case when  $MN_i$  enters the network. In this case,  $MN_i$  randomly selects a transmission power  $p_i$  from the  $L$  permitted power levels.

For any  $MN_i$ , once it enters the network, it dynamically adapts its transmission power  $p_i$ . We denote this case as Adaption. Its goal is to maximize the utility function by adapting its transmission power. In this case,  $MN_i$  records the average utility between its two consecutive adaption and the utility at last adaption, which we denote as  $\bar{\Psi}(t)$  and  $\Psi(t - 1)$ , respectively. We also define a parameter  $\theta$  to illustrate the decision of the transmission power adaption. If the transmission power of  $MN_i$  increases at last adaption, we set  $\theta$  to be 1; otherwise, we set it to be -1. Based on  $\bar{\Psi}(t)$ ,  $\Psi(t - 1)$ , and  $\theta$ ,  $MN_i$  determines its new transmission power. The detail is illustrated in Algorithm 2.

As shown in Algorithm 2, each MN dynamically repeats the Adaption Case. This Adaption considers  $\bar{\Psi}(t)$ ,  $\Psi(t - 1)$  and  $\theta$ . When  $\bar{\Psi}(t)$  increases after last Adaption,  $MN_i$  follows last decision because this decision may increase the utility again. On the contrary, when  $\bar{\Psi}(t)$  decreases,  $MN_i$  chooses opposite decision from last Adaption conditionally aimed to increase the utility this time. Specifically, this reaction is similar to simulated annealing.

Similar as the proposed association approach (See Algorithm 1), our proposed power adaption approach is also greedy. With this approach, each AP determines its new transmission power level

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**Algorithm 2: Power Selection Approach**


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- Initialization :

1. Randomly select  $p_i$ ;

- Adaption :

1. If  $\bar{\Psi}(t) > \Psi(t - 1)$ ;
  2.     If  $\theta = 1$ , then increase  $p_i$ ;
  3.     Else decrease  $p_i$ ;
  4. Else
  5.     If  $\theta = 1$ , then increase  $p_i$  with probability;
  6.     Else decrease  $p_i$  with probability;
  7.      $\theta \leftarrow -\theta$ ;
  8. End if
-

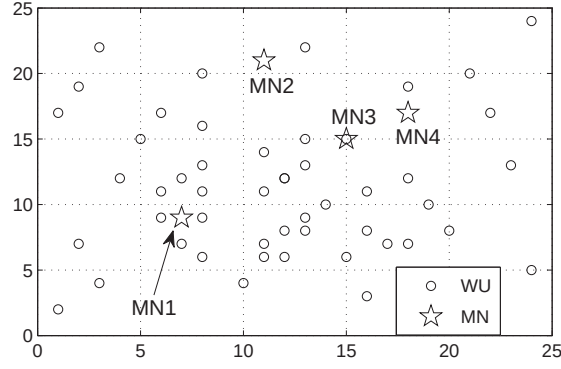


Figure 4.3 Network topology used in simulation

so that its utility can be maximized. After an AP adjusts its transmission power, the interference to its neighboring MNs would change as well. As a result, other MNs are triggered to adapt their transmission powers.

To sum up, we combine association and power adaption to maximize the utility of the entire network. Specifically, our proposed joint association and power adaption scheme is a distribute mechanism.

### 4.3 Evaluation

In this section, firstly the performances of association and power adaption approaches are evaluated individually, then the simulation of their jointly working is conducted. In these simulations, a multi-rate, multi-channel IEEE 802.11a network with 4 MNs and 50 WUs is set up with the topology as shown in Figure 4.3. Other simulation parameters are as follows.

- Each MN may choose one of the following ten power levels: 1 mW, 10 mW, 20 mW, 30 mW, ..., 100 mW. When a MN is powered on, it starts with a transmission power of 50 mW.
- It is assumed that approximately 40% suppression of the interference from a MN to which a WU is not associated. This can be accomplished using signal processing techniques.
- A WU cannot connect to a MN with SINR lower than 0 dB.

Table 4.1 The relationship between SINR and physical layer data rate used in simulation

| SINR (dB) | Rate (Mbps) |
|-----------|-------------|
| 0         | 1           |
| 3         | 6           |
| 7         | 11          |
| 16        | 18          |
| 20        | 23          |

- The relationship between SINR and physical layer data rate used in the simulation is shown in Table 4.1, which is selected based on the simulation results in ns-3 [110]. Moreover, WUs have auto-rate adaptation enabled using ARFF scheme in the ns-3 simulations.

Figure 4.4 illustrates the functioning of the proposed association approach (see Algorithm 1). In our simulation, we fix the power levels of the four MNs at 60 mW, 50 mW, 40 mW, and 30 mW, respectively. The WUs are allowed to execute the proposed association approach. The  $x$ -axis shows all the WUs and the  $y$ -axis shows the AP to which the WU is associated. Initially, all WUs are associated with the MNs providing the largest the largest SINR to them. These associations are shown with a “□”. After running the proposed approach for a sufficiently long period, the associations converge to those shown as “○”. Note that, some of the WUs have changed their associations to increase their utility.

Figures 4.5 and 4.6 illustrate the functioning of the power control algorithm. For each MN, the left bar shows its initial transmit power. The right bar shows its transmit power after the power control algorithm executed for sufficiently long time. Note that each WU associates with its largest SINR MN and the transmit powers of all the MNs change as a result of the proposed algorithm. Above each bar, there are two numbers. One of them shows the number of WUs associated to that MN. The other shows the link layer data rate for the WUs associated to that MN. Note that, there are a total of 50 WUs in the network. Initially, five of the WUs are not associated with any AP because the SINR from all the MNs are below the threshold of 0 dB. After executing the power control algorithm, all the WUs are associated with a MN in these results. However, our algorithm cannot guarantee that all WUs will always be associated with an MN. Also observe that, as a result of the power adaption algorithm, the link layer data rate of most of the WUs have increased. Once

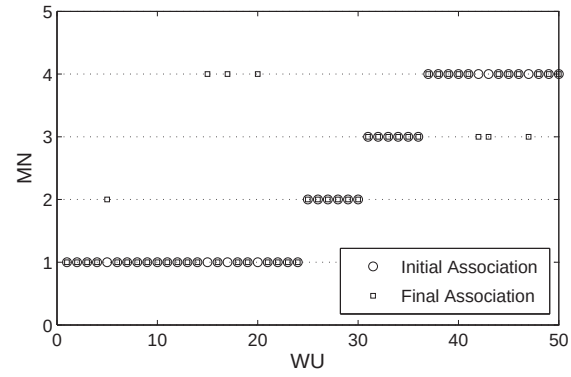


Figure 4.4 Association mapping with association approach

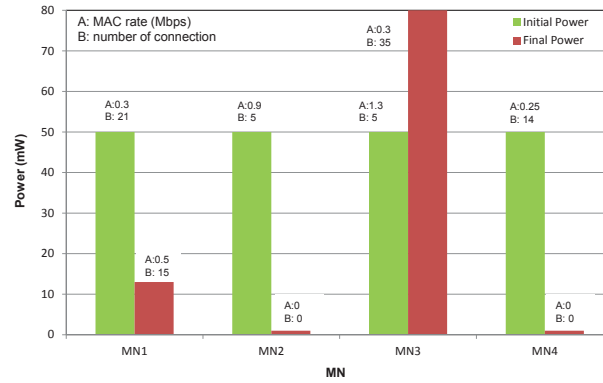


Figure 4.5 Transmission power with power adaptation approach

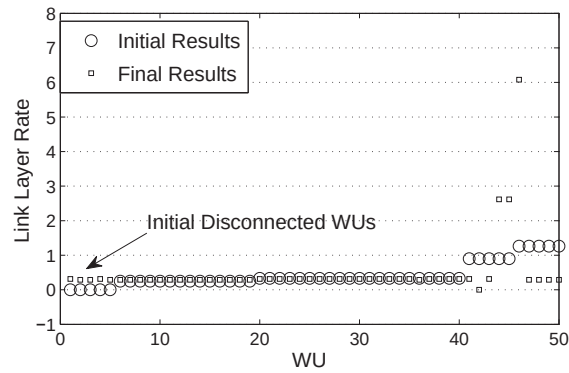


Figure 4.6 Link layer rate with power adaptation approach

again, our power adaption algorithm does not guarantee that the link layer data rate of each WU will always increase. Instead, it strives to increase to total utility of all WUs due to their link layer data rates. For convenience of comparing these link layer data rates, Figure 4.6 re-plots the initial and the final values for all the WUs.

Figure 4.7 shows the results for the joint association and power adaption approach. Initially, all MNs start with a transmit power of 50 mW and all WUs associate to the AP to which they have the highest SINR. In addition, in our algorithm, we also did an exhaustive search (a total  $11^4$  possibilities) on all the possible transmit power levels. The  $x$ -axis shows the time over which the algorithm executes. The  $y$ -axis shows the total utility in the proposed approach normalized by the maximum total utility from the exhaustive search. Note that, the initial normalized utility is around 88% of the maximum total utility. At the end, as a result of the transmit power and the changes in associations, the normalized utility increases to 99%. This shows that the proposed approach works well. The resulting transmission powers, the link layer data rates, and the number of WUs connected to the MNs are shown in Figure 4.8. The changes in the associations of the WUs are shown in Figure 4.9. Note that, all the WUs are associated with an AP at the end. Also, observe that, some WUs receive a lower link layer data rate than at the start. However, as shown in Figure 4.7, the total utility of all the WUs has increased as a result of the proposed approach.

Simulation results show that the network can achieve nearly the maximum throughput with a few computational complexities. In the future, we will extend our framework to incorporate with uplink transmission traffic.

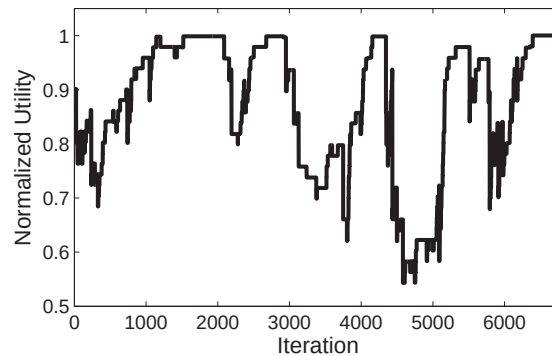


Figure 4.7 Normalized utility of our proposed joint association and power adaptation scheme

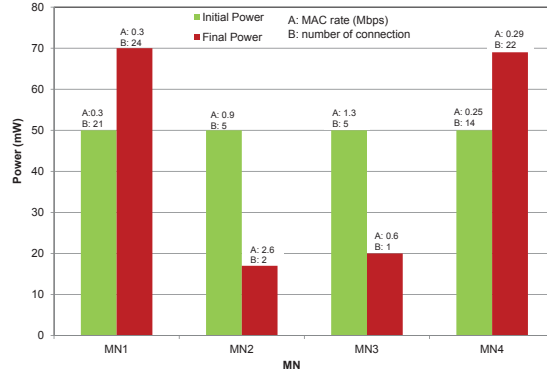


Figure 4.8 Power change of joint association and power adaptation scheme

## 4.4 Conclusions

We propose a distributed Join User Association and Power Adaptation Scheme to maximize the throughput of a wireless mesh network. Each wireless user's utility is defined as a function of the transmission power of its associated mesh node, which can reflect the users' satisfactory to their throughput. Since we incorporate both association and transmission power in our utility definition, we can consider association and power adaption separately. We first propose an associate approach, which allows each wireless user to select its associated AP based on the estimated link layer rate. We then introduce a power adaption scheme, which enables mesh nodes to adapt their transmission power with the consideration of the entire network throughput. Simulation results show that the network can achieve nearly the maximum throughput with a few computational complexities. In the future, we will extend our framework to incorporate more uplink transmission traffic.

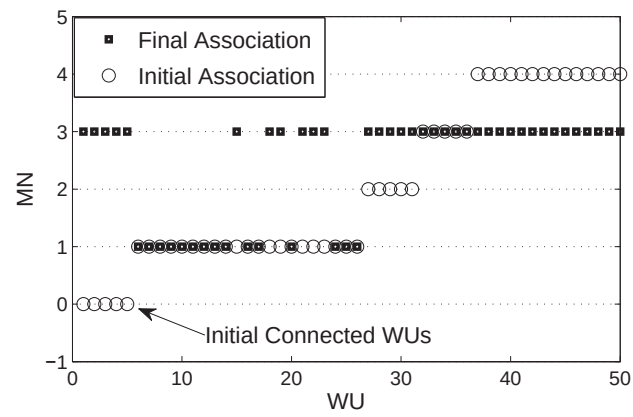


Figure 4.9 Association mapping of joint association and power adaptation scheme

## Chapter 5

### Competitive Resource Pricing in Cognitive Networks

In general, in a mesh network, each mesh node forwards several traffic flows to the corresponding destinations, and these flows have different QoS constraints base on their applications. For example, real-time streaming is sensitive to latency, but can tolerate little packet losses. FTP file transfer requires zero packet errors, but do not have packet delay criteria. To maintain the QoS performance, the mesh nodes have manage packet forwarding differently base on the QoS criteria of each flow instead of evenly sharing the network resources for all flows. Specifically, the mesh nodes prioritize traffic flows into several classes for resource allocation (i.e., scheduling, channel assignment, bandwidth allocation, etc..). Traditionally, resources are allocated by mesh nodes considering different type of traffic flows to improve QoS requirement. Such management is mostly controlled by the mesh nodes. To effectively maintain QoS, unlike traditional approaches, we consider pricing-based approach to manage resource allocation for packet transmission. Specifically, based on the characteristic in the mesh networks, each mesh node purchases free spectrum from primary users, and then sell the total bandwidth to the wireless users associate with it. The mesh nodes set different prices to sell their resources depending on their available resource and traffic loads. Furthermore, typically, multiple service providers deploy their mesh nodes within the same geographic range. Under this condition, the mesh nodes cannot monopoly the network resource market and arbitrary announce their selling prices. Instead, the price of neighboring mesh nodes of other service providers will effect the price setup. Base on the price and the QoS criteria, the wireless users adaptively purchase resources from mesh nodes for transmitting their packets. Under this condition, the QoS is managed in a distributed fashion, and the wireless users have more control on packet transmission to maximize the performance of their flows.

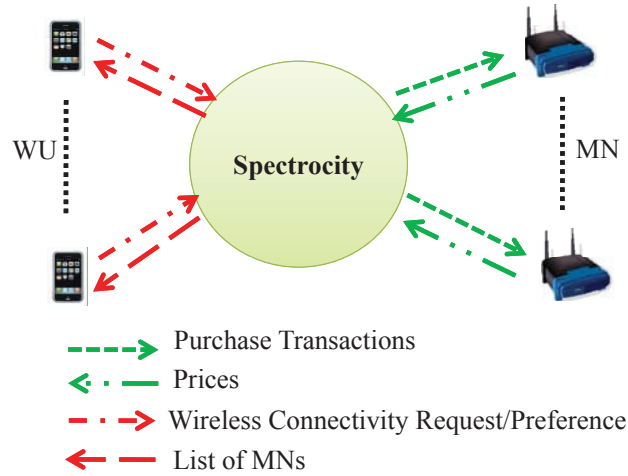


Figure 5.1 Envisioned market framework for channel access services.

In this Chapter, we propose and promote a dynamic pricing mechanism, PriceMyRate, to sell wireless channels to wireless users in the network.

## 5.1 System Model

Figure 5.1 shows the three major entities in the proposed framework, namely mesh nodes (MNs), wireless users (WUs), and *Spectrocity*. Each MN purchases spectrum from primary users and re-sells them to multiple WUs. The MNs compete with each other to provide the needed channels to the WUs. The *Spectrocity* serves as a broker between MNs and WUs. It allows WUs to compare the MNs on their offered price and to purchase the needed channels from a MN of choice.

Note the similarity between this framework and the more familiar “online hotel booking” framework. MNs are analogous to a hotel offering rooms at a fixed location. WUs are analogous to customers with intentions to travel to a specific place and plan to stay at that location for rest. *Spectrocity* is analogous to Expedia which helps customers shop for a hotel of choice. Expedia provides multiple hotel choices to a customer and it also serves as broker to book a room on the selected hotel(s). Similarly, *Spectrocity* offers multiple wireless connectivity options to the WUs based on the prices set by each MN. Once a WU has selected a MN, *Spectrocity* helps the

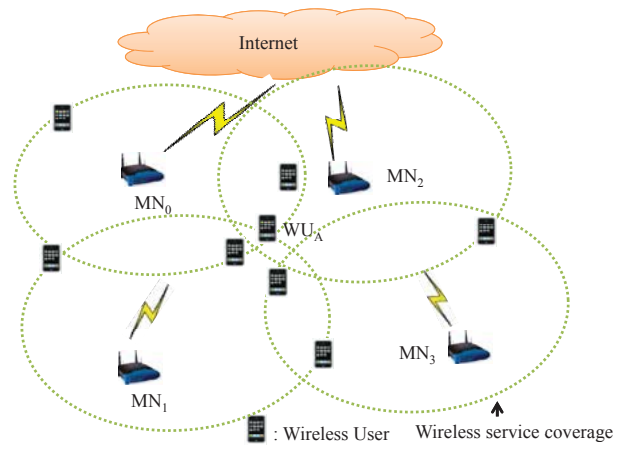


Figure 5.2 Example of a mesh network to illustrate a context for the proposed strategy.

WUs complete the purchase transaction and reserve the requisite channels from the MN of choice. A MN's price per unit channel for a particular time period is based on the available channels in its network, the prices being charged by competing MNs, demand for the channels, and the amount of time remaining to sell the channels. This is analogous to hotel booking where the price of a room varies with time, i.e., customers pay a different price for a room based on how far in advance the room is booked, the demand for a room relative to the capacity available, and the prices being charged by other hotels. In this Chapter, we propose a pricing strategy for the MNs that strives to increase the MN revenue and meets the demands of the WUs.

We further illustrate this problem using the following simple example. Figure 5.2 shows a network with four WSPs puts their own MNs on a small geographic area. Specifically, each WSP deploys its MNs depending on their deployment plan regardless the deployment of other WSPs. Typically, each WSP may leave certain space between their two closest MNs, but two MNs belonging to two different WSPs may be geographically very close to each other. *Description of the tology more detail for wireless coverage, etc..* For example, as shown in the figure, WSP 0, 1, 2 and 3 set one of their MNs at the location geographically around the  $WU_A$  to provides the wireless connectivity around the coverage range of the MNs individually. Suppose that each MNs has got certain extra portion of free spectrum, and divide its total bandwidth into several channels for sell.

For simplicity of presentation, assume that WUs only want unit channel for a unit time period. Straight forward generalizations are possible to deal with the cases where WUs want to purchase either integral number of channels and/or channels for an integral amount of time. Without loss of generality, assume that the time period of interest is  $[t_0, t_0 + 1]$ . A MN has purchased a certain number of channels for this time period at say time 0. WUs can purchase unit channel from the MN at any time  $0 < t < t_0$ . The channels that a MN does not sell by time  $t_0$  will not bring any revenue to the MN. although the MN has already incurred a cost to purchase that bandwidth from primary users. Therefore, a MN adjusts the price of unit channel over time with an objective of increasing its revenue by selling as much channels as possible given the competition it faces from other MNs. In this work, we propose a price adaptation strategy for the MNs to sell their owned free channels.

## 5.2 Pricing Algorithm

In this section, we describe the proposed pricing strategy for a MN. The proposed strategy is motivated by schemes in literature on dynamic pricing and revenue management of perishable products in a competitive environment. Although there are several significant differences between airline and MN pricing, our work began as modification of the scheme in [111].

Our approach, henceforth called PriceMyRate, assumes that there are  $N$  MNs, denoted by  $C_1, C_2, \dots, C_N$ , competing to provide connectivity between set of Internet locations, denoted by  $L$ . It uses a dynamic programming approach to solve an underlying optimization problem for revenue management. In formulating this optimization problem, PriceMyRate makes the following modeling assumptions.

- M1. The arrival of requests for WUs forms a Poisson process with rate  $\lambda$ . We assume that each MN has a good estimate of  $\lambda$ .
- M2. The set of possible prices selected by a MN is discrete and finite. Let  $\pi_i$  denote the set of possible prices of  $C_i$ .
- M3. Each WUs has preference for one of the MNs. A WU prefers  $C_i$  with probability  $\alpha_i$ , independent of other WUs.
- M4. Each WU has a certain maximum price it is willing to pay for a connection from a particular MN. A WU is usually willing to pay a higher price for a connection on its preferred MN. These maximum willing prices are not known to anyone but the WU. However, each MN knows the probability distribution function which characterizes the maximum willing prices of different WUs. We assume that the maximum willing prices of the WUs are independent of each other.
- M5. A WU purchases channels from a MN only if its offered price is less than or equal to the NU's maximum willing price for the connection from that MN. If the offered price from the preferred MN is less than or equal to the corresponding maximum willing price then the WU

purchases the channels from its preferred MN. Otherwise, the WU is equally likely to purchase the channels from any other MN whose offered price is lower than the corresponding maximum willing price.

Modeling assumptions M1 and M2 can be relaxed. Other inter-arrival processes can be handled, although we have not investigated them in detail. Similarly, one can easily handle a continuous set of possible prices. In fact, the theory does not require the set of prices to be discrete. The algorithms discussed in the paper, however, make use of this assumption to simplify the search for optimal solutions. The remaining three modeling assumptions, namely M3–M5, are consistent with customer purchasing behavior in many other situations. For instance, customers often have preferred vendor for an item of interest. Furthermore, the customer considers other vendors only if the preferred vendor is not able to satisfy his/her requirements, i.e., the price is greater than the maximum price the customer is willing to pay for that item from that vendor.

Given these assumptions, we describe the proposed strategy in three steps. First, we consider the simple case of two competing MNs with point of presence in only two Internet locations. Then, we extend this description to the case of  $N$  competing MNs, but with all having point of presence in only two Internet locations. Finally, we extend the description to the more general case where there are many Internet locations and more than two MNs competing to provide connectivity services for WUs. We adopt this stepwise approach primarily for ease of understanding.

### 5.2.1 Two MNS Scenario

In this simple scenario, there are only two MNs, referred to as  $C_1$  and  $C_2$  provide wireless access to WUs close to the  $WU_A$ .

Before presenting the theory, we introduce a few additional notations to further clarify modeling assumption M4. Specifically, as indicated in assumption M3, each WU prefers either  $C_1$  or  $C_2$ . Depending on this preference, a WU has a certain maximum price he/she is willing to pay for the wireless connectivity, independent of other WUs. Let  $F_H(\cdot)$  denote the probability distribution function which characterizes the variation in the maximum willing price of different WUs towards their preferred MN. i.e.,  $F_H(u)$  is the probability that the maximum willing price of a WU for

wireless connection of its preferred MN is less than or equal to  $u$ . Likewise, let  $F_L(\cdot)$  denote the probability distribution function which characterizes the variation in the maximum willing price of different WUs towards their less preferred MN. To reflect the preference, suppose that  $F_H$  and  $F_L$  are such that  $F_H(u) \leq F_L(u)$  for all  $u$ .

Let  $p_1(t)$  and  $p_2(t)$  denote the price set by  $C_1$  and  $C_2$  for unit channel in the time period  $[t_0, t_0 + 1]$ ,  $t < t_0$ . Further, let  $n_1(t)$  and  $n_2(t)$  denote the unsold channels at  $C_1$  and  $C_2$  at time  $t$ . Note that, each MN knows its unsold channels but not that of the other MN. We, however, assume that each MN knows the prices set by the other MN prior to time  $t$ . For simplicity of presentation, assume that prices are set periodically, once every  $\Delta$  time units. Assume  $\Delta \rightarrow 0$ . Let  $V_i(n, p, t)$  denote the optimal expected revenue for  $C_i$  at time  $t$  when  $n$  is the unsold channels on  $C_i$  at that time and  $p$  is the most recent price of the other MN. Then, assuming that the other MN does not change its most recent price, an analytic expression for  $V_1(n, p, t)$ ,  $n > 0$ ,  $t < t_0$ , is as follows.

$$\begin{aligned}
 V_1(n_1(t), p_2(t - \Delta), t) = \max_{p \in \pi_1} \{ \\
 (V_1(n_1(t) - 1, p_2(t - \Delta), t + \Delta) + p) * Q_1(p, p_2(t - \Delta)) + \\
 V_1(n_1(t), p_2(t - \Delta), t + \Delta) * (1 - Q_1(p, p_2(t - \Delta))) \}
 \end{aligned} \tag{5.1}$$

where,

$$Q_1(p, q) = \lambda * \Delta * (\alpha_1 * (1 - F_H(p)) + \alpha_2 * F_H(p) * (1 - F_L(q))).$$

In the above expression,  $C_1$  searches for the best price  $p$  which maximizes the expression on the right. In the first term on the right hand side expression,  $Q_1(p, p_2(t - \Delta))$  is the probability that a WU will purchase an unit channel from  $C_1$ . When  $C_1$  successfully sells an unit channel, its unsold channels reduce by 1 and gets a revenue of  $p$ . The second term on the right hand side corresponds to the situation where no channels are sold during  $[t, t + \Delta)$ . In the expression for  $Q_1(p, q)$ ,  $\lambda * \Delta$  is the probability that a request from NU arrives during the next  $\Delta$  time units. The first term inside the parenthesis on the right hand side comes from the WUs that prefer  $C_1$  over  $C_2$  whereas the second term comes from the WUs that prefer  $C_2$  over  $C_1$ .

The expression for  $V_2(n, p, t)$  can be written similarly as

$$\begin{aligned}
 V_2(n_2(t), p_1(t - \Delta), t) = \max_{p \in \pi_2} \{ \\
 (V_2(n_2(t) - 1, p_1(t - \Delta), t + \Delta) + p) * Q_2(p, p_1(t - \Delta)) + \\
 V_2(n_2(t), p_1(t - \Delta), t + \Delta) * (1 - Q_2(p, p_1(t - \Delta))) \}
 \end{aligned}
 \tag{5.2}$$

where,

$$Q_2(p, q) = \lambda * \Delta * (\alpha_2 * (1 - F_H(p)) + \alpha_1 * F_H(p) * (1 - F_L(q))).$$

These two equations can be recursively solved using the following base cases.

- If all channels have been sold, there is no possibility of future revenue. That is,

$$V_1(0, p, t) = 0 \tag{5.3}$$

$$V_2(0, p, t) = 0. \tag{5.4}$$

We also assume that in this case the MN sets its price to  $\infty$ .

- When  $t = t_0$ , the unsold channels will not produce any additional revenue. That is,

$$V_1(n, p, t_0) = 0 \tag{5.5}$$

$$V_2(n, p, t_0) = 0. \tag{5.6}$$

for all  $n$  and  $p$ .

**Example:** Suppose that both  $C_1$  and  $C_2$  have 10 units of channels available between A and B on a particular day for the time period 10 a.m. to 11 a.m. For simplicity, assume that the WUs can purchase this channel only one hour in advance. That is, the channels are available for purchase between 9 a.m. and 10 a.m. The channels that are unsold at 10 a.m. does not produce revenue for the MN. Further suppose that the set of possible prices for both MNs is  $\{50, 60, \dots, 150\}$ . Also suppose that requests arrive at a rate of 1 request/minute.

Figure 5.3 plots the changes in the optimal price for  $C_1$  as a function of time left to buy when it has either 10, 5, and 1 unit of unsold channels given that  $C_2$  is charging \$100. The optimal prices

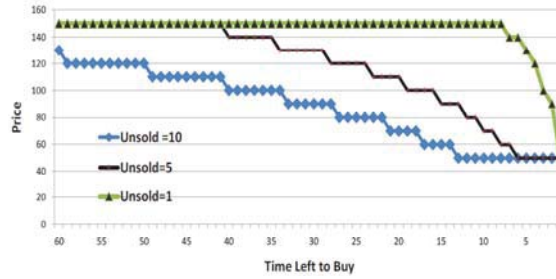


Figure 5.3 Variation in optimal price as a function of time left to buy.

decrease as time left to buy decreases, i.e., as 10 a.m. approaches, because any unsold channels at 10 a.m. will not produce any revenue and therefore, it is better to sell as much capacity as possible. Also, observe that the prices are lower for larger unsold capacity in order to quickly sell off more capacity. Figure 5.4 plots the changes in the optimal price for  $C_1$  as a function of unsold channels when 60, 30, and 1 minute is the time left to buy. Here again, the price charged by  $C_2$  is \$100. As expected, the optimal price decreases with increase in unsold capacity at a given time.

### 5.2.2 Multiple MNs Scenario

In this section, we generalize the solution in the previous subsection to the case where there are more than two MNs competing for providing connectivity to  $WU_A$ . As described above for two MNs, assume that  $F_H(\cdot)$  is the probability distribution function characterizing the variation in the maximum willing prices of WUs on their preferred MN. Similarly, assume  $F_L(\cdot)$  is the probability distribution function characterizing the variation in the maximum willing price of WUs on any of the non-preferred MNs.

Further, let  $p_i(t)$  denote the price set by  $C_i$  for unit channel in the time period  $[t_0, t_0 + 1]$ ,  $t < t_0$ . Further, let  $n_i(t)$  denote the unsold channels at  $C_i$  at time  $t$ . Note that, each MN knows its unsold channels but not that of the other MN. We, however, assume that each MN knows the prices set by the other MNs prior to time  $t$ .

Consider  $C_i$ . In selecting its price  $p_i(t)$ ,  $C_i$  could make use of its knowledge of the exact prices of other MNs prior to time  $t$ . However, such an approach may be too cumbersome for a MN and hence not practical. Therefore, we assume that a MN sets its price using the minimum price and

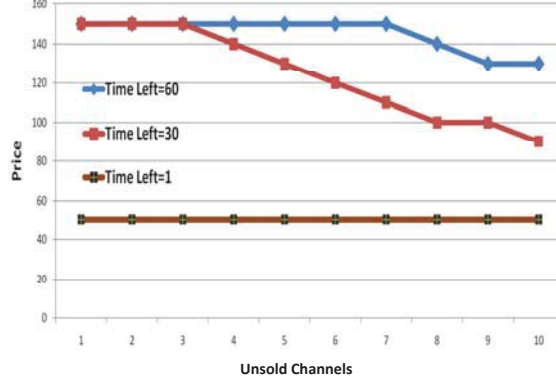


Figure 5.4 Variation in optimal price as a function of unsold channels.

the maximum price charged by other MNs. Specifically, let

$$p_{i,\min}(t) = \min \{p_j(t - \Delta) : 1 \leq j \leq N, j \neq i\}, \quad \text{and}$$

$$p_{i,\max}(t) = \max \{p_j(t - \Delta) : 1 \leq j \leq N, j \neq i\}.$$

Let  $V_i(n, p_{i,\min}(t), p_{i,\max}(t), t)$  denote the optimal expected revenue for  $C_i$  at time  $t$  when  $n$  is the unsold channels on  $C_i$  at that time. Then, for  $n > 0, t < t_0$ ,

$$V_i(n_i(t), p_{i,\min}(t), p_{i,\max}(t), t) = \max_{p \in \pi_i} \{$$

$$(V_i(n_i(t) - 1, p_{i,\min}(t), p_{i,\max}(t), t + \Delta) + p) *$$

$$Q_i(p, p_{i,\min}(t), p_{i,\max}(t)) +$$

$$V_i(n_i(t), p_{i,\min}(t), p_{i,\max}(t), t + \Delta) *$$

$$(1 - Q_i(p, p_{i,\min}(t), p_{i,\max}(t)))$$

$$\},$$

where,

$$Q_i(p, q_{\min}, q_{\max}) = \lambda * \Delta * (\alpha_i * (1 - F_H(p))$$

$$+ (1 - \alpha_i) * F_L(p) * (1 - F_H(q_{\min}))) *$$

$$\sum_{k=1}^{N-1} \binom{N-1}{k} (F_L(q_{\max}))^{(k-1)} * (1 - F_L(q_{\min}))^{(N-1-k)}.$$

In the above expression,  $C_i$  searches for the best price  $p$  which maximizes the expression on the right. In the first term on the right hand side expression,  $Q_i(\cdot, \cdot, \cdot)$  is the probability that a WU will purchase an unit channel from  $C_i$ . When  $C_i$  successfully sells an unit channel, its unsold channels reduce by 1 and it gets a revenue of  $p$ . The second term on the right hand side corresponds to the situation where no channel are sold during  $[t, t + \Delta)$ . In the expression for  $Q_i(\cdot, \cdot, \cdot)$ ,  $\lambda * \Delta$  is the probability that a request from a WU arrives during the next  $\Delta$  time units. The first term inside the parenthesis on the right hand side comes the WUs that prefer  $C_i$  over other MNs whereas the second term comes from WUs that prefer one of the other MNs over  $C_i$ .

The above set of equations can be recursively solved using the following base cases.

- If all channels have been sold, there is no possibility of future revenue. That is, for all  $p$ ,  $q$ , and  $t$ ,

$$V_i(0, p, q, t) = 0. \quad (5.7)$$

We also assume that in this case  $C_i$  sets its price to  $\infty$ .

- When  $t = t_0$ , the unsold channels will not produce any additional revenue. That is, for all  $n$ ,  $p$ , and  $q$ ,

$$V_i(n, p, q, t_0) = 0. \quad (5.8)$$

### 5.3 Evaluation

In this section, we present results of our empirical evaluation of the PriceMyRate strategy described in Section 5.2. The evaluation is done using a discrete event simulator. The goals of this evaluation are two-fold: (i) to illustrate the key characteristics of PriceMyRate, and (ii) to compare its performance to that of a static scheme and to that of RateBazaar modifying the proposed scheme in [112].

### 5.3.1 Simulation Setup

As in Section 5.2, we present the results in several stages. First, we consider the simple case of two MNs' competition in selling channels to WUs within a specific area. The simplicity of the topology helps in an intuitive understanding of the performance characteristics of PriceMyRate. Second, we show results for the simple topology, but with four MNs competing to provide wireless connectivity (i.e., sell their channels). The results show that the good performance characteristics of PriceMyRate remain true even as competition increases. Finally, PriceMyRate requires estimation of certain parameters such as user request arrival rate. We characterize the sensitivity of PriceMyRate performance to errors in estimation.

For each of the above three scenarios, the simulator implements the MN agents, the WUs, and the online Spectrocity service. The set of MN locations, number of available channels of each MN, and the range of prices for each MN are input to the simulator of the MN agent. If a MN cannot provide wireless service to a WU either due to its topology or due to lack of unsold capacity, the corresponding MN agent returns a price of  $\infty$ . The simulation of the WU implements the arrival process, WU preference for a MN, selection of maximum willing prices of the connection on each MN and the decision to purchase or not. The Spectrocity part of the simulator implements the interactions between the WU and the MN agents including the completion of the purchase transaction.

For the results presented in this section, all channels are assumed to be available only in one-hour blocks, i.e., 8 a.m. to 9 a.m., 9 a.m. to 10 a.m., 10 a.m. to 11 a.m., and so on. Furthermore, it is assumed that the time block of channels go on sale one hour in advance, i.e., channels for the 9 a.m. to 10 a.m. can be purchased in the period 8 a.m. to 9 a.m. Performance statistics for PriceMyRate are collected from a run simulating 168 hours (i.e., one week) of user requests. For RateBazaar, the performance statistics are collected from a run simulating 720 hours (i.e., a month) of user requests; the first 552 hours of this run are needed for RateBazaar to converge to a good set of prices for each MN and the performance statistics are presented for the user requests in the final 168 hours of the run. Note that, since we assume that the user request arrival rate is known (albeit with some error) there is no need for any convergence time for PriceMyRate. If PriceMyRate has

to estimate the user request arrival rate, then some convergence time will be required. Instead of simulating this convergence time, we present results evaluating the sensitivity of the performance statistics to the error in estimating the user request arrival rate.

The simulator collects several performance statistics. In particular, it maintains the average revenue per hour for each MN. Note that, as mentioned above, an hour corresponds to the duration for which a connection block is available for purchase. Of course, each MN wants to have as high an average revenue per hour as possible. Therefore, a pricing strategy which results in higher average revenue per hour is better from the MN's perspective. The simulator also maintains the number of user requests per hour that successfully end in a purchase transaction. Clearly, some user requests don't end in purchase transaction because the price from all MNs is larger than the corresponding maximum prices the WU is willing to pay for the wireless connectivity. From the WU's perspective, it is better if a request ends in purchase transaction. Therefore, a pricing strategy which results in more purchase transactions per hour is better from the WU's perspective. In the rest of this section, we use purchase transactions per hour as a measure of *WU Satisfaction*.

The following simulation input parameters are common to all the results presented in this section.

- All the MNs chose a price from the set  $\{50, 60, 70, \dots, 150\}$ .
- WU's maximum willing price for a channel follows the conventional constant elasticity demand curve [113, 114]. That is, the probability that a WU will be willing to pay a certain price decreases exponentially with price. More formally, the probability that a WU will be willing to pay a certain price  $p$  is  $e^{-\eta p}$  for constant  $\eta$  with  $1/\eta$  representing the average price the WUs are willing to pay for the connection.

For a  $h$ -hop route, the average price that WUs are willing to pay is assumed to  $100 * h$  on their preferred MN and  $80 * h$  on their less preferred MN.

- For most of the results, it is assumed that all MNs are equally likely to be preferred. One set of results explore the effect of some MNs being more preferred than other MNs.

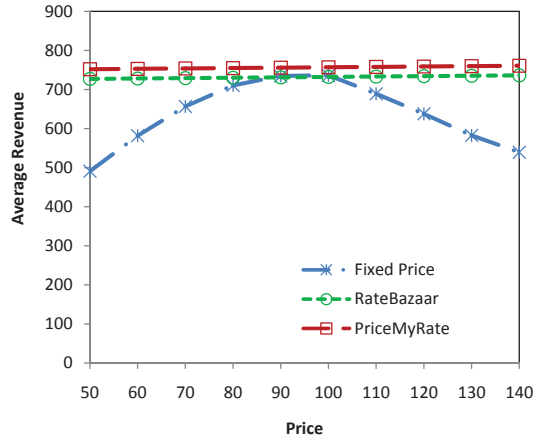


Figure 5.5 Comparing revenues in PriceMyRate, RateBazaar, and Fixed Prices Scheme for two MNs' price competition.

## 5.3.2 Evaluation Results

### 5.3.2.1 Impact of price competition between two MNs in performance

Figure 5.5 compares the average revenue per hour (averaged over both MNs) for three pricing strategies. In the *Fixed Prices* strategy, the price of channels of a MN never changes. We simulate for different values for this fixed price. The x-axis shows the different fixed prices simulated for the *Fixed Prices* scheme. The other two strategies are RateBazaar and the proposed PriceMyRate. The RateBazaar strategy searches the space of prices and tries to identify the best possible price for the channel. Once the best price is identified, RateBazaar does not usually change channel price. However, since RateBazaar is always searching for the best price, there may be slow fluctuations in the price. In PriceMyRate, the link price varies as user requests are serviced and as the remaining time to purchase a channel block decreases. Since the average revenue per hour in RateBazaar and PriceMyRate are not a function of the price chosen for the *Fixed Prices* scheme, the curves corresponding to RateBazaar and PriceMyRate are straight lines parallel to the x-axis. The average revenue per hour for the *Fixed Prices* scheme initially increases with price and then drops. This is because, initially, each NU who ends up purchasing a channel pays a higher price and the increase in price more than compensates the decrease in the number of WUs purchasing at a higher price. Eventually, however, decrease in the number of WUs purchasing at a higher price starts to dominate

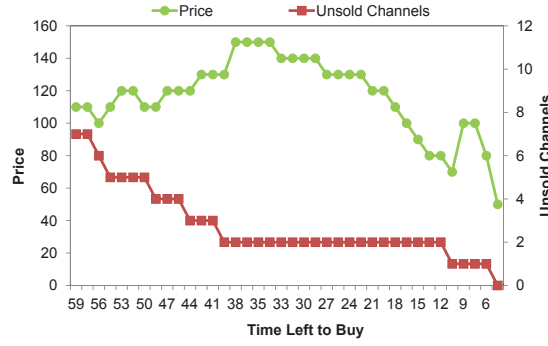


Figure 5.6 Variation in prices and unsold capacity of one MN as it competes with three other MNs.

the increase in the revenue due to higher prices and the average revenue starts to drop. Observe that, as proved in [112], RateBazaar eventually converges to the best price and its average revenue per hour is equal to that for the best possible fixed price. The average revenue per hour for PriceMyRate is marginally larger than that for RateBazaar due to the price adaptations in PriceMyRate.

### 5.3.2.2 Impact of price competition among four MNs in performance

In this subsection, we present results for four MNs competing the price selling their available channels. Unlike in the previous subsection, all MNs are not equally likely to be preferred by WUs. For the results presented in this subsection, 40% of the WUs prefer  $MN_0$  (i.e., WSP 0), 25% of the WUs prefers  $MN_1$  (i.e., WSP 1) and  $MN_2$  (i.e., WSP 2) respectively, and only 10% of WUs prefer  $MN_3$  (i.e., WSP 3). Figure 5.6 shows the changes in prices for one time block of connection in PriceMyRate. The figure also shows the variation in the unsold capacity during this period. In Figure 5.6, observe that the price starts off at \$110 when 60 minutes of selling time remain and the unsold capacity is 10 units. As capacity gets sold, the price increases to \$150 when only 2 units of channels remain unsold and approximately 30 minutes of selling time still remains. It appears that due to the high price, NU stop purchasing channels from this MN. This causes the MN to drop his/her price to \$70 when about 8 minutes of selling time remain. Now, due to the low price, the WUs quickly purchase the remaining 2 units of channels. The total revenue for this MN from this time block of 10 connections is \$1160. In contrast, RateBazaar keeps the price constant at \$90.

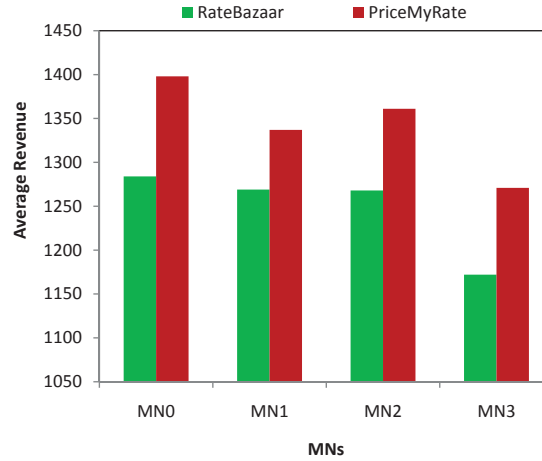


Figure 5.7 Comparing revenues in PriceMyRate and RateBazaar for four MNs' price competition.

For this particular time block, maintaining a constant price is adequate to sell off all the 10 units of channels, resulting in a revenue of only \$900 as compared to \$1160 in PriceMyRate.

Figure 5.7 compares the average revenue of each MN in PriceMyRate and RateBazaar. Figure 5.8 compares the same two strategies based on WU Satisfaction. Observe that, the average revenue for each MN is larger for PriceMyRate as compared to RateBazaar. With respect to NU Satisfaction, both schemes are comparable with PriceMyRate performing better for one MN. Collectively, these two figures show that PriceMyRate is better than RateBazaar from MN and WU perspectives.

### 5.3.2.3 Impact of errors in parameter estimation

The methodology used in PriceMyRate for computing the price of a virtual link depends on an estimate of the user request arrival rate for that link, which in turn, depends on the estimate of the overall user request arrival rate  $\lambda$ . RateBazaar does not require this estimate. PriceMyRate performs better than RateBazaar partly because it makes use of this additional information in selecting the prices. In this subsection, the results characterize the sensitivity of the performance of PriceMyRate in the presence of estimation errors.

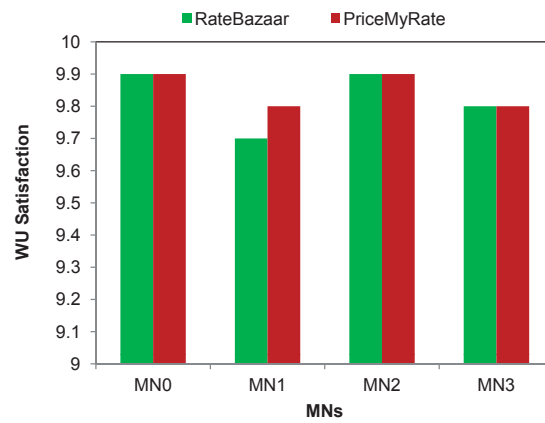


Figure 5.8 Comparing WU satisfaction in PriceMyRate and RateBazaar for four MNs' price competition.

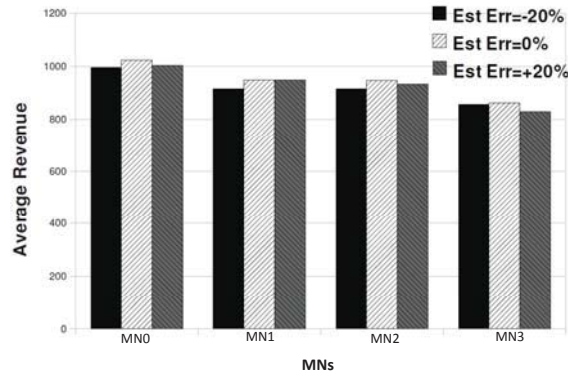


Figure 5.9 Effect of estimation error in  $\lambda$  on average revenue of MNs

Figure 5.9 shows the average revenue of the four MNs in three different cases. All three cases consider four MNs competing prices selling channels, and  $MN_0$  preferred by 40% of WUs,  $MN_1$  and  $MN_2$  preferred by 25% of WUs, and  $MN_3$  preferred by 10% of WUs. The three cases differ in the amount of estimation error. The true value of  $\lambda$  is 1 NU arrival per minute. In the first case (i.e.,  $-20\%$  error), the estimated value of  $\lambda$  is 0.8 NU arrivals per minute. In the second case, there is no estimation error. In the third case (i.e.,  $+20\%$  error), the estimated value of  $\lambda$  is 1.2 NU arrivals per minute. In the figure, observe that the average revenue of each MN is not very sensitive to estimation errors in  $\lambda$ . A 20% error in estimating error produces less than 2% error in the average revenue of each MN. Also, as expected, in both cases with error (i.e., with  $\pm 20\%$  estimation error), the revenue is slightly smaller than if we have no estimation error. Since average revenue is not very sensitive to estimation errors in  $\lambda$ , small time-dependent fluctuations in user request arrival rate do not adversely affect the performance of PriceMyRate. This is clearly a very desirable feature.

## 5.4 Conclusions

In present day Internet, network users do not have much flexibility in the selection of data rates for packet transmission. Instead, the mesh node oriented control unifies the resource allocation strategies for all flows. With CR, in this Chapter, we explore a market-based framework for

providing a different approach in resource allocation. The proposed scheme envisions an online service called Spectrocity through which performance-constrained channels can be sold by multiple mesh nodes, who in turn, purchase channels from primary users. Similar to online hotel booking service such as Expedia, Spectrocity allows network users to shop for the best price for their desired wireless connectivity.

Given this framework, a pricing strategy for mesh nodes is proposed. The proposed strategy is similar to those used in the airline industry. The paper uses simulations to compare the performance of this strategy with that of RateBazaar, a recent related scheme in literature. The comparison shows that the proposed strategy is better than the scheme in literature from the perspective of both the mesh nodes and the network wireless users. In addition to this comparison, the key ideas in the proposed strategy are also illustrated through simulations. These results show that the proposed strategy adapts well to changes in user demand. The results also show that the performance of the proposed strategy is robust to errors in estimating the values of certain design parameters of the overall system.

## Chapter 6

### Real-Time Streaming to Mobile Users

The focus of this chapter is on support for real-time streaming to mobile users. The challenge stems from the fact that a mobile user needs bandwidth from different infrastructure nodes over times to sustain the application. In this chapter, we describe a strategy, called Adaptive Rate Purchase (ARP), for the mobile user to maintain the quality of the streaming application by purchasing bandwidth from service providers based on price, predicted future locations, and the needs of the application.

#### 6.1 Problem Description

Multiple wireless service providers (WSPs) deploy their mesh nodes (MNs) within a geographic region of interest to provide Internet connectivity to users (e.g., pedestrians, vehicles). Each MN has fixed service coverage range. Some of the users in the service range of an MN associate with it in order to access the Internet. To increase its data rate, the wireless user may also purchase additional channels sold by mesh nodes. At any time  $t$ , a wireless user may predict its locations up to time  $t + T$  and purchase channels possible use in the future. MNs from different WSPs compete with each other to sell channels to wireless users by adapting their prices over time based on supply, demand and the competition. For example, MNs may adapt their prices using the strategy proposed in Chapter 5.

In this network, consider a wireless user who is real-time streaming from the Internet while driving on a road, and the real-time application is sensitive to packet delay and losses. To maintain the quality of the application, one must ensure that the application's buffer always has sufficient

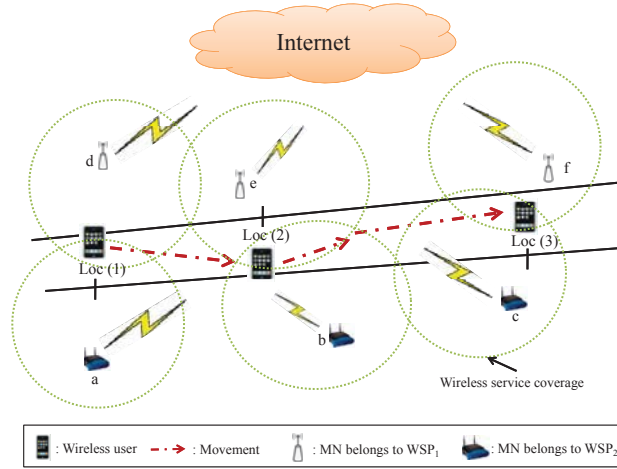


Figure 6.1 Example of a wireless user's mobility behavior and mesh node deployment.

number of packets for further processing (e.g., video decoding). These packets are downloaded from the Internet through the MN using channels purchased by the user.

Take Figure 6.1 as a simple example, the wireless user first associates with  $MN_d$  providing the highest  $\gamma$  at  $Loc(1)$ , and receives packets from Internet via  $MN_a$ . As shown in Figure 6.1, when moving to  $Loc(2)$ , the wireless user loses the connection with  $MN_d$ . Therefore, the wireless user re-associates with another MN (e.g.  $MN_b$ ) in order to keep receiving packets from the Internet. Similarly, the wireless user will re-associate with  $MN_f$  to connect to the network when the wireless user is at  $Loc_3$ . However, during handoff, packet losses will occur during the time within a particular period of Internet disconnectivity. Further, the wireless users associating to a MN share the limited resources for wireless packet transmission, and each wireless user may receive low throughput when the traffic loads sent through the same MN are high. Under this condition, the performance of real-time streaming degrades significantly.

To improve the performance, the wireless user is encouraged to buy more channels from the MNs it wants to connect to. Furthermore, from the perspective of cost effectiveness, the wireless user only purchases more channels when its buffer may not have enough packets for steaming. The MNs dynamically adjust the price of the channels they are selling, the wireless user has to intelligently choose number of channels, not only for sustaining the quality of service (QoS) for

the streaming but also for minimizing the cost being paid for the QoS (i.e., channels). We develop schemes for purchasing channels to support real-time applications for wireless users while minimizing the cost buying channels. Each wireless user relies on the channel selling prices, its own estimated buffer size, and estimated location when considering channel purchase in order to properly sustain the QoS of streaming.

### 6.1.1 Utility function for wireless users

The wireless user wants to stream real-time contents smoothly while moving on its route, and to reach this goal is to maintain non-zero buffer as much as possible. To sustain non-zero buffer, the wireless user needs to receive certain amount of packets from the associated MN. As a consequence, the wireless user will buy channels from some MNs aimed to keep non-zero buffer. Under the condition, at time  $t$ , denote the utility as  $U(t)$  to represent user satisfactory, and the utility consists of  $U_B(t)$  and  $U_C(t)$ , the former is the buffer utility and the latter is the cost utility for purchasing channels from APs.

$$U_B(t) = \begin{cases} 1, & \text{if } B(t) > 0 \\ 0, & \text{else} \end{cases}$$

$$U_C(t) = \exp\left(-\frac{C}{C_{exp}}\right)$$

$U_B(t)$  is defined to reflect the user satisfaction in streaming experience. It is set to be 1 at time  $t$  when the buffer is non-empty after streaming, and 0 otherwise. It is because the wireless user only thinks of the smoothness during real-time content streaming instead of worrying about the current buffer size since. Even though at time  $t$ , the buffer length is around 0, the buffer may be filled out at  $t + 1$  for streaming. Under this condition, wireless user experience consecutive streaming.

Furthermore, the cost utility at time  $t$ ,  $U_C(t)$ , is function of the ratio of exact payment for channels at time  $t$  over  $C_{exp}$ .  $C_{exp}$  is the minimum cost the wireless user needs to pay to continuously maintain non-zero buffer.

Combining  $U_B(t)$  and  $U_C(t)$ , the utility is formulated as

$$U(t) = U_B(t) \times U_C(t)$$

In the following sections, we will describe and evaluate these utility functions to validate our proposed channel purchase mechanisms.

## 6.2 Mobility Management

In this section, we will first describe our proposed Spectrum Purchase Framework, and then introduce the proposed Adaptive Rate Purchase.

### 6.2.1 Adaptive Rate Purchase (ARP)

To maximize utility for real-time content delivery, we formulate an optimization problem. Specifically, the targets are two-fold, to minimize the payment for cost and to maintain non-zero buffer. Furthermore, to cope with mobility, the wireless user predicts possible locations for each time interval and use it in the channel purchase decision making.

Before describing our proposed approach, we first define some notations which are used throughout this paper. We use  $MN_i$  to represent the MN  $i$ ,  $P_i$  to represent the transmission power of  $AP_i$  and  $B(t_0)$  to represent the buffer size of a wireless user at time making purchase decision (e.g.,  $t_0$ ). Moreover,  $T$  is defined to be the maximum number of time intervals allowed to be purchased ahead. We denote the number of channels to purchase from  $MN_i$  and the streaming rate of the wireless user for time  $t$  as  $x_i(t)$  and  $Q(t)$ , respectively. The price  $MN_i$  charges for its channels at time  $t$  is denoted as  $C_i(t)$ . Further,  $p_\ell$  is the probability the wireless user will be at the location  $\ell$ ,  $d_i(\ell)$  is the distance between the  $MN_i$  and location  $\ell$ . The data link rate  $MN_i$  provides at location  $\ell$  is denoted as  $\Phi_i(\ell)$ . In addition, we denote  $\Omega_t$  to be the set of all MNs to which the wireless user can purchase channels from at time  $t$ .

In order to react to the price charges and channel availability which maintain smoothly streaming, the full optimization problem can be solved. Assume that current time is  $t_0$ ,

$$\begin{aligned}
& \min \sum_{t=t_0+1}^{t_0+T} \sum_{i \in \Omega_t} C_i(t) x_i(t) \\
s.t. \quad & B(t) \geq 0, \\
& B(t) = B(t-1) - Q(t) \\
& \quad + \sum_{\ell} \max_i \{ \Phi_i(\ell) (x_i(t) + n_i(t)) \} p_{\ell}(t), \\
& B(0) = B(t_0), \\
& 0 \leq x_i(t) \leq k_i(t), \\
& t_0 + 1 \leq t \leq t_0 + T
\end{aligned}$$

where

$$\Phi_i(\ell) = f \left( \frac{P_i/d_i^2(\ell)}{\sigma^2} \right), \forall \ell \tag{6.1}$$

---

**The Rate Purchasing Problem :**


---

For each time  $t$ ,  $t_0 + 1 \leq t \leq t_0 + T$

$$\begin{aligned}
 & \min \sum_{t=t_0+1}^{t_0+T} C_t(R(t)) \\
 s.t. \quad & B(t) \geq 0, \\
 & B(t) = B(t-1) + R(t) - Q(t), \\
 & B(0) = B(t_0), \\
 & t_0 + 1 \leq t \leq t_0 + T
 \end{aligned}$$

The solutions,  $x_i(t)$ , indicates the ideal purchase for all time interval to maximize the utility. Since number of available channels, number of MNs, number of locations, streaming time period, and the physical layer rate are finite, the optimal solution exists.

However, the above problem is computationally expensive to solve. Instead, we modify the formulation and divide it into two sub-problems, the rate purchasing problem and the rate pricing problem. Specifically, rate means the expected received data rate from the purchased MNs. Through the rate pricing problem, we obtain the relationship between price and the rate, and apply the relationship to the rate purchasing problem for further optimization. In the rate pricing problem, given a data rate, the cost of purchasing channels to obtain that expected rate is minimized. This information is used in the rate purchase problem to determine the optimal expected rate to be purchased such that the streaming buffer constraints are not violated. The objective of the rate purchase problem is to minimize the total cost at this time instance.

The modified optimization problems are as follows :

### 6.3 Spectrum Purchase Framework

Figure 6.3 shows the framework for channel sell/purchase interactions. A channel broker runs within a geographic range as a local server to maintain information from all nearby MNs and wireless users. Due to the limited communication range of each MN and each wireless user, a

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**The Rate Pricing Problem :**


---

For each time  $t$ ,  $t_0 + 1 \leq t \leq t_0 + T$

$$\begin{aligned}
 C_t(R(t)) &= \min \sum_{i \in \Omega_t} \{C_i(t)x_i(t)\} \\
 s.t. \quad R(t) &\leq \sum_{\ell} \max_i \{\Phi_i(t)(x_i(t) + n_i(t))\} p_{\ell}(t) \\
 0 &\leq x_i(t) \leq k_i(t),
 \end{aligned}$$

where

$$\Phi_i(\ell) = f\left(\frac{P_i/d_i^2(\ell)}{\sigma^2}\right), \forall \ell \tag{6.2}$$

---

**Opportunistic Streaming (ARP) Channel Purchase Algorithm for a wireless user**


---

1. For each time  $t$ ,  $t_0 + 1 \leq t \leq t_0 + T$ , identify the set of possible locations of the wireless user  $L_t$ .
  2. Let  $\Omega_t$  be the set of MNs accessible from locations in  $L_t$ .
  3. For each possible rate  $[R_{min}, R_{max}]$ , solve the rate purchasing problem for each time  $t$ . Let Given  $\Omega_t$ , calculate expected data rate and the corresponding cost the wireless user may get for each time  $t$ . Let  $C_t(R(t))$  be the minimum cost of achieving expected rate at time  $t$  (i.e.,  $R(t)$ ).
  4. Solve the rate purchasing problem.
  5. Purchase channels based on the solution to the rate purchasing problem.
- 

Figure 6.2 The procedure of Adaptive Rate Purchase.

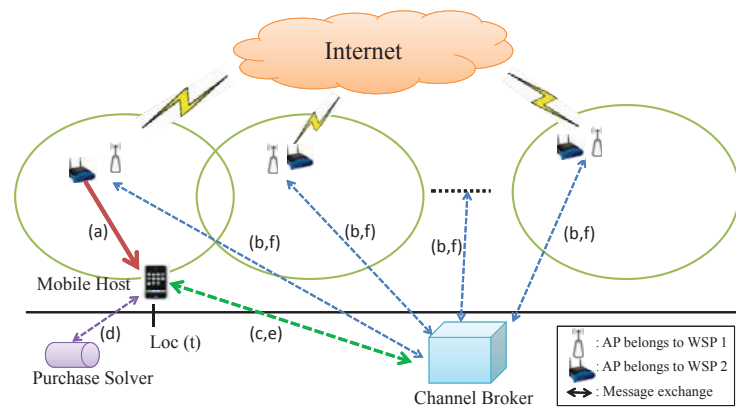


Figure 6.3 Spectrum Purchase Framework.

wireless user cannot directly interact with all MNs simultaneously, the channel broker provides the information exchange between a wireless user and an MN. Further, in the figure, the arrow shows the communication occurs between two entities, and each communication relies on several packets/messages exchange. Each purchase happens through multiple communication (i.e., message exchange). The detail of each communication is as follows.

(a) Packets downloaded by the wireless user.

The wireless user connects to  $MN_i$  which provides the highest data rate among all MNs the wireless user has purchased channels from for time interval  $t_1$ . Then, wireless user receives packets from Internet through  $MN_i$ .

(b.i) MN status query message.

The channel broker requests the price from each MN in its service range.

(b.ii) MN status reply message.

$MN_i$  returns the channel price to the channel broker.

(c.i) MN information request message.

The wireless user asks channel price of a set of MNs from the channel broker.

(c.ii) MN information reply message.

The channel broker sends the price and location information of all MNs to the wireless user.

(d) Purchase decision message.

The wireless user solves rate pricing and rate purchasing optimization problems to make its purchasing decisions.

(e.i) Purchase request message.

The wireless user sends its purchase decision to the channel broker.

(e.ii) Purchase permission message.

The channel broker returns the permission for purchasing after confirming with the corresponding MNs.

(f) Purchase update message.

The channel broker sends the purchase results to each corresponding MN individually.

## 6.4 Evaluation

### 6.4.1 Overview

Consider the network in Figure 6.3. Assume that there are two WSPs deploy their MNs to provide wireless connectivity. For simplicity, we assume the deployment is well planned, and each MN serves fixed geographic range. More specifically, we assume at a given location, either no MNs are put or every WSP simultaneously puts one MN there. Further, the physical layer data rate is calculated by  $C \log(1 + \frac{P_{tx}}{d^2})$ ,  $d$  is the distance between a mobile host and the MN it connects to.

In the network, each MN divides its total link capacity into 20 channels for selling. These 20 channels are sold over  $T$  time intervals. Further, at a given time  $t_0$ , the  $MN_i$  sells its owned channels for time interval  $u$  with the price,  $C_i(t_0 + u)$ . Also, to avoid monopoly in the channel sell/purchase market, at the given time  $t$  (i.e.,  $t_0 + u$ ), a wireless user is allowed to buy no more than  $k_i(t)$  channels from a specific  $MN_i$ .

### 6.4.2 Evaluation Setup

In all the experiments, we specifically set the time scale (i.e., time interval) for each purchase to be 3 min. Further, the minimum distance between two MNs belonging to the same WSP is 2.5 km, and the radius of the coverage of each MN is approximately 1.25 km. We define the total link capacity of a MN varies from 3.5 to 0 Gbps as a function of the distance from the MN. Furthermore, the streaming rate is set to be 250 Mbps, and the wireless user moves with the mean speed of 60 km/hr and certain speed variation.

Considering the price setup for channel purchase, we applied the proposed pricing model in Chapter 5 as the pricing strategies from WSPs to dynamic adjust channel selling price in accordance to the channel availability. Additionally, to investigate the performance of the mobility management under the dynamic channel pricing environments, we consider two common purchase strategies as a comparison with our proposed scheme base on most common marketing behavior.

These two approaches take cost and buffer size into consideration to maintain buffer size. The detail is as follows:

**Fix Channel for First  $u$  time intervals (FCFu) Strategy :** When the buffer is below a pre-determined threshold, FCFu buys channels for the next  $u$  time intervals I.e., at time  $t_0$ , it buys channels for time  $t_0 + 1, \dots, t_0 + u$ . For each of these time instants, the expected location of the wireless user is predicted, and the MNs offering the highest data rate at these locations are selected. From each selected MN the strategy purchases the maximum allowed number of channels.

**$u$  Least Cost time intervals (LCu) Strategy:** When the buffer size is smaller than a pre-determined threshold, LCu purchases channels at  $u$  out of the  $T$  next time intervals. For each of the  $T$  time intervals, the user's expected location is first predicted. From the sets of the MNs reachable from the expected location, the MNs offering the highest data rate at these locations are selected. Among the MNs selected for the next  $T$  time intervals, LCu buys channels from the MNs with the first  $u$  lowest channel prices. From each selected MN the strategy purchases the maximum allowed number of channels.

### 6.4.3 Evaluation Results

We show results for ARP, FCFu, and LCu under different scenarios. First, we will show the behavior of each strategy in detail. The performances under different parameters (threshold and  $u$ ) for FCFu and LCu are illustrated comparing with ARP which is independent of specific parameter selection.

Further, the impact of different wireless user arrival rate on the utility is present. Due to the dynamic change of pricing in response to the number of available channels for purchase, the wireless user will experience different channel price in response to different channel availability. In addition to investigate the performance for supporting mobility, the utility under different mobility is evaluated. Specifically, we consider different coefficient of variation (CV) for the speed of movement. The results show the ARP still reliably sustains the performance under different mobility

conditions. Moreover, with the change of network condition, both  $FCF_u$  and  $LC_u$  need to pick appropriate  $u$  and threshold aimed to maximize their utility. However, ARP shows the improvement of utility under different network situations.

#### 6.4.3.1 The impact of parameter selection

In this experiment, we investigate the change of utility under different parameter choosing for each purchase method. Consider the wireless user arrival rate to be 1 wireless user every 1.5 time interval, and consider the mean and CV of the mobility to be 60 km/hr and CV 0.33, respectively.

Figure 6.4 presents the utility under different methods. Furthermore, given a purchase strategy, each bar shows the best achievable utility under the best combination of  $u$  and the threshold. As shown in the figure, ARP obtains the highest utility without any specific parameter selection which is required in  $FCF_u$  and  $LC_u$ . For,  $FCF_u$ , when  $u = 10$  with the best selected threshold, the best utility reaches 0.6, and similarly, the  $LC_u$  obtains best utility 0.5 when  $u = 9$  while the utility of ARP is 0.7. Furthermore, when  $u$  is small, the utility decreases because the wireless user cannot buy enough number of channels for supporting packet transmission which in turn results in insufficient data for streaming. Note that ARP does not have any specific parameters effecting purchase decisions. We also present the relationship among utility, threshold, and  $u$  for  $FCF_u$  and  $LC_u$  in Figure 6.5. As displayed in Fig 6.5(a), when  $u > 6$  and threshold  $< 10$ , the utility increases with the increasing of threshold. When the threshold  $> 15$ , the utility decreases.

Figure 6.6 illustrates the buffer and cost utility with the best threshold for the combination of different  $u$  and different strategies. ARP,  $FCF_u$  with  $u > 6$ , and  $LC_u$  with  $u > 5$  sustains buffer size properly, and then the buffer utility reaches 1. When  $u \leq 6$ , MNs may not have sufficient number of channels for selling, the buffer size of the wireless user will not stay non-zero properly, and the utility decreases.

In Figure 6.6(b), considering  $0 < u \leq 6$  at which the buffer utility is almost 0, the cost utility decreases with the increasing of  $u$ . Specifically,  $u$  decides how much time interval ahead the wireless user should purchase channels for the future. As shown in Figure 6.4, the buffer utility stays almost 0 which in turn indicates that the buffer always does not have sufficient number

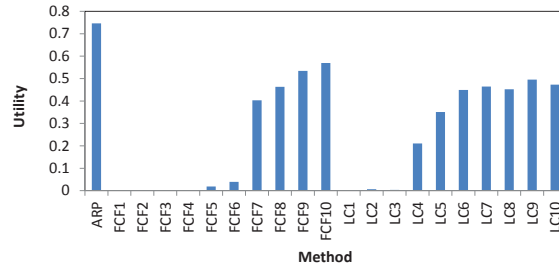


Figure 6.4 Utility under different methods

of packets, and the wireless user has to keep purchasing channels from prospective MNs. As a consequence, when  $u$  is large, the wireless user purchases channels up to  $u$  time interval. Under this condition, the cost increases.

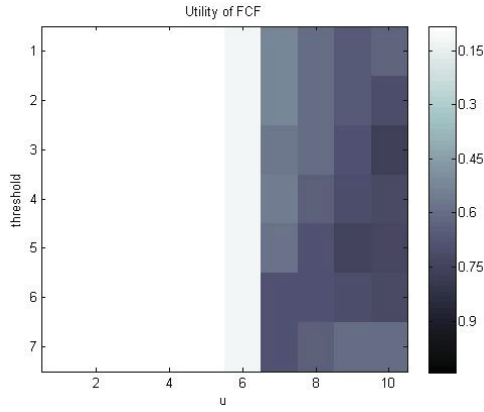
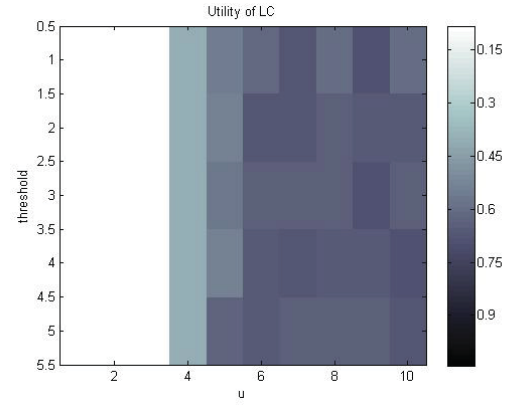
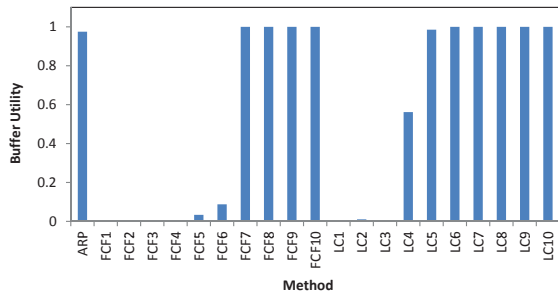
On the other hand, the cost utility increases when  $u > 6$ . For  $u > 6$ , the buffer utility is about 1 which indicates that the wireless user has sufficient packets in its buffer all the time. Specifically, if the wireless user keeps collecting channels for a specific time  $t$  from  $u$  time interval ahead, the wireless user may have more channels (i.e., larger link data rate) for packet transmission. Under this condition, the cost for large  $u$  increases. However, the probability that the buffer size with large  $u$  is greater than the threshold is higher than that with smaller  $u$ . The wireless user does not purchase channels until its buffer size is lower than the threshold, and the average cost would be lower when  $u$  is large.

However, ARP adaptively collects channels when the price is low to maintain buffer size, and reaches better cost utility as well as buffer utility. Under this condition, ARP improves the utility for supporting mobility and streaming without selecting specific parameters.

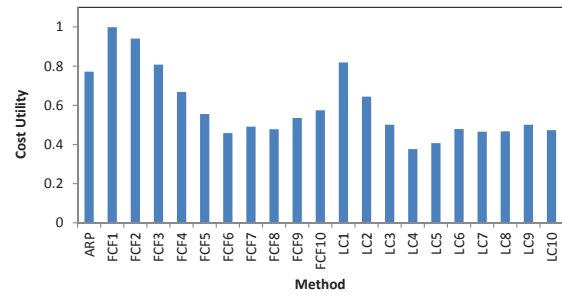
#### 6.4.3.2 The impact of wireless user arrival rate

The effect of wireless user arrival rate is evaluated in this experiment. In this experiment, the mobility is formulated as normal distribution with mean 60 km/hr and with CV 0.33.

Figure 6.7 shows the utility as a function of different user arrival rate. The x-axis presents different purchase approaches, and the y-axis indicates the corresponding utility. Specifically, the pair of number on top of each bar shows the best selected pair for  $u$  and the threshold. Further,

(a) Utility of FCF $_u$  under different threshold and  $u$ .(b) Utility under different threshold and  $u$ .Figure 6.5 Utility under different threshold and  $u$ 

(a) Buffer utility under different methods.



(b) Cost utility under different methods.

Figure 6.6 Buffer and cost utility under different methods

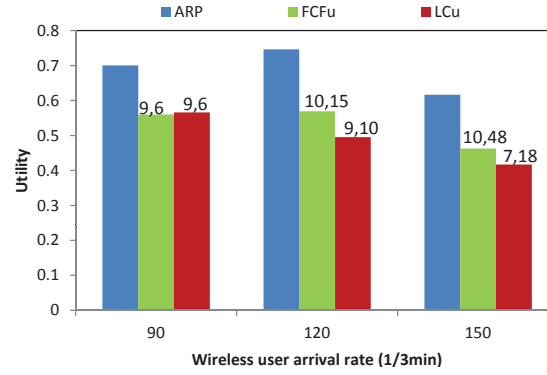


Figure 6.7 Utility under different wireless user arrival rate.

Figure 6.8 illustrates the varying of utility under different  $u$  and the best threshold according to different  $u$ . Figure 6.9 lists the detail of  $U_C$  and  $U_B$  in all scenarios.

Overall, ARP obtains higher utility than the best utility both FCFu and LCu can reach under all different user arrival rates. ARP purchases channels based on the expected buffer size and the cost for buying channels. Further, ARP reserves channels for packet transmission at each predicted location. As a result, ARP is able to collect enough number of channels for streaming with less payment. FCFu and LCu also consider all possible locations for channel purchase, but they only buy channels from the MNs which the wireless user will arrive above certain probability. To improve the utility FCFu or LCu could reach, in addition to carefully select threshold and  $u$ , the relationship between the mobility and the purchased MNs needs to be considered in further.

Further, combining Figure 6.8 and Figure 6.9 together, the buffer utility for proper  $u$  selected FCFu and LCu and ARP is 1. As for cost utility, small  $u$  obtains high utility, since the buffer utility is almost 0 (i.e., the buffer size is zero), the utility is very low. However, with higher cost utility and non-zero buffer, the ARP outperforms under different wireless user arrival rate.

### 6.4.3.3 The impact of mobility

In this experiment, we evaluate the utility under different CV. Specifically, the mobility is modeled as normal distribution with mean 60 km/hr and standard deviation  $\sqrt{\sigma^2 \Delta t}$ , where  $\sigma^2$  is the variance of the mobility and  $\Delta t$  is the time difference between two time intervals.

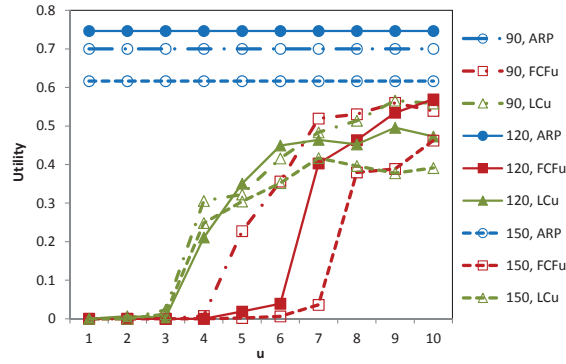
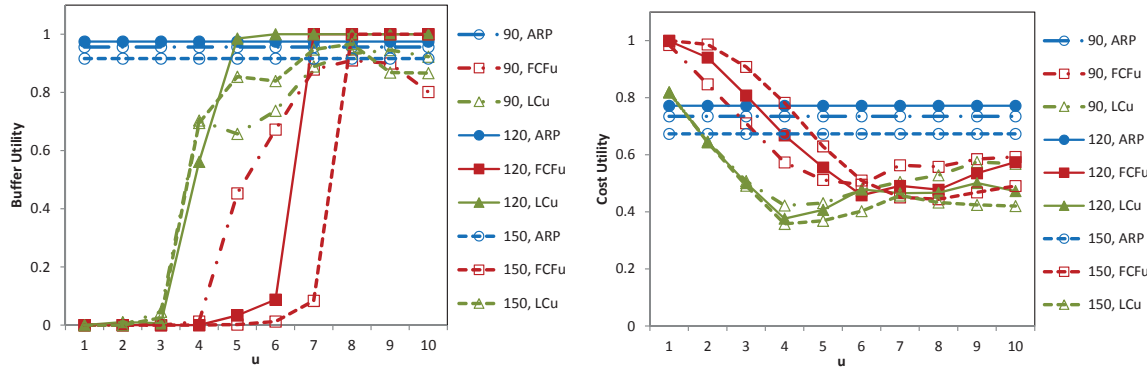


Figure 6.8 Utility under different wireless user arrival rate and purchase decision.

Table 6.1 shows the radius (km) of the possible area the wireless user will arrive with 95% probability corresponding to the standard deviation (i.e.,  $\sigma$ ) and the time intervals the wireless user considers ahead for channel purchase. Each MN only services 2.5 km area in radius, the number of MNs the wireless user will meet within next  $T$  time intervals changes from 1 to 7 relying on the [time intervals,  $\sigma$ ] pair varying from [1,0] to [10,4]. To manage mobility for supporting streaming, the wireless user considers all prospective MNs for channel purchase based on the expected buffer length, channel prices, and the mobility uncertainty (i.e.,  $\sigma$ ). For example, when wireless user purchases channels for time  $t_0 + 10$ , which is 10 time intervals ahead from now, it does not simply buy channel from the MN whose location is the closest to the predicted mean location. Due to the variance of the movement, if the wireless user only considers average movement for deciding a specific MN for channel purchase, the wireless user may face two challenges for sustaining the streaming quality. Taking purchase channels for time interval 10 (i.e., for time  $t_0 + 10$ ) as an instance : First, the channels bought for the 10th time interval ahead may not be able to provide any wireless access to the wireless user if at time  $t_0 + 10$ , the wireless user is out of the service range of the MN from which has only purchased channels. Second, the wireless user will not receive enough number of packets at time  $t_0 + 10$  for streaming even though the wireless user may get certain channels from the MN it exactly associates with before  $t_0 + 10$ . Because at each time interval the wireless user is only permitted to buy certain number of channels which generally is



(a) Buffer utility under different wireless user arrival rate and purchase decision. (b) Cost utility under different wireless user arrival rate and purchase decision.

Figure 6.9 Buffer and Cost under different wireless user arrival rate and purchase decision.

unable to transmit enough data to sustain the buffer size. Consequently, the utility may decrease due to the variance of the mobility if the wireless user does not consider channel purchase carefully.

For ease of understanding, we only show and conclude four mobility combinations under two different mean and standard deviation. Further, to emphasize the effect on mobility, the wireless user arrival is set as 30 (1/min) in order to reduce the impact on the channel competition among wireless users. The rest of setup stays the same.

Figure 6.10 illustrates the varying of utility under different  $u$  and the best threshold in accordance with  $u$ . Figure 6.11 presents the utility degradation under different purchase strategies with the increasing of CV. For every CV, only the best utility is considered for each strategy. In addition, Figure 6.12 lists the detail of  $U_C$  and  $U_B$  in all scenarios.

As shown in Figure 6.10 and 6.11, the utility decreases with the increasing of CV (i.e.,  $\sigma$ ). Although the utility of ARP decreases with the increasing of CV, it is the least sensitive to the mobility uncertainty comparing to other two strategies. Under large uncertainty (i.e., large  $\sigma$ ), as illustrated in Table 6.1, with higher probability the purchased channels many time intervals ahead may end up with being wasted because the wireless user arrive at the location at which is out of the service range of that MN. However, to sustain the streaming, the wireless user will still buy channels from all MNs within the expected arriving area. Under the condition, as present in Figure 6.12

Table 6.1 The radius (km) of wireless user expected arriving area in response to the CV and the time intervals the wireless user considers ahead for channel purchase

| time intervals \ $\sigma$ | 0 | 1   | 2   | 3   | 4   |
|---------------------------|---|-----|-----|-----|-----|
| 1                         | 0 | 0.5 | 1.0 | 1.5 | 2.0 |
| 2                         | 0 | 0.7 | 1.4 | 2.1 | 2.8 |
| 3                         | 0 | 0.9 | 1.7 | 2.6 | 3.5 |
| 4                         | 0 | 1.0 | 2.0 | 3.0 | 4.0 |
| 5                         | 0 | 1.1 | 2.2 | 3.4 | 4.5 |
| 6                         | 0 | 1.2 | 2.4 | 3.7 | 4.9 |
| 7                         | 0 | 1.3 | 2.6 | 4.0 | 5.3 |
| 8                         | 0 | 1.4 | 2.8 | 4.2 | 5.7 |
| 9                         | 0 | 1.5 | 3.0 | 4.5 | 6.0 |
| 10                        | 0 | 1.6 | 3.2 | 4.7 | 6.3 |

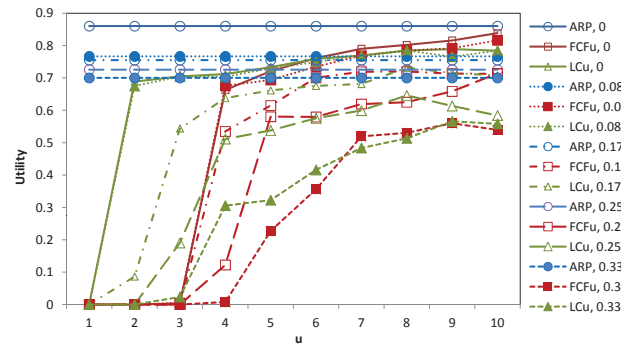


Figure 6.10 Utility under different mobility and purchase strategies.

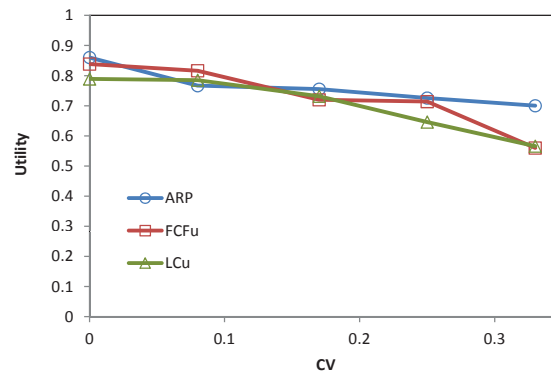


Figure 6.11 Utility of different coefficient of variation (CV).

the cost will increase in order to support streaming for higher moving standard deviation or the buffer may not have enough data for streaming due to the channel wastage. Therefore, the utility decreases. Nevertheless, overall, ARP under all cases adaptively considering the buffer size and cost for channel purchase. Furthermore, ARP carefully collects channels from each location  $\ell$ , and then even though the wireless user still waste some channels, the buffer is able to keep enough data for streaming, and the utility increases.

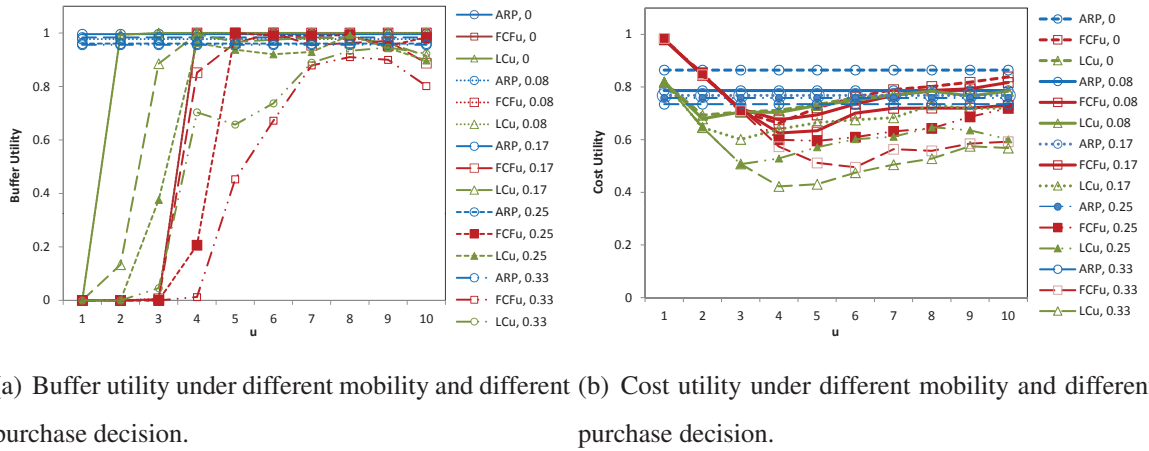


Figure 6.12 Buffer and Cost utility under different mobility and different purchase decision.

## 6.5 Conclusions

Mobility management has been known to an important issue providing seamless wireless connectivity for wireless users. With the increasing demands on high data rate and low latency real-time applications, wireless users eager to download real-time contents more efficiently aimed to sustain the quality for these applications. In this paper, ARP is proposed to promote another direction managing mobility for delivering real-time contents. Through ARP the wireless user reserves channels in advance through purchasing channels from several MNs which it may access with high probability base on its mobility pattern. Furthermore, the wireless user considers channel price as well as its buffer size making purchase decision to maximize its utility. Simulation results show the proposed ARP improves the utility by selectively buying channels in response the change of network environment and its buffer size. Specifically, the utility is improved without any specific

parameters tuning, and is less sensitive to the mobility variance comparison with other channel purchase schemes.

## Chapter 7

### Summary and Future Work

#### 7.1 Summary of Thesis Contributions

In this thesis, three challenges in ensuring the performance of each wireless user's running application are identified, namely *Mesh Network Support for Gigabit Throughput*, *Competitive Load Balancing With and Across Service Providers*, and *User-Directed Access Management*. Specifically, these applications are executed on the mobile devices and require multi-gigabit throughput to sustain the performance. To overcome the challenges, schemes are designed and developed from both the network approach and the user approach, and these schemes are *Spare-bandwidth Rate-adaptive Network Coding*, *Joint User Association and Power Adaptation*, *PriceMyRate*, and *Adaptive Rate Purchase*. These schemes build a stable framework so that multi-gigabit flows are reliably delivered from the Internet through the network to the corresponding wireless users. Moreover, the schemes can be distributed locally and incorporated with existing network stacks to seamlessly support the performance for multi-gigabit flows in the network.

The main contributions of this dissertation are:

- Reliably route TCP flows:

The proposed SRNC are the first few works that adapt the properties of network coding to improve end-to-end TCP performance in the network. With SRNC, each mesh node sends packets to the network based on the network condition (i.e., available link bandwidth). Specifically, each mesh node locally control the number of redundancy forwarding to its outgoing links to recover packet losses during transmission without any feedback messages.

The simulation shows that the mesh nodes effectively manage the packet transmission to the corresponding wireless users, and the end-to-end throughput is enhanced.

- Distributedly manage wireless coverage:

The relationship between wireless user association and mesh node power adaptation is accounted for and the network performance through the proposed Joint User Association and Power Adaptation scheme is significantly improved. In the proposed scheme, each wireless user associates with a mesh node, providing them the highest MAC layer data rate. Furthermore, The mesh nodes adjust their transmission power to maximize the network utility. Specifically, each mesh node maximizes the network utility belonging to its wireless service provider. Under this condition, even though existing mesh node deployment is not optimal for supporting different active wireless users simultaneously, the traffic load can be dynamically managed across multiple mesh nodes belonging to the same wireless service provider through the adjustment of user association and power adaptation. Simulation results illustrate the improvement of the proposed scheme.

- Dynamically allocate wireless resources:

Unlike traditional wireless service provider based resource allocation, wireless users access wireless channels through purchasing the required channels in advance. Specifically, the wireless service provider sells its owned channels to wireless users. The price of each channel is decided according to the channel demands from the wireless users, the number of available channels to be sold, and the price competition among different wireless service provider. To adaptively set the price for selling channels, PriceMyRate is proposed to maximize the revenue of the wireless service providers. With PriceMyRate, the optimal price is decided through runtime operation. The simulation results show the effectiveness of maximizing the revenue for each wireless service provider.

- Effectively maintain performance with mobility:

To sustain the streaming performance on mobile devices, each wireless user must receive enough data from the Internet. Different from traditional wireless service-based channel allocation approach, wireless users purchase channels from the target wireless service providers. Facing the change of channel price and availability, the proposed ARP scheme makes purchase decision depending on the amount of data in the buffer for streaming, the streaming rates, and the price of each sold channel. Furthermore, in response to the challenge of user mobility, in ARP, the user moving uncertainty is taken into consideration to ensure that a sufficient number of packets can be received for steaming. The evaluation results show the proposed purchase scheme maximizes utility under different network conditions without any parameters tuning/selection.

## 7.2 Future Work

### 7.2.1 Routing Digraph Selection

In Chapter 3 it is showed that SRNC requires digraph for multiroute transmission. Disjoint multipath routing can provide multiroute diversity for packet transmission, and the routing paths can be found easily. However, disjoint multipath routing fails to take the advantage of utilizing the path diversity obtained by packet re-encoding at the intermediate nodes. Consequently, the improvement of packet losses probability is limited which in turn limits the end-to-end throughput enhancement.

Furthermore, in a mesh network, a gateway forwards packets to more than one egress nodes, and each egress node decodes network coding packets belonging to its network coding group. Moreover, multiple gateways exist in the mesh network at the same time, and each gateway network encodes packets based on the corresponding destinations. Therefore, with SRNC, multiple digraph routing topologies coexist in the network, and different encoding groups share the link bandwidth for packet transmission. In SRNC, each link bandwidth is fairly shared by different network encoding groups forwarded through that link. However, if a single link shared by too

many traffic flows, packet congestion will occur on that link, and then the performance of the traffic flows sent through that link degrades.

Hence, it is necessary to design a mechanism to create the routing diagraph efficiently. Further, in the presence of multiple diagraph exists in the network, the bandwidth need to be further partitioned properly. In response to the dynamic change of traffic loads, the diagraph needs to be further maintained adaptively and distributed aiming to efficiently make use of SRNC for multi-gigabit communication.

### **7.2.2 Last Hop Resource Allocation**

Many PHY layer technologies are developed to utilize the network resources to increase the link capacity, such as MIMO, advanced encoding/decoding schemes, etc. Furthermore, in the presence of CR, link capacity can be increased substantially through accessing the free spectrum for wireless communication. However, to dynamically sense and access free spectrum still requires certain investigations. With the presence of CR, each secondary user requires an integrated framework to detect the available spectrum, to predict the availability of borrowed spectrum, to select an appropriate transmission power level, and to efficiently route packets for providing higher data rate for packet transmission. In this thesis, the scheme for power control and reliable packet forwarding in a systematic viewpoint are addressed. To further improve the network performance, support of intelligently sending and estimating free spectrum is needed.

In addition to CR, existing resource management approaches, power adaptation, channel access, node placement, etc., are proposed in order to provide better network performance for wireless users through appropriate resource allocation at the last hope communication (i.e., the communication between a wireless user and its associated access point). Moreover, within a network, multiple devices compete with limited resources for packet transmission, and the resource require to be properly allocated. Among existing resource management approaches, power adaption, channel access, node placement, etc. are considered to fully utilize the network resources.

Furthermore, the number of different communication systems (e.g., 3G, WLAN) are deployed within the same geographic area increased greatly within five years. Such heterogeneous networks results in interference or performance degradation when the network resources are improperly allocated. In addition, due to the dynamic change of network condition, coordinating with multiple communication networks would improve network performance through adaptively balancing traffic loads or utilizing the resources from different network systems. As a consequence, managing last hop communication requires investigation of the characteristics of each communication system, and utilization of the properties and advantages of all systems to maximize the network performance.

### **7.2.3 New Transport Layer Protocol Design**

Today, the real-time transport protocol (RTP) is standardized for delivering audio and video packets aimed to guarantee the streaming QoS (i.e., high throughput, low packet loss rate and low packet delay). RTP is usually implemented on top of UDP, which sends packets as fast as possible, but does not guarantee the success of packet transmission. Therefore, although packets can be sent to the corresponding destination as fast as possible, when the network has high packet loss probability, the performance of the streaming would be degraded. Different from UDP, RTP is also implemented on top of TCP, which ensures the packet delivery, but TCP sends packets to the network in a more conservative way when packet loss occurs. As a result, even though wireless users ultimately receive every transmitted packet, the average packet delay would be high when packet loss, packet re-ordering, or packet error happens which in turn reduces packet transmission rate of the packet sender.

The demand of real-time content delivery grows dramatically, and the importance of providing QoS guarantee for such applications also increases. To efficiently maintain the performance for such real-time traffic flows, the characteristics of such bandwidth intensiveness and low latency traffic flows need to be well investigated. Furthermore, in addition to TCP and UDP, a new transport layer protocol should be designed and developed for better fitting the property of real-time streaming.

### 7.2.4 Apply Redundancy Elimination to the Proposed Framework

Redundancy elimination (RE) is applied to network content delivery, aiming to increase link bandwidth through removing duplicated contents of each packet. Under this condition, the network will have additional bandwidth for supporting more traffic flows without resulting in packet congestions. Moreover, RE shrinks packet size by removing duplicated contents, and with the same data link rate, the packet delay would be reduced if no extra flows are sent through the same link.

Further, with the assistance of CR, spectrum can be effectively utilized for packet transmission. Moreover, in the gigamesh, by combining different resource allocation approaches, the network performance is improved. However, the available network resources are still limited. When more and more traffic flows with large data rate are sent from the network to the gigamesh, congestion will occur, and the end-to-end throughput may still be limited after fully utilizing available resources through all kinds of resource management and allocation frameworks. If RE can be applied and integrated to our proposed framework properly, the link bandwidth may be increased to better support traffic flows through effectively eliminating redundancy during packet transmission. Therefore, the gigamesh may provide higher performance for long-lived multi-gigabit flows.

### 7.2.5 High Throughput Testbed Implementation

Network coding, as described above, will be used to approach the goal of this thesis, supporting packet transmission for multi-gigabit flows. To ensure that the network coding operation is not the bottleneck supporting multi-gigabit throughput transmission in the network, hardware implementation is required since hardware is known to process operations with much higher speed than software operation can achieve.

Future work would investigate all the parameters affecting the network encoding and decoding performance on NetFPGA, a line-rate, flexible, and open platform that has been used by many researchers to verify their methods and incorporate with different existing platforms. To that end, a prototype of SRNC on NetFPGA will be built and deployed at a network testbed to evaluate the performance of supporting multi-gigabit throughput.

Furthermore, it is expected that all mesh nodes will also be equipped with the pricing-based resource allocation functionalities. Then, the real implementation issues (e.g., latency of resource purchase and access) can be addressed and the performance for different real-time applications (i.e., QoS constraints) can be evaluated. Last but not the least, the effectiveness of resource re-allocation through user association and power adaptation is worth exploring in the experimental testbed, too. Through the investigation of each scheme deployed in the experimental testbed, the whole framework in support multi-gigabit flows can be more stably integrated with existing network stack so that wireless users could seamlessly obtain high performance of real-time content delivery in the future.

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