Investigating Topology Control and Cognitive Radios to Exploit Television Whitespace in Building Sparse Broadband Networks

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Abstract

Described in this paper is my proposed Ph.D. thesis research which is to investigate the use of television whitespace (TVWS) to build sparse broadband networks. In order to overcome topographical, environmental, and power issues the approach I propose is to use a topology control solution that uses TVWS to connect smaller, localized networks. These smaller local networks are traditional wireless networks that have been augmented with a set of cognitive radios that can route traffic between the local wireless network and the topology control network. Additionally, I propose to investigate the dynamic, periodic election of these gateway nodes to ensure robust connectivity; one approach I propose to investigate for the dynamic election of gateway nodes is using Game Theory. This paper includes a discussion of the background relevant to the proposed topic including wireless technology - including recently available whitespace frequencies, rural broadband issues and solutions, topographical and weather issues that arise. This paper also includes a presentation of the progress made to this point and proposes a plan for future research.

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Chapter 1

Introduction

Broadband internet connectivity has become an assumed resource in most of the first world, in second world nations most of the population has broadband access through modern cellular networks. One of the largest factors that affect the quality and coverage of robust broadband infrastructure is population density. This is drives the investment in expensive terrestrial broadband infrastructure. Further exacerbating the deployment of this infrastructure, if remote users are not only in sparsely populated areas, but in areas where terrain and weather drive the need for more dense infrastructure the deployment and maintenance costs increase. These regions of highly varying terrain with low population densities can be found all over the world.

Residents of these areas typically do not have access to broadband internet; if they do, it's a costly service that is unfortunately unaffordable for many with a fairly low performance. Examples include WildBlue [1] and HughesNet [2] satellite internet which cost approximately $80 per month or $960 per year and provide bandwidths of approximately 1-2Mbps down and 200-400kbps up, which is not classified as broadband according to the Federal Communications Commission [3]. Historically, when there has been no commercial opportunity for technology deployment and maintenance, one of two solutions - or a combination of both - have been used to solve the problem: the rural cooperative model or the stimulation of commercial interest through federal funding.

Wireless networking provides a strong basic solution to the problem of providing broadband to citizens located where there is insufficient cost justification for wired infrastructure. However, the same cost problem exists for the commercial wireless broadband market because that infrastructure involves the same high cost infrastructure requiring a high population density to justify the cost. Wireless towers can cost in excess of $1M, which necessitates that they are deployed in areas where there are enough subscribers to justify the cost. Expensive infrastructure, either terrestrial (Fiber, Co-location spaces) and wireless require a significant investment and therefore a minimum population density to make them commercially viable, therefore they are not present in areas with a population density below that threshold.

How then can a society move towards a digitally engaged citizenry when as much as 20% of the populace has no broadband access? There are two solutions: rely on the commercial market, who through tax-based incentives and subsidies lower the threshold of population density and invest in the infrastructure required to reach the remaining citizens with broadband, or enable the citizens to cost-effectively provide broadband infrastructure for themselves. The latter solution has been used in rural areas for hundreds of years, it's call the cooperative. Historically, cooperatives were goods based, agriculture, crafts, or other products, but increasingly cooperatives have become organizations of scale, engaging in both the buying and selling of goods, but also services for the members of the cooperative. Electrification of rural American was accomplished through federal funding of electrical cooperatives, the same legislation that brought electricity to rural America has more recently been used to justify fiber based broadband infrastructure deployments.

1.1 Motivation

However in order to overcome the technical issues involved in the deployment and maintenance of technical infrastructure work must be done to ensure the technology is simple to setup, easy to maintain and cost effective. The market is driving the cost-effectiveness by driving down costs of wireless components and products. There are now multiple vendors providing lost cost wireless devices with high-bandwidth, a variety of frequencies, and ruggedized hardware. Some of these vendors are also providing open platforms for research and development. Tools from the vendors include more and more setup and maintenance support enabling non-technical end-users to setup, deploy and maintain a wireless infrastructure.

There is, however, still work to create robust planning tools and better architectures and algorithms to provide the most robust infrastructure possible. My ultimate goal is to build a toolkit of hardware, software, and documentation that provides everything necessary for the smallest, least technologically endowed populations to implement their own broadband infrastructure and participate in the increasingly digital world. In order to build this toolkit there are a set of fundamental technologies that must be developed. In particular, there are solutions needed to numerous hardware, software and social challenges. Fundamental research needs to be engaged that will provide robust wireless solutions, open hardware platforms upon which research can happen, and locations where test networks can be deployed and studied for long periods of time. As more and more resources are discovered and re-discovered, such as unlicensed access to TV whitespace, research needs to incorporate these resources into their proposed solutions to the problem of sparse broadband solutions. By breaking this problem down into a well structured set of parameters, I hope to develop a highly robust set of algorithms and resources that can be used to solve the larger problem of broadband for rural regions.

I propose to investigates three specific areas that can improve existing and future wireless infrastructure in rural and/or sparsely populated regions with highly varying topography: extending existing beam scheduling, beam selection, and routing/channel selection simulations to three dimensions and include TV white space frequencies, using a game theoretic solution to the selection of backbone gateway nodes from local wireless clouds and then simulating a sparse broadband network architecture in sparsely populated, highly varying terrain.

1.2 Contents

The sum of this proposal is organized into sections including background on wireless networking with an emphasis on sparse, highly varying terrain, a research plan, evaluation criteria and the expected contributions of this research. The background section includes an overview of relevant wireless networking fundamentals, a deep, rich literature review, and a summary of my previous work. My research plan addresses three specific sub-problems and how I plan to solve those problems, the evaluation section describes the papers, software, and simulations I propose to produce as evidence of successfully solving the three sub-problems I have chosen. Contributions are summarized in the that section including the papers, software, documentation, and implementation of a solution that I propose.

Chapter 2

Background

Rural broadband connectivity continues to be a challenge even as technology continues to improve networking-related products and services. The driving factor is population density, which relates directly to the recovery of infrastructure costs. In areas of low population density there are not enough customers to cover the necessary infrastructure that can enable cost-effective infrastructure investment. The challenges of developing rural broadband are similar to the challenges this nation faced when rural electrification was an issue. As recently as the 1930s, 90% of rural homes and farms were without electricity. After the federal government stepped in and enabled rural electric cooperatives in 1935, the installation of electrical systems spread quickly; by 1953 more than 90% of rural homes and farms had electricity.

Delivering broadband networking to sparsely populated parts of America is a continuing challenge. Terrestrial broadband, using fiber or copper networking, requires the same investment in rural areas as in sub-urban and urban areas. However, in rural areas there are many fewer customers to share the cost of the infrastructure which makes the cost per customer of the infrastructure unattractive to commercial providers. This has left many rural residents with few options for internet access; often only two alternatives existsatellite internet or cellular broadband.

The federal government and several non-governmental research and public policy organizations have conducted in-depth examinations of the extent of broadband infrastructure in the US, and the results all point to the same conclusions: a significant gap remains between the availability of high-speed internet services in rural areas relative to metropolitan and suburban areas [4–6]. These reports further identify major differences in the typical speeds of networks in rural areas relative to metro area networks, and that rural users are paying higher prices for lower quality services. While some argue that the demographics of rural areas do not generate the demand for broadband network investment, the evidence has repeatedly shown that the availability of broadband infrastructure leads to economic growth, higher quality education and healthcare services, and more citizen engagement in community, state and federal services.

There are essentially three tiers of internet access: 1) locations with broadband (cable-modem and/or digital subscriber line) internet, 2) locations with satellite and/or cellular broadband, and 3) areas where no service of any kind is available. Cable-modem and DSL customers are privileged to have significantly higher bandwidths than satellite and cellular customers, and they also benefit from significantly lower costs. Satellite and cellular broadband are differentiable from cable-modem or digital subscriber lines (DSL) because they have bandwidth limits. The bandwidth limits throttle the network connection or charge additional fees, after a certain amount of bandwidth is used.

Satellite and cellular broadband are not equivalent to options like cable-modem and digital subscriber lines (DSL) available in densely populated areas. While satellite and cellular solutions can provide relatively high throughput, they do not provide low latency, and cost significantly more than cable-modem and DSL. Satellite and cellular solutions often have bandwidth usage policies that are enforced by limiting or disabling the internet connection or charge significant fees for additional usage. While these bandwidth pricing models make sense in order for the providers to maintain competitiveness and still provide internet access to rural areas, there are better and more cost-effective models that dont suffer from the same constraints.

Because rural broadband can be enabled using wireless technology, it is possible to build the necessary infrastructure with significantly reduced costs; there are no long-haul networking connections to put in place. All wireless networking requires is wireless nodes deployed in proximity of other wireless nodes and electricity to each wireless node [7, 8]. Wireless internet service providers (WISPS) are already providing access to many communities, but their reach is limited by what is economically viable for their business. Technology cooperatives can fill the gap. Technology cooperatives, like rural electrical cooperatives, can operate without the same profit constraints as other providers and deploy a wireless network solution by sharing the cost among the members.

With the recent conversion of television from analog to digital transmission, an additional portion of radio spectrum has been made available to unlicensed wireless use. The availability of more radio spectrum and the potential to use lower frequencies via the TV white spaces initiative than are currently used by WiFi networks (e.g., 2.4 GHz) offers enormous potential for rural area networks. Radio signal range D is governed by a frequency-dependent power law relationship. In areas where there is a clear, line of sight path, where f is the frequency, and in areas where he antenna hight is low or where there are significant obstructions, the range is considerably less. Furthermore, lower frequency radio signals propagate around obstructions, whereas the higher frequency signals are blocked. Hence the use of TV white space spectrum at 500 MHz could lead to an extension in range by a factor of 25 or more relative to one that operates in the current 2.4 GHz band used by most WiFi systems.

As an example, Montana's Gallatin County has an average population density of twenty-five people per square mile, estimated to reach approximately 45 people per square mile in 2030, according to the 2000 U.S. Census Bureau, Montana Department of Commerce, and the Gallatin County Planning Department. If a single radio, antenna and power system can be constructed for $250 and cover that same square mile, then for $10 per person per square mile startup costs, plus ongoing maintenance and service fees of approximately $5 per person per month, the entire county could provide a bare minimum of wireless broadband to everyone. Quadrupling the cost to $40 per person for startup expenses, plus $20 per month for operations would enable construction of a moderately robust system with significantly more capabilities, and the cost would still not approach the typical $250 startup, plus $75 per month costs of alternative solutions [9]. A recent examination of the life cycle costs for deploying and operating wireless fixed internet access in Gallatin county communities, in areas not covered by current wire line systems, yielded similar results [7].

There are a few challenges that inhibit the average citizen from building a wireless cloud. The choice of hardware, antennas, locations that include electricity, and the ongoing maintenance and operation of the wireless network are not effort-free using today's technology. In fact it takes expert network operators and technicians to design, install, deploy and support existing WISP installations. Fortunately, many of these questions can be simplified through robust software and testing infrastructure, enabling end users to deploy wireless with minimal effort and a high success rate.

Efforts like MIT's RoofNet [10] – which was commercialized as Meraki, Inc. [11], FreiFunk [12], Open-WRT [13], and Open-Mesh are providing hardware and software that solves many of the associated issues for high-density urban and suburban populations. Much of the existing work is focused on communities where population density is high and electricity is relatively easy to access. Ubiquiti Networks, Inc. has been incorporating these lessons into the software they use to drive the comprehensive hardware solutions they have been developing and presents a product line that is commercially available, robust, flexible, and can be extended and enhanced by our proposed work.

Some projects have been reported that address the distances typical of rural area networks. WILDNet, for example, was built by a group at the University of California, Berkeley, using conventional WiFi technology operating at 2.4GHz [14]. Their demonstration network yielded high throughput over distances of up to 50-100km, obtained by making minor adjustments to the radio system protocols. Other work, using WiMAX (IEEE 802.16d) shows comparable results [15], and this technology is now being put in place for fixed wireless access in several networks in developing countries where conventional wireline infrastructure is poor or nonexistent. These projects provide excellent solutions for point-to-point, long distance links, which could link remote areas, but they don't provide a solution for a local area network that doesn't have line of sight.

Projects in high population density areas make sense because the impact, the ratio of affected users to cost, is high; however, defining the impact with this ratio immediately defines areas of low population density as areas of low impact. Its not until this digital division produces significant enough disparity between high impact and low impact opportunities to be identified as inequitable that these definitions change. Our aim is to find an efficient, cost effective solution for areas of low population density to avoid the widening of the digital divide and enable rural communities to participate in the opportunities afforded by broadband internet access.

2.1 Wireless Networking Fundamentals

The fundamental difference is wireless and wired networking is that wireless networking uses radios to convert bits to radio frequencies instead of electrical signals conducted by wires. From an application point of view any differences in networking protocols are hidden in the operating system and driver software, presenting a uniform network interface. The radios used in wireless networking come in a variety of different configurations, supporting a growing number of different wireless networking standards. The configuration variations include radio frequency, antenna types, radio capabilities, and radio power output.

A typical wireless network consists of one or more gateways, providing access for users of the wireless network to resources outside of the wireless network, these act similarly to consumer internet routers like a cable, DSL or satellite modem. The most common consumer network connects the modem directly to a computer, but more and more consumers are inserting wireless routers into the modem providing the ability for more than one computer to share the internet connection. Similarly, in a wireless network the internet gateways are connected to a set of relay nodes that provide the core routing functionality of the network. These relay nodes track each other and reconfigure the network as needed to provide the highest performance for the users possible. The users in a wireless network are traditionally named Subscriber Nodes, since they are subscribing to wireless services where there may be multiple choices for services.

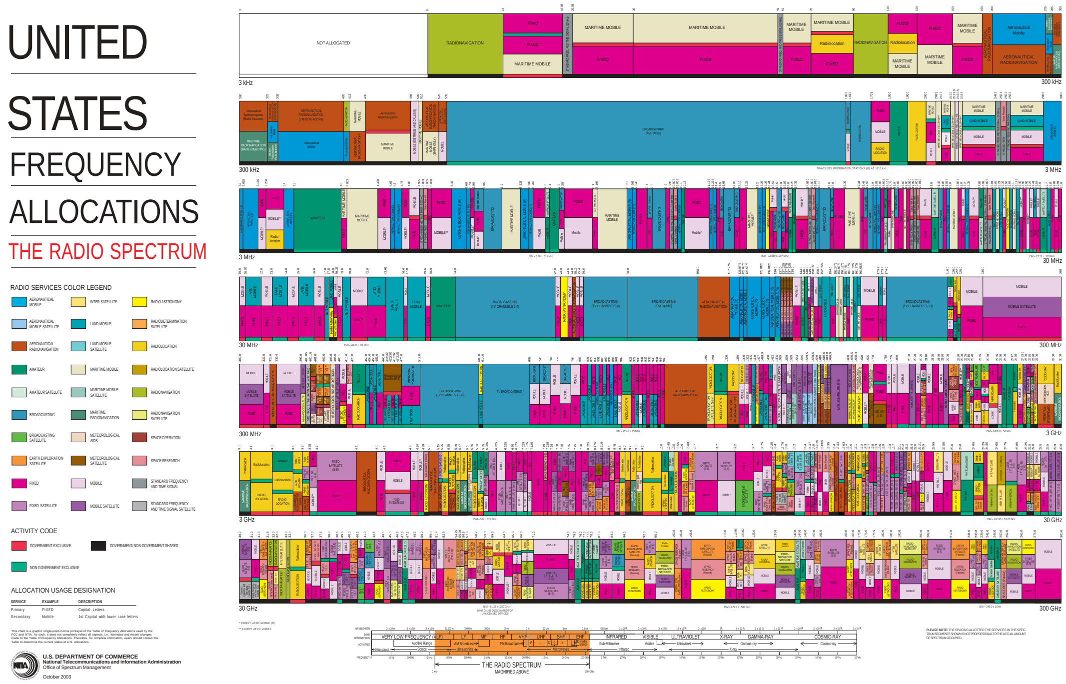
There are multiple wireless network architectures but the most common are: a tree, where the root is the internet gateway, the internal nodes are the relay nodes and the leaves are the subscribers; the mesh, where there can be one or more internet gateways, a set of relay nodes, and a set of subscribers; and a ladder, where there are two internet gateways, relay nodes configured in two parallel lines, and subscribers follow the lines. These architectures correspond to the most common functions of wireless networking: enterprise networking, cellular/sensor/environmental networking, and transportation networking.

Consumer wireless networking has been traditionally done in the 2.4GHz and 5GHz frequency space, but more recently devices using the 900MHz range have become available, offering more choice to consumers. Power output (and thus consumption) is not a typical factor for most wireless network implementations, but when installed in remote locations where power is not available it becomes a significant influence on design. Similarly, most radios have an integrated antenna, providing basic coverage for a typical usage scenario – but more and more radios are providing external antenna connectors to enable augmenting the radio with higher powered antennas to improve range and performance. Most consumer wireless products do not have advanced capabilities – like the ability to sense signals and adapt their configuration to adjust for performance – however some products have been emerging with an open software platform allowing aftermarket modification to enable these types of advanced functions.

2.2 Frequency Selection

The frequencies available for unlicensed use are a fairly small part of the overall radio spectrum, typically in the 700-900MHz, 2.4GHz, and 5.8GHz regions. These frequencies provide very different transmission characteristics with the 5.8GHz providing higher bandwidth, but at a significantly shorter distance than the 700-900MHz range. However the lower frequencies typically provide lower bandwidth, although recent developments with multiple frequency, multiple antenna, and MIMO-type radios ensure that solutions at almost any frequency provide robust, high bandwidth for the end users.

One aspect of the different frequencies are the propagation characteristics and the performance in the presence of interference (from weather, foliage, or other intermittent obstruction). The higher the frequencies, e.g. 5.8GHz, there is less penetration of solid objects and there is more sensitivity to obstructions. The lower frequency signals are able to penetrate better, go farther, and are less vulnerable to signal obstruction.



2.2.1 Whitespace Frequency Allocation

For the same reasons that 700-900MHz perform differently than the 2.4 and 5.8GHz frequencies, TV White space – which is approximately between 50MHz and 700MHz – is even more robust in terms of propagation distances and interference. As this space frees up because of the switch to digital TV signaling, proposals are emerging [16–18] to use this frequency space to provide better rural broadband. There are various discussions of the impact on wireless microphone technologies, which operate at very specific frequencies, but it's fairly obvious that there is more than enough frequency space to accommodate all of these requirements.

2.3 Radios

Radios are the electronic component that convert analog radio waves, to be transmitted or received with the antenna to meaningful data – whether that analog sounds (as in radio stations), or digital communications protocols (as in WiMAX), the radio is the interface in both directions between the antenna and the device producing or consuming the signal. There are a variety of radios, most locked to a specific frequency or range, to segment unlicensed operation of equipment. There are however multi-frequency scanning devices that allow the user to receive signals on any frequency they can tune, but because of the large differences in how the broad range of frequencies respond radio and antenna pairs are typically only able to receive (and/or transmit) on a narrow range of frequencies.

Of the factors radios contribute to the overall solution historically the only parameters were transmission power, receive gain and transmission gain. The receive and transmission gain were factors of the radio design, including internal antennas, wire paths, routing, and electrical design. The transmitter power is a regulated control that defines an optimal maximum transmission distance.

2.3.1 Cognitive Radios

Cognitive radios are a relatively recent development that augment traditional radios with the ability to scan and sense other traffic and modify their own settings to avoid congestion and interference. Because there is a limited amount of frequency space and radio transmission power is regulated cognitive radios provide the ability to enable radios to intelligently cooperate to provide as many users the opportunity to share the frequency space as possible. This technique shows significant promise both in terms of frequency resource allocation but also in dynamically responsive radios that are deployed in areas with cyclic, but constantly changing conditions that could affect resource management. Examples of situations where cognitive radios could optimize both connectivity and performance are in resource management on a daily cycle, learning when users are active and inactive and allocating resources appropriately, providing different qualities of services even though there is fixed bandwidth, and smart power management – allowing radios to go into low-performance modes during periods of low use.

2.4 Antennas

Antennas are the first and last physical component that transfers signals from the air to electrical signal. Antennas come in a variety of designs, with wildly different performance characteristics. In recent years there has been a very active "build-your-own-antenna"' community primarily building custom antennas for 2.4GHz wireless networking. However, antenna research has been pursuing various smart antennas to try and break down monolithic antennas into systems of components that can be independently controlled, configured, and used. Beam forming antennas were one of the first solutions that allowed multiple components to work in concert to produce a higher quality signal than any single component. Subsequently, there are been numerous improvements and inventions.

2.5 Power

Often electrical power is not a consideration in terrestrial wireless network solutions because electricity is so pervasive and available. However many wireless systems are primarily power management platforms – cellular phones, radios, and sensor network (both terrestrial and satellite) – therefore must manage power very carefully. The challenge of power management is the balance between using as little electrical power as possible, while maximizing transmit power to ensure communications are robust and consistent. This trade-off is exacerbated for satellite, ocean, and wireless systems that are not able to connect to the electrical grid. In these cases, the systems are very carefully designed with the power use carefully accounted for to ensure that the power supplying subsystem can last as long as necessary before regeneration or replacement.

In the context of this proposal power is not available where some wireless relays need to be located so solar and wind power generation systems are being designed to provide a low-cost, robust power generation system that can be buffered with off the shelf battery components to provide continuous power when there is no sunlight or wind.

2.6 Challenges

Sparse networks have many challenges that emerge from the low-density of nodes and large distances between them. The basic challenges in any sparse network are the same as more dense networks, connectivity, throughput, and reliability. The overlap and redundancy of nodes in a dense network provide many alternatives to solve problems of throughput and reliability and in a very dense network connectivity is dependent upon the ration of relay nodes to subscriber stations because it's assumed that 100% of the space is covered by the network. As the network density decreases the challenge of connectivity becomes more important, and as soon as the network is not covering 100% of the area of the subscriber stations then when a subscriber station moves to an uncovered area connectivity fails for that subscriber.

Sparse networks are designed differently, instead of being designed to saturate an area with wireless signals sparse networks seek to saturate only the relevant areas with signal. This choice is determined by the complexity and cost of pervasive coverage versus selective coverage. This technique of selective coverage is also used by commercial providers, because the resource allocation issue for commercial providers is also a profitability and existence issue. If commercial providers saturated the space with the necessary equipment to provide coverage, then they would have areas of high profit (where the costs are far less than the number of customers paying for service), areas where they break even (where the costs are roughly equivalent to the customers paying for service) and areas where they would lose money (where the costs are far greater than the customers paying for service).

2.6.1 Population Density

Rural broadband connectivity continues to be a challenge even as technology continues to improve networking-related products and services. The driving factor is population density, which relates directly to the recovery of infastructure costs. In areas of low population density there are not enough customers to cover the necessary infrastructure that can enable cost-effective infrastructure investment. The challenges of developing rural broadband are similar to the challenges this nation faced when rural electification was an issue. As recently as the 1930s, 90% of rural homes and farms were without electricity. After the federal government stepped in and enabled rural electric cooperatives in 1935, the installation of electrical systems spread quickly; by 1953 more than 90% of rural homes and farms had electricity.of wireless deployments.

In the Buffalo Jump Technology Cooperative, as an example, the area of the network coverage is proposed to be 20 x 5 = 100^2 miles. In this area there are approximately $2,500$ residents, $1,500$ of whom are located within 1^2 mile in Three Forks, Montana. The other $1,000$ residents are distributed non-uniformly over 99^2 miles. Assuming a simplified uniform distribution that's 10 people per square mile.

With the large distances between non-uniformly distributed residents in such a large area the challenge of designing a reliable, well connected network drives costs up significantly. But in addition to this, other issues emerge as long term challenges: maintenance of the equipment and the skills necessary to deploy and maintain the network. Unless these challenges can be mitigated, both by reducing the costs and skills required and by increasing the value of the network to residents, then there is not much utility in deploying a network that can't be maintained.

2.6.2 Topography

In addition to low population density, topography can be a major challenge in designing a sparse network. People tend to cluster around natural resources that can make wireless communications difficult, such as rivers, confluences of rivers, valleys, and areas with enough water to support large trees and vegetation. This makes it easier to establish and maintain domestic lifestyles, but it makes it more challenging to get wireless signals delivered reliably. In the case of the Buffalo Jump Technology Cooperative, the main challenges are leaf and terrain interference. The trees near peoples homes tend to scatter the point-to-point wireless signals and the sharp elevation changes create many shadow areas for the wireless signals.

The net result is that sparse networks in these areas segment naturally with terrain based boundaries, cliffs, rivers, valleys become dividers, areas of high-density and subnetworks, respectively. This natural segmentation into sub-networks or wireless clouds challenges the ongoing maintenance because sometimes it is necessary to locate network equipment in places very difficult to reach. In fact, there is one location in the Buffalo Jump Technology Cooperative that is only accessible part of the year, therefore the design of the equipment at that location has to take into account that it can't be repaired or replaced during that time.

2.6.3 Environment

Environmental factors can significantly impact wireless signal propagation. Rugged terrain that doesn't gracefully propagate signals and weather patterns that cause temperature differentials and inversions are the two primary challenges affecting sparse wireless networks. Primarily because these networks, when deployed in highly variable terrain, have network locations near the tops of ridges and mountains. There are natural weather systems that occur in the valley floors below these high places, cold air settles into the valleys and warmer air rises, causing the temperature differentials, then when sudden changes such as the sun warming the air in the valley in the morning, then inversions can occur. These affects change the signal propagation through air causing less predictable behavior and causing possible intermittent outages. Beyond the challenges of maintaining connectivity and throughput in the presence of varying environmental conditions these same conditions increase the wear and tear on the networking components causing them to have a shorter lifespan.

2.6.4 Power

Electrical power is a resource that is not pervasive in all areas; every home has electricity but in the locations where wireless network equipment might need to be deployed there is no guarantee there is electricity near-by. The cost to install electricity in new locations is prohibitive, nearly $10,000 per pole from an existing location to the desired location. Therefore, designing the network to co-locate relays and subscribers near existing electrical installations is a cost-reducing choice that also increases the likelihood that the locations have greater accessibility year-round.

In some cases equipment must be deployed in locations with out electrical power, in these cases using solar, wind, or generator supplied power systems is possible. The most efficient solution in the Buffalo Jump Technology Cooperative solar, followed by wind. There already exist many solar powered homes and devices throughout the area and it doesn't require a substantial solar cell size to efficiently charge a large capacity battery. With the relatively low power requirements for networking equipment a large capacity battery should be able to power the equipment for 5-7 days, which is usually sufficient time for recharging.

2.6.5 Cost

The issue of cost is tied directly to population density, there are no economies of scale for sparse networks, each participant needs to pay their full share of the cost of the system – some of which is exclusive to that user and some of which is shared with other users. This raises the issue of fairness and resource management. However, rural American's have a rich history solving the problem of shared costs using cooperatives. Rural cooperatives have long history of bringing together people to form groups that are beneficial to the members for economic, housing, agricultural, electrical and other reasons. Rural America and western states in particular have a long history of developing cooperatives to solve problems that are too large for individuals but not economically viable for large companies.

Rural cooperatives can address both initial and ongoing costs by have a tiered cost model where there is an initial cost to participate and an ongoing cost. The initial cost is basically the cost to extend the sparse network to the user, cover the space the user requires and stock enough hardware to be able to replace or repair the equipment in a reasonable timeframe. The ongoing costs are for internet connectivity and hardware replacement and upgrade. These costs are much lower than the initial costs and therefore some portion of the initial costs can be pro-rated and combined into the ongoing costs, as long as there are enough resources to replace or repair existing hardware and pay for internet connectivity at the gateways.

2.7 Literature Review

There is a significant amount of relevant literature on the various subtopics that I have combined into my proposed work. I have broken the work down into these subtopics and done a review of the relevant literature in each area. I begin with a review of the overall topic of rural wireless networking, because this is the umbrella under which all of the other topics fall. I follow that with a review of whitespace literature, including historic analysis of TV bandwidth and propagation data. I then review smart antennas, topology control, cognitive radios, join routing and channel selection and finally game theory in wireless networking.

2.7.1 Rural Wireless Networking

Rural wireless networking has been studied [19–21] in detail only over the last five years, and the focus of most of that research has been in three primary areas: long distance wifi links, network protocol level analysis, and end-user access systems coupled with network equipment. Lond distance wifi-based links have been studied extensively starting with [22] and [23] and more recently WiLDnet by [14], a South African deployment by [24], two deployments, one in Venezuela and one in Italy [25], and a deployment in the village of Wray [21]. Much of the work involving long distance wifi to enable internet connectivity for rural regions – mostly in underdeveloped parts of the world – is based on various analysis that have been done on the various layers of the network protocol stack including the MAC layer [14, 26–31], various multi-path routing challenges [32–35], and also radio based interference [36–40].

2.7.2 Whitespace Frequency Usage

Now that the FCC has allowed the use of specific TV whitespace [41], much work is being done to determine how to use TV whitespace for wireless networking. Whitespace research is not new, and many of the relevant sources of information are not necessarily in digital form. However there is recent literature studying the possibility of using TV whitespace for wireless networking and some of that literature both reviews the historical research and re-examines the research to produce better estimates of the bandwidths capable using modern hardware [42, 43]. Work is already being pursued in algorithms to efficiently share TV whitespace [44], although devices have not yet come out commercially. This is an area of intense research and activity.

2.7.3 Smart Antennas

The cross-layer approach has also been studied for multihop wireless networks with directional antennas. MAC protocols were in [28, 29] for 802.11-based ad-hoc networks with switched beam antennas. The authors of these papers modified the original 802.11 MAC protocol to explore the benefits of directional antennas. In [45], Sundaresan *et al.* presented a constant factor approximation algorithm for Degree-Of-Freedom (DOF) assignment and a distributed algorithm for joint DOF assignment and scheduling in ad-hoc networks with Digital Adaptive Array (DAA) antennas. A unified representation of the physical layer capabilities of different types of smart antennas, and unified medium access algorithms were presented in [30]. Another important type of smart antennas is Multiple Input Multiple Output (MIMO) antenna which is able to support multiple concurrent streams over a single link. The authors of [46] presented a centralized algorithm as well as a distributed protocol for stream control and medium access in ad-hoc networks with MIMO links. A constant factor approximation algorithm was proposed for a similar problem in [47]. In [48], Hu and Zhang devised a MIMO-based MAC protocol. They also studied its impact on routing and characterized the optimal hop distance that minimizes end-to-end delay. In [49], Bhatia and Li presented a centralized algorithm to solve the joint routing, scheduling and stream control problem subject to fairness constraints for multiple wireless networks with MIMO links.

2.7.4 Topology Control

Smart antennas have received tremendous research attentions. Topology control with directional antennas has been studied in [50–54]. In one of the first works on this topic [52], Kumar *et al.* presented a topology control approach to effectively using directional antennas with legacy MAC protocols, which uses multiple directional antennas on each node and orients them appropriately to create low interference topologies while maintaining network connectivity. They showed via empirical studies that this approach can reduce interference significantly and improve network throughput without increasing stretch factors to any appreciable extent. In [53], the authors considered the problem of power-efficient topology control with switched beam directional antennas, taking into account their non-uniform radiation pattern within the beamwidth. Two cases were considered: one where the antenna orientation is assumed given and another where the antenna orientation needs to be derived. For the first case, they presented optimal and approximation algorithms for constructing power-efficient topologies. For the second case, they proved the problem to be NP-complete and presented heuristic algorithms. In [51], Huang and Shen presented several heuristic algorithms for topology control with multibeam directional antennas, and showed that compared to the omnidirectional topology control approach, the proposed algorithms provide equivalent performance in terms of the probability distribution of the number of symmetric neighbors in their resulting topologies, but can reduce hop count, save power and provide symmetric links. The authors of [50] presented a bandwidth-guaranteed topology control algorithm for TDMA-based ad hoc networks with sectorized antennas. In a recent paper [54], the authors introduced a measurement-based optimization framework for topology control in dense 802.11 networks using sectorized antennas. They presented a distributed measurement protocol to measure the RSS of these antenna patterns and a greedy distributed topology control protocol that uses this information to achieve topologies of minimal interference. Extensive measurements showed that the protocols operate very close to optimal and yield significant increase in network throughput compared to omni-directional antennas. Topology control with omni-directional antennas have been extensively studied in the literature [55, 56].

2.7.5 Cognitive Radios

Cognitive radio networks have recently received extensive attention. Spectrum allocation and access are the most important problems in such networks. In [57], the authors derived optimal and suboptimal distributed strategies for the secondary users to decide which channels to sense and access with the objective of throughput maximization under a Partially Observable Markov Decision Process (POMDP-JRCS) framework. In [58], Zheng *et al.* developed a graph-theoretic model to characterize the spectrum access problem and devised multiple heuristic algorithms to find high throughput and fair solutions. In [44], the concept of a time-spectrum block was introduced to model spectrum reservation, and a centralized and a distributed protocol were presented to allocate such blocks for cognitive radio users. Tang *et al.* introduced a graph model to characterize the impact of interference and proposed joint scheduling and spectrum allocation algorithms for fair spectrum sharing based on it in [59]. In [60], a distributed spectrum allocation scheme based on local bargaining was presented.

2.7.6 Joint Routing and Channel Selection

Routing and channel selection have been studied for cognitive radio networks. In [61], a novel layered graph was proposed to model spectrum access opportunities, and was used to develop joint spectrum allocation and routing algorithms. In [62], the authors presented distributed algorithms for joint spectrum allocation, power control, routing and congestion control. A mixed integer non-linear programming based algorithm was presented to solve a joint spectrum allocation, scheduling and routing problem in [63]. A distributed algorithm was presented in [64] to solve a joint power control, scheduling and routing problem with the objective of maximizing data rates for a set of communication sessions.

The Spectrum Aware Mesh Routing (SAMER) [65] is a routing protocol that accounts for long term and short term spectral availability, which seeks to utilize available time-spectrum blocks by routing data traffic over paths with higher spectrum availability, without ignoring instantaneous spectral conditions. SPEctrum-Aware Routing (SPEAR) presented in [66] aimed at maximizing throughput by combining end-to-end optimization with the flexibility of link based approaches to address spectrum heterogeneity.

In [67], Hincapie *et al.* proposed a novel distributed routing protocol which can select a route and allocate channels and timeslots for a connection request to satisfy its end-to-end bandwidth requirement. The proposed protocol is based on Dynamic Source Routing (DSR) and select time-spectrum blocks for links using a novel metric to obtain high capacity and low interference blocks for links during the route discovery procedure. In [68], Mumey *et al.* considered the problem of finding a transmission schedule and a channel selection solution for a given path and presented a constant factor approximation algorithm based on graph coloring.

In addition, routing and channel selection have also been studied in the context of traditional WMNs with homogeneous channels [36,69,70]. A constant-bound approximation algorithm was proposed in [69] to jointly compute channel assignment, routing and scheduling solutions for fair rate allocation. The authors of [70] studied a similar problem and derived upper bounds on the achievable throughput using a fast primal-dual algorithm. In [36], Tang *et al.* proposed an interference-aware channel assignment algorithm along with an optimal routing scheme for end-to-end bandwidth guarantees.

2.7.7 Game Theory in Wireless Networking

The notion that all members of a wireless network must cooperate to maintain connectivity and maximize throughput and compete for the resulting throughput is what makes it a natural fit for game theoretic approaches. In fact game theory has been applied to wireless networking [71–74]. Game theory has also been applied to power management in wireless networking [75], but more frequently in routing and topology control [76–79].

2.8 Computational Complexity

In previous work described below, each of the problems is either NP-hard or solved in polynomial time. The solutions involved creating an approximation algorithm that could be proven to be correct and run in less time than the optimal solution. Thus far, I have been able to accomplish this goal, however moving forward involves increasing the dimensionality of the problems and addressing a multiphase problem where each phase is at least polynomial time for the optimal solution, if not NP-hard. The computational complexity of the problems proposed make this exciting and interesting work, as well as contributing to the intellectual merit of the research.

Chapter 3

Current Work

3.1 In Situ Wireless Network: The Buffalo Jump Technology Cooperative

The author is a member and resident of the community and has built the prototype wireless network covering approximately 100-square miles that connects four locations. There are currently six end-users at three locations sharing a 1.5Mbps DSL line delivered through fourth location, the internet gateway located near the Three Forks Central Office. These locations are shown in Figure 1, with the wireless connections indicated by the darker blue lines in the light blue shaded area (which indicates wireless coverage of the existing network). The red shaded area shows the proposed expanded wireless coverage. This prototype has been developed over the last twenty-four months and has been in production for six months.

This prototype was privately funded by Judson so he could obtain residential access to broadband internet. During construction of the prototype Judson has made all of the necessary community contacts, negotiated appropriate access to required locations and use of the locations and spaces that support the wireless network. Through this process he has become intimately familiar with the needs of his rural community, the costs of large scale deployment, and the technical and user challenges that must be overcome to successfully deploy a RWBI. The current implementation is a set of five Ubiquiti Networks, Inc. 802.11 wireless nodes designed for Wireless Internet Service Providers (WISP's). These are augmented with high performance antenna's that enable the radios to function for 15+ miles. This configuration is done using directional antenna's as a proof of concept and the only participants of the current system are Judson and the rest of the people contributing either tower space or gateway space in Three Forks.

Judson has also established strong support among the local schools, governments and residents for this project. Nearly 75% of the people in the lower Madison Valley have been approached and all of them have expressed interest in participating. Discussions of cost and reliability have included everyone and sentiment is very positive that the community is whole-heartedly supportive of the RWBI as their internet solution.

The lessons learned from this prototype directly drive the proposed work. Our experience with the prototype wireless broadband network is that it is difficult to select the appropriate hardware, software, antennas and configuration needed to set up and deploy a wireless broadband network. There is incomplete documentation provided by a variety of sources, none of whom have tried to deploy a rural wireless broadband solution; the applicability is marginal. The hardware and software choices have become more plentiful over the duration of our prototype, making it easier to find effective technology.

The prototype coverage includes two towns, Three Forks and Willow Creek, plus another approximately 100 square miles of rural land including Willow Creek School (K-12), Three Forks Schools (K-12); Three Rivers Clinic; Three Forks Public Library; Headwaters History Museum and many ranches, businesses and homes. Outside a two mile radius of the telephone central offices there are only tier-two broadband solutions (satellite and cellular), which are too expensive for many of the residents$75-$100 per month.

This work is complemented by the expertise and experience provided by advisors Mumey and Wolff. Wolff has extensive experience in wireless technology application for rural areas including point-to-multipoint networks, multi-hop, or relay networks, and the use of emerging technologies such as WiMAX radio and

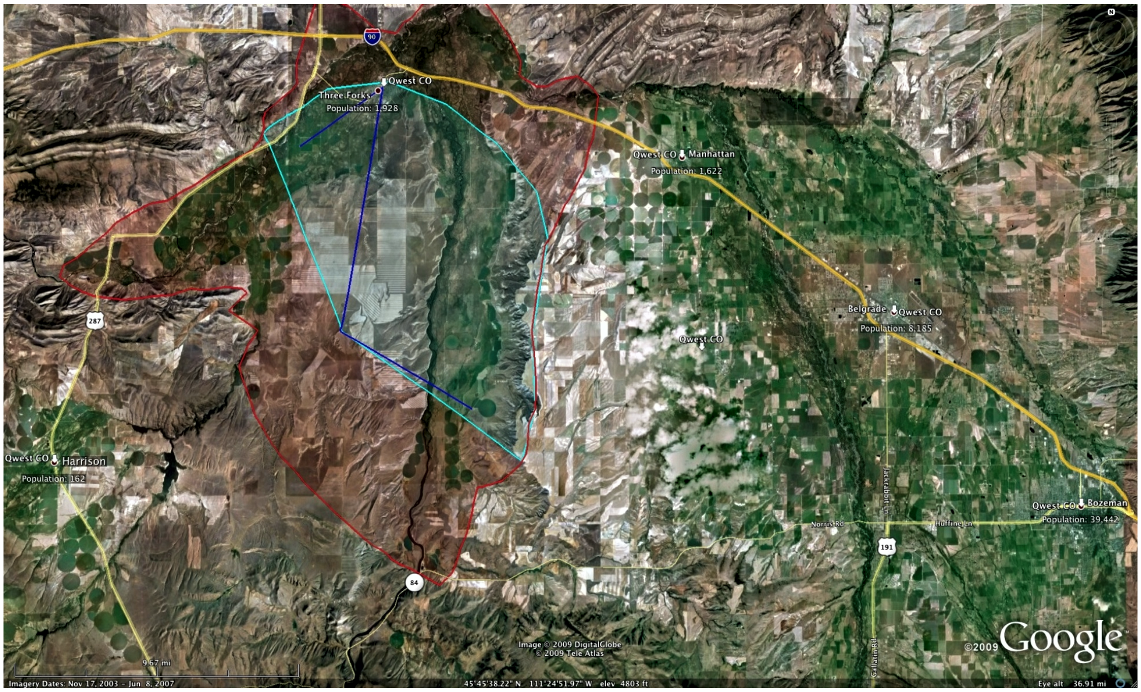


Figure 3.1: Rural Wireless Broadband Infrastructure; the prototype is shown in the light blue shaded area, with existing links in darker blue. The proposed expansion is shown by the red shaded region.

smart, adaptive antennas [33]. Wolff has also examined the costs and practicality of rural area wireless networks, using Gallatin County MT as an example [31, 34]. His examinations of internet usage and availability in different parts of Montana highlight the disparities between metro and rural communities and complement the work by Judson.

This project creates a sustainable, reproducible economic model for rural communities to provide themselves with broadband internet connectivity. Through the process of finishing the implementation of the RBWI prototype network in the Three Forks area, the project will lead to the following outcomes.

Complete the construction of the existing rural wireless broadband infrastructure. Create a rural technology cooperative to expand the impact of the rural wireless broadband infrastructure through greater participation. Collect sufficient data to get an accurate assessment of the planning, installation, deployment, maintenance and growth costs. Create documentation about building rural wireless broadband infrastructure for use by other communities. Provide education and training to any Montana communities attempting to implement a rural wireless broadband infrastructure.

3.2 Topology Control in Multihop Wireless Networks with Multibeam Smart Antennas

Compared to a conventional omni-directional antenna, which wastes most of its energy in directions where there is no intended receiver, a smart (directional) antenna offers a longer transmission range and lower power consumption by forming one or multiple beams only toward intended receivers. This paper was co-authored with Drs. Mumey and Tang and Yun Xing, it was submitted to IEEE GlobeCom 2011, but was rejected. It has been revised and resubmitted to the IEEE International Conference on Computing, Networking and Communications 2012.

There are primarily two approaches to exploit the benefits of smart antennas for mesh networking: the cross-layer approach [46] and the topology control approach [52]. With the cross-layer approach, a joint antenna pattern assignment and scheduling solution is provided to switch beams to communicate to different neighbors at a fast time scale (e.g., on a per-time slot basis). However, the topology control

$$\text{SNR}_{ij} = \frac{P_t G_t^a G_r \lambda^2}{(4\pi)^2 d_{ij}^{\alpha} N_0} \tag{3.1}$$

approach pre-computes an antenna pattern for each node such that a certain network topology can be formed for future communications. Using this approach, antenna beam switching is conducted in a slower time scale (in the order of seconds or more) at the potential expense of performance. Compared to the cross-layer approach, the major advantage to using the topology control approach is that it is purely a link layer solution that does not require any modifications to a standard MAC protocol. Hence, it can be easily implemented in a system using Commercial-Off-The-Shelf (COTS) and standard protocols. The topology control approach is the focus of this paper, which may lead to performance comparable to the cross-layer approach with a carefully designed algorithm and full consideration for link capacity.

Our contributions are summarized as follows:

1) We formally define the corresponding optimization problem as the Sector Selection Problem (SSP). 2) We present a Mixed Integer Linear Programming (MILP) formulation to provide optimal solutions. 3) We present an effective Linear Programming (LP) rounding based algorithm for the SSP. 4) We present extensive simulation results to show that the proposed algorithm provides close-to-optimal performance and yields good solutions in terms of both capacity and fairness compared to alternative approaches including a Minimum Spanning Tree (MST) based algorithm and the k nearest neighbors algorithm.

3.2.1 System Model

We consider a multihop wireless network composed of n nodes. Each node v_i is equipped with an adaptive directional antenna that can form beams in any of M different sectors (see Figure 3.2). Each sector that is activated (turned on) creates a beam of width $\frac{360}{M}$ degrees.

We assume that the data rates available to a node depends on the number of sectors it has activated. Let $c_{i,j}^a \geq 0$ be the maximum data rate that can be supported by the link (v_i, v_j) assuming v_i has activated a sectors in total, including the sector in which v_j falls in. Typically, $c_{i,j}^a$ depends on the transmit power at v_i, the distance between v_i and v_j, the operating frequency, and maybe other factors. If the free space path loss model [80] is considered, then the Signal to Noise Ratio (SNR) at node v_j for a transmission over link (v_i, v_j) is where G_t^a is the transmitter gain assuming that v_i has activated exactly a sectors, G_r is the receiver antenna gain (omni-directional reception), d_{ij} is the distance between v_i and v_j, λ is the wavelength and N_0 is the background noise power. α is the path loss exponent and is usually between 2 and 4. We assume a fixed transmit power P_t, operating frequency and receiver gain G_r, so SNR_{ij} varies only with the number of sectors activated by v_i and the transmission distance.

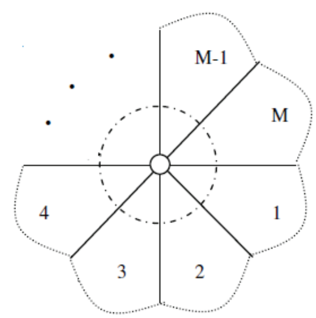


Figure 3.2: A multi-beam antenna

Practically, if a radio is capable of Adaptive Modulation and Coding (AMC), the maximum link data rate c_{ij}^a is given by a discrete step increasing function of SNR at the receiver (instead of the continuous Shannon's function). A set of SNR thresholds, and the corresponding modulation indices and maximum data rates (link capacities) specified by IEEE 802.16e [81] is given in Table 3.3, which was used for our simulations. For each $1 \leq a \leq M$, we compute the transmission range for a node using a sectors as

$$\left(\frac{P_t G_t^a G_r \lambda^2}{(4\pi)^2 \text{SNR}_{\min} N_0}\right)^{\frac{1}{\alpha}},$$

where $\text{SNR}_{\min}$ is the minimum SNR threshold.

3.2.2 Problem Formulation

We are interested in the problem of choosing which antenna sectors each node should activate. We will assume that the power available to each activated sector for transmission depends on the number of sectors activated. Thus, there is a trade-off between activating additional sectors to increase the number of directions that a node can use to reach other nodes and the transmission rates achievable to those nodes. We formally define the optimization problem as follows.

In this problem, our objective is to maximize the summation of link capacities since this summation gives the *maximum (possible) capacity* (note that the actual network capacity may depend on many other factors such as the MAC protocol). It may be argued that maximizing the total link capacity may lead to unfairness, however we will show that our SSP algorithm offers good performance in terms of both maximum capacity and fairness via simulation results.

3.2.3 Simulation Results

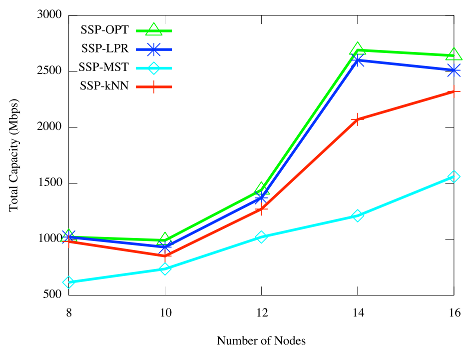


Figure 3.3: Scenario 1: The proposed algorithm VS. optimal

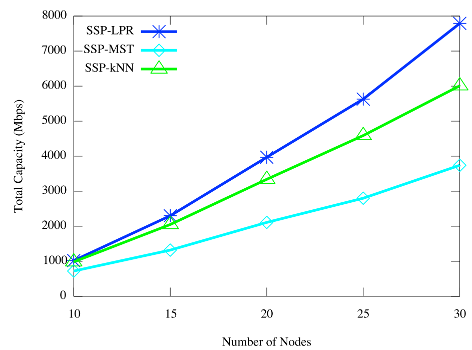


Figure 3.4: Scenario 2: Performance VS. the number of nodes in the network.

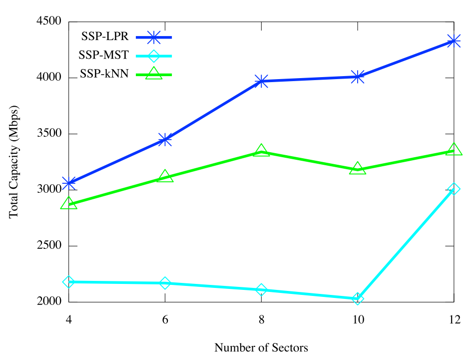


Figure 3.5: Scenario 3: Performance VS. the number of sectors in each node.

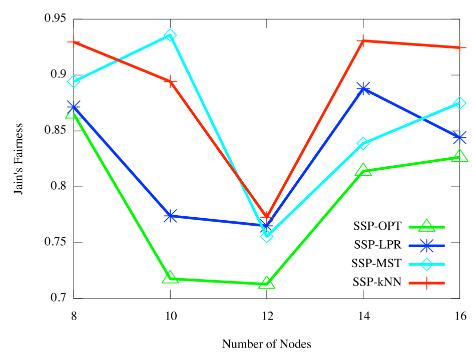


Figure 3.6: Average Jain's Fairness for each of the algorithms.

In our simulation scenarios we change either the value of n or M while keeping the other value fixed. We evaluate the performance of the proposed algorithm, i.e., the SSP-LP rounding algorithm (labeled as SSP-LPR), a Minimum Spanning Tree Approach (labeled, SSP-MST), and a K-Nearest Neighbors based algorithm (labeled as SSP-kNN) in terms of the summation of link capacities (i.e. maximum capacity) and the well-known Jain's fairness index,

$$f(r_1, r_2, \cdots, r_n) = \frac{\left(\sum_{i=1}^{n} r_i\right)^2}{n \sum_{i=1}^{n} (r_i)^2},$$

where r_i is the capacity of each edge in the network. Further we compute the fairness into and out of each node to verify the results. Jain's fairness index is the most commonly used metric for evaluating the performance of resource allocation algorithms in terms of fairness. In the first scenario, we compared the proposed algorithms against the optimal solutions given by solving the MILP in small cases. In the other scenarios, we compared the proposed algorithm in terms of both metrics on large input cases. We summarize our simulation scenarios in the following and present the corresponding simulation results in Figs. 3.3–3.5. Each number in these figures is an average over 10 runs, each with a different randomly generated network.

- Scenario 1: Change n from 8 nodes to 16 nodes with a step size of 2. Fix $M = 8$.
- Scenario 2: Change n from 10 nodes to 30 nodes with a step size of 5. Fix $M = 8$.
- Scenario 3: Change M from 4 sectors to 12 sectors with a step size of 2. Fix $n = 20$.

The following observations can be made from the simulation results:

1) From Fig. 3.3, we can see that the maximum capacity values given by the proposed algorithm closely track the optimal values. The average difference is only 3.61% for the SSP-LPR algorithm.

2) From Figs. 3.4–3.5, we see that when the number of nodes in the network varies, the SSP-LPR algorithm outperforms the SSP-MST by approximately a factor of two and it outperforms the SSP-kNN algorithm by an average of 30%. As the number of sectors per antenna is increased the SSP-LPR outperforms the SSP-MST algorithm by an average of 30% and the SSP-kNN by an average of 23%, however this performance shows increasing gains for the SSP-LPR algorithm as the number of sectors grows.

3) Although the goal of the proposed algorithm is to maximize the network capacity, maximizing capacity can lead to poor fairness. In Scenario 1, we computed the fairness of both incoming and outgoing node capacities. The average of these values for for each algorithm is shown in Fig. 3.6. All algorithms are relatively fair (fairness > 0.7), with SSP-kNN and SSP-MST providing the best average fairness.

3.2.4 Conclusions

In this paper, we have studied the topology control approach for efficient communications in wireless relay networks with smart antennas. The corresponding optimization problem was formally defined as the SSP. We first presented an MILP formulation to provide optimal solutions. Then we presented a new LP rounding algorithm. It has been shown by extensive simulation results that the proposed algorithm provides close-to-optimal performance and is superior to several alternative approaches in terms of both network capacity and fairness.

3.3 Beam Scheduling

A wireless relay network is composed of a Base Station (BS), multiple Relay Stations (RSs) and a large number of Subscriber Stations (SSs), which is illustrated in Fig. 3.7. The BS serves as a gateway connecting the network to external networks such as the Internet. A spanning tree that is rooted at the BS and connects all SSs is usually formed for routing. If an SS is out of the transmission range of the BS, it can communicate with the BS via one or multiple RSs in a multihop manner. This kind of network architecture has been adopted by emerging wireless networking standards such as IEEE 802.16j. The IEEE 802.16j [82] was proposed to extend the scope of IEEE 802.16e to support multihop relay. Compared to a single-hop wireless network in which each SS directly communicates with the BS, a relay network can significantly extend the coverage range, reduce dead spots and improve network capacity [82]. Therefore, such relay networks are considered as a promising solution to provide low-cost, high-speed and long-range wireless communications for various applications such as broadband Internet access and emergency communications. This paper is being prepared for submission to a conference, preferrably ACM Mobihoc 2012 or ACM Sigmetrics.2012.

Compared to a conventional omni-directional antenna, which wastes most of its energy in directions where there is no intended receiver, a smart (directional) antenna offers a longer transmission range and lower power consumption by forming one or multiple beams only toward intended receivers. Therefore, smart antennas can enhance the functionalities of RSs and help a wireless relay network better achieve its goal. We focus on a smart adaptive antenna whose main beam can be pointed to any direction.

There are primarily two approaches to exploit the benefits of smart antennas for mesh networking: the cross-layer approach [46] and the topology control approach [52]. With the cross-layer approach, a joint antenna pattern assignment and scheduling solution is provided to switch beams to communicate to different neighbors at a fast time scale (e.g., on a per-timeslot basis). However, the topology control approach pre-computes an antenna pattern for each node such that a certain network topology can be formed for future communications. Using this approach, antenna beam switching is conducted in a slower time scale (in the order of seconds or more) at the potential expense of performance. The cross-layer approach is the focus of this paper.

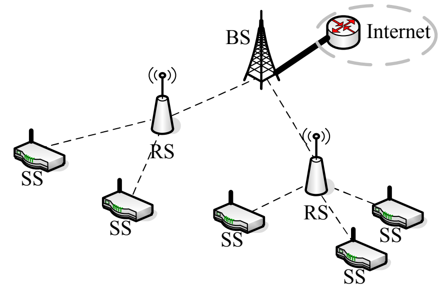


Figure 3.7: A wireless relay network

Our contributions are summarized as follows:

1) We formally define the corresponding optimization problem as the Beam Selection Problem (BSchP). 2) We present a Mixed Integer Linear Programming (MILP) formulation to provide optimal solutions. 3) We present two greedy algorithms for the BSchP and show that one has a constant approximation ratio. 4) We present extensive simulation results to show that the proposed algorithms provide close-to-optimal performance.

To the best of our knowledge, we are the first to present a provably good algorithm for this resource allocation problem in wireless relay networks with smart antennas.

We summarize the differences between our work and related works as follows: 1) Topology control with directional antennas and that with omni-directional antennas [55, 56] are significantly different due to directional beam patterns. 2) Generally, topology control with directional antenna problems are NP-hard. Most of the related works present heuristic algorithms [50–54], that cannot provide any performance guarantees. Our work, however, presents a constant factor approximation algorithm. 3) Most of previous research on directional antennas focused on switched beam (sectorized) antennas [28, 29, 50, 52–54], which can only form main beams towards a few pre-defined directions. However, we consider smart adaptive antennas whose main beams can be pointed to any direction, which makes the corresponding topology control problems much harder. 4) We focus on the topology control approach for communications with directional antennas, which is quite different from the cross-layer approach [28–30, 45–49].

3.3.1 System Model

We consider a 2-hop wireless relay network with a BS, m RSs $\{R_1, \ldots, R_m\}$ and n SSs $\{M_1, \ldots, M_n\}$. Each SS can communicate with the BS through an RS. The BS has an omni-directional antenna and transmits at a fixed high power level such that it can reach every RSs with a high data rate. Each RS R_i is equipped with an adaptive directional antenna that can form a main beam in any direction with a beamwidth chosen from a set of angles $\Theta = \{\theta_1 < \ldots < \theta_t\}$. We do not make any assumption on antennas at SSs, i.e., an SS can have either an omni-directional antenna or a directional antenna. Both RSs and SSs transmit at fixed power levels. For uplink communications (i.e, from an SS to an RS or from an RS to the BS), the transmitting node can simply point its main beam towards the receiving node. Hence, we focus on determining antenna orientations of RSs for downlink communications from RSs to SSs.

Let $r_{ijk} \geq 0$ be the maximum data rate that can be supported by assigning M_j to R_i and adjusting the directional antenna at R_i to cover M_j with a beam of width θ_k, i.e. the capacity of the wireless link from R_i to M_j with beamwidth θ_k. Typically, r_{ijk} depends on the transmit power at R_j, the beamwidth, the distance between M_i and R_j, the operating frequency, and maybe other factors. If the free space path loss model [80] is considered, then the Signal to Noise Ratio (SNR) at node M_j for a transmission over link (R_i, M_j) is

where G_t, G_r are the transmitter and receiver antenna gains, d_{ij} is the distance between R_i and M_j, λ is the wavelength and N_0 is the background noise power. α is the path loss exponent and is usually between 2 and 4. Note that since we assume a fixed transmit power, operating frequency and given beamwidth, G_t and G_r are considered as constants within a main beam. Note that the optimization schemes proposed in

$$\text{SNR}_{ij} = \frac{P_t G_t G_r \lambda^2}{(4\pi)^2 d_{ij}^{\alpha} N_0} \tag{3.2}$$

this work is independent of the propagation model. Practically, if a radio is capable of Adaptive Modulation and Coding (AMC), the maximum link data rate r_{ijk} is given by a discrete step increasing function of SNR at the receiver (instead of the continuous Shannon's function). A set of SNR thresholds, and the corresponding modulation indices and maximum data rates (link capacities) specified by IEEE 802.16e [81] is given in Table 3.3, which was used for our simulations. We can easily compute the transmission range R_i^T for RS R_i by

$$R_i^T = (\frac{P_t G_t G_r \lambda^2}{(4\pi)^2 \text{SNR}_{\min} N_0})^{\frac{1}{\alpha}},$$

where $\text{SNR}_{\min}$ is the minimum SNR threshold. The main beam of a directional antenna at RS R_i is modeled as a sector with an angle of $\theta_i \in \Theta$ and a radius of R_i^T. We summarize the major notations in Table 3.1.

Table 3.1: Major Notations

B_{ikl}	The lth beam set of R_i using beamwidth θ_k
M_j	The jth SS
r_{ijk}	The maximum data rate of link (R_i, M_j) with beamwidth θ_k
R_i	The ith RS
R_i^T	The transmission range of R_i
$\mathcal{S}_{ijk}$	The collection of beam sets of R_i of width θ_k that contain M_j
SNR_{ij}	The SNR at node M_j for transmission over link (R_i, M_j)
K_i	the number of available channels at RS R_i

3.3.2 Problem Formulation

For each RS R_i, we imagine rotating the main beam direction through 360 degrees (recall that the width of the beam is some angle $\theta_k \in \Theta$ degrees). As the direction changes, SSs will enter and leave the beam sector. For any fixed direction α and beamwidth θ_k there will be a set of SSs that are currently covered by the beam. We refer to this set of SSs as a *beam set* for α and θ_k. We note that there will be finite collection of distinct beams sets for all $\alpha \in [0, 360]$ degrees and $\theta_i \in \Theta$. We further assume that any beam set that is a proper subset of another is removed from the collection. Let these *beam sets* be $\mathcal{B}_{ik} = \{B_{ik1}, B_{ik2}, \ldots, B_{ikn_{ik}}\}$. For each mobile station M_j, let $\mathcal{S}_{ijk}$ be the collection of beam sets for R_i with angle θ_k that contain M_j, i.e. $\mathcal{S}_{ijk} = \{B_{ikl} \in \mathcal{B}_{ik} : j \in B_{ikl}\}$. Even thought the main beam of a directional antenna can be pointed in any direction, as explained above, we only need to consider a finite number of directions in terms of coverage for SSs. We are interested in the problem of choosing the beam orientations of each relay station as well as which relay station should serve each mobile station in each timeslot. Beam orientation is equivalent to the problem of selecting a beam set for each RS since once a beam set is chosen, the RS can point its main beam towards any direction whose corresponding sector can cover all the SSs belonging to that beam set. In addition, once a beam set is selected for each RS, every SS will know which RSs can cover it and it will be assigned to the one which can provide the highest data rate. We are interested in the problem of creating a beam set schedule for each relay in order to best serve the mobile stations; we assume that at each timeslot, a relay is able to select one of its beam sets to be active in that time slot. Following [83], we assume that each mobile station M_j has a capacity demand represented as a queue length q_j. We formally define the optimization problem as follows.

Definition 1 (BSchP)**.** *Given the queue lengths q_j for each M_j, the* **Beam Scheduling Problem (BSchP)** *is to select a beamwidth θ_{k_i} and beam set B_{i,k_i,n_i} for each RS to use in the current timeslot such that the utility function $\sum_j q_j \min(q_j, \max_{\{i: j \in B_{i,k_i,n_i}\}} r_{ijk_i})$ is maximized.*

It is known that if a scheduling algorithm can maximize the above objective in each frame or timeslot, then it can keep the system stable, i.e., keep the length of each queue finite [83]. As mentioned before, such a stable scheduling algorithm is also considered to achieve 100% throughput [84].

MILP Formulation

In this section, we present an MILP formulation for the BSchP, which can be used to provide optimal solutions and is also the basis for our LP rounding algorithm. We define the following decision variables:

- $x_{ijk} = \begin{cases} 1 & \text{if } M_j \text{ is assigned to } R_i \text{ and } R_i \text{ uses beamwidth } \theta_k \\ 0 & \text{otherwise.} \end{cases}$
- $s_{ikl} = \begin{cases} 1 & \text{if } R_i \text{ uses beam set } B_{ikl} \\ 0 & \text{otherwise.} \end{cases}$
- $y_j \geq 0$: the useful capacity supplied to M_j.

MILP: BSchP

$$\max \sum_j q_j y_j \tag{3.3}$$

Subject to:

$$y_j \leq q_j, \quad j \in [1, n] \tag{3.4}$$

$$y_j \leq \sum_{i,k} r_{ijk} x_{ijk}, \quad j \in [1, n] \tag{3.5}$$

$$\sum_{i,k} x_{ijk} \leq 1, \quad j \in [1, n] \tag{3.6}$$

$$\sum_{k,l} s_{ikl} = 1, \quad i \in [1, m] \tag{3.7}$$

$$\sum_{l \in \mathcal{S}_{ijk}} s_{ikl} \geq x_{ijk}, \quad i \in [1, m], j \in [1, n], k \in [1, t] \tag{3.8}$$

$$\sum_{j,k} x_{ijk} \leq K_i, \quad i \in [1, m] \tag{3.9}$$

In this formulation, constraint (3.6) ensures that each mobile station M_j is assigned to at most one relay station $R_i j$ and beam angle θ_k. Constraint (3.7) ensures that each relay station R_i selects exactly one beam angle θ_k and beam set B_{ikl}. Constraint (3.8) ensures that if M_j is assigned to R_i with beam angle θ_k, then R_i must choose a beam set from $\mathcal{S}_{ijk}$. Constraint (3.9) ensures that each relay station R_i serves at most K_i subscriber stations (using its available independent channels).

3.3.3 Proposed Algorithms

We present two algorithms to solve the BSchP. Both are based on greedy strategies. The first algorithm has a constant factor approximation guarantee and the second is shown to be somewhat more effective in practice.

The First Greedy Algorithm

The idea of the *BSchP-Greedy1* algorithm is to first get a tentative assignment of subscriber stations to relays and then use that assignment to guide choosing a beam set of reach relay to use. Steps 1 and 2 of the algorithm assigns subscribers to relays optimistically assuming that any subscriber M_j can communicate with any relay R_i using the best narrow-beam transmission rate available r_{ij1}. Thus, beam directions are ignored for the time being. This simplifies the problem to a form of the *generalized assignment problem (GAP)*; this problem considers that there are some number of activities (subscriber stations) and agents (relay stations) with various capabilities. Assigning an activity to an agent provides some value (v^r_{ij1}) and requires some cost (1). The objective is to assign activities to agents to maximize total value with agents constrained to given budgets (the available channels K_i at relay R_i). Once this tentative subscriber assignment is found, each relay choses a beam set that maximizes its reward given this assignment (Step 3). Any remaining unassigned subscriber stations are then assigned to relays if possible (Step 4).

The Second Greedy Algorithm

The second greedy algorithm is a variation on the first. The main difference is that beam set selection and subscriber assignment is done jointly. This is done in Step 2 of the algorithm, which loops through all the relays and for each, chooses the best beam set to use given the previously made subscriber assignments. Once a beam set is chose for a relay R_i then up to K_i subscribers are assigned to that relay and the loop continues.

3.3.4 Simulation Results

In this section, we present simulation results to show the performance of the proposed algorithms. The ILOG CPLEX [85] optimization software was used to solve all the MILP and LP problems. In the simulation, n SSs were randomly deployed within a square $l \times l$ km region, with a single BS placed at the center of the square. Then, m RSs were deployed radially from the center of the region with uniform angular spacing and random radii between zero and the maximum distance. In the simulation, we calculated SNRs using the free space path loss model [80] as described in Section 3.3.1. The transmitter antenna gain of each node was set to $\frac{360}{\theta}G_o$, where G_o is the gain of an antenna working in the omni-directional mode. In addition, each node was assumed to be able to receive signals from all directions, i.e., the receiver antenna gain of each node was set to G_o. The values of those parameters relevant to the propagation model and other related parameters were set according to Table 3.2.

Table 3.2: Common Simulation Settings

Omni-directional antenna gain G_o	2dB;
Operating frequency	5.8GHz;
Path loss exponent	2;
Transmit power of each RS (P_t)	1W;
Noise power	-174dBm/Hz;
Channel bandwidth	10MHz;

As described before, the link capacity is given by a discrete step increasing function. A set of SNR thresholds, and the corresponding modulation indices and link capacities specified by IEEE 802.16e [81] are given in Table 3.3.

Table 3.3: SNR VS. Link Capacity

SNR Threshold (dB)	Modulation Index	Link Capacity (Mbps)
10	QPSK 1/2	10
14.5	16QAM1/2	20
17.25	16QAM 3/4	30
21.75	64QAM 2/3	40
23	64QAM 3/4	45

To simplify the scenarios, we just considered that each RS could use either the beamwidth θ or the beamwidth 2θ. In each simulations scenario, we changed the value of one parameter and fixed the values of the others. We evaluated the performance of the proposed algorithms, i.e., the LP rounding algorithm (labeled as "LP Rounding") and the greedy algorithm (labeled as "Greedy"), in terms of the total BSchP objective function, (3.3). In all scenarios, we also computed optimal solutions given by solving the MILP for the BSchP (labeled as "Optimal"). We summarize our simulation scenarios in the following and present the corresponding simulation results in Figs. 3.8–3.12. Each number in these figures is an average over 10 runs, each with a different randomly generated network.

- Scenario 1: Vary n, the number of subscribers, in the range $\{20, 30, 40, 50, 60\}$.
- Scenario 2: Vary m, the number of relay stations, in the range $\{6, 8, 10, 12, 14\}$.
- Scenario 3: Vary θ, the minimum beam angle, in the range $\{20, 30, 40, 50, 60\}$. We assume that each relay station has angles θ and 2θ available.

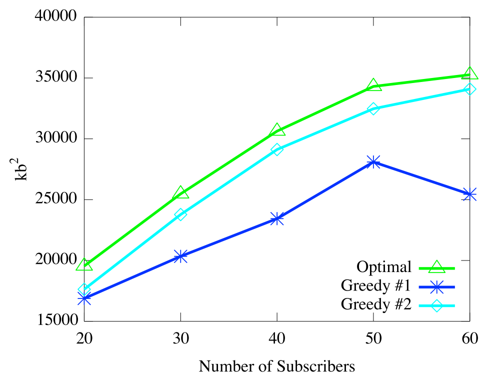


Figure 3.8: Scenario 1: Performance VS. the number of SSs (n)

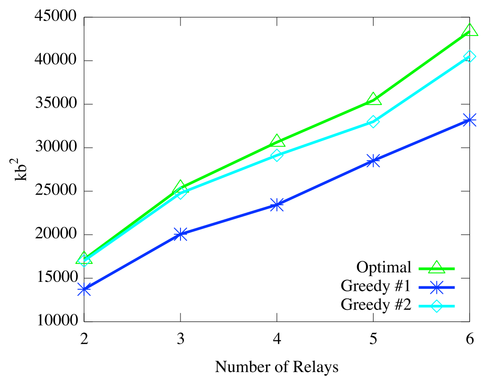


Figure 3.9: Scenario 2: Performance VS. the number of RSs (m)

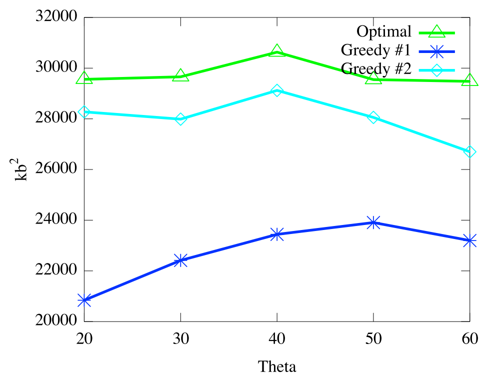


Figure 3.10: Scenario 3: Performance VS. beamwidth (θ)

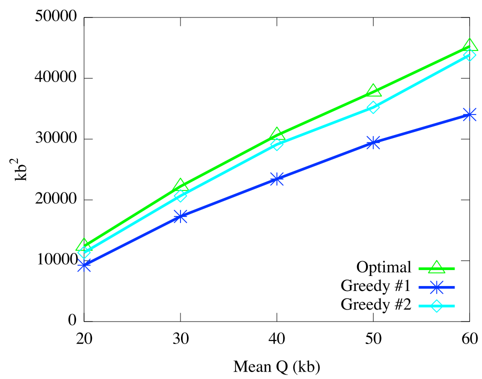


Figure 3.11: Scenario 4: Performance VS. mean queue length (μ)

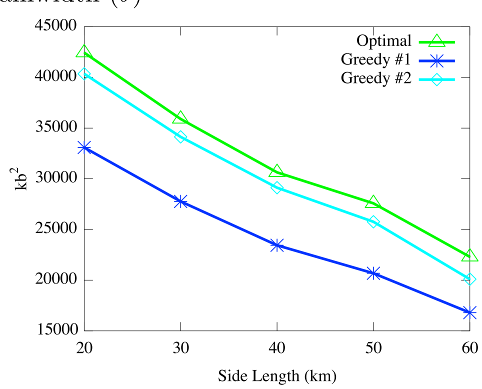


Figure 3.12: Scenario 5: Performance VS. region side length (l)

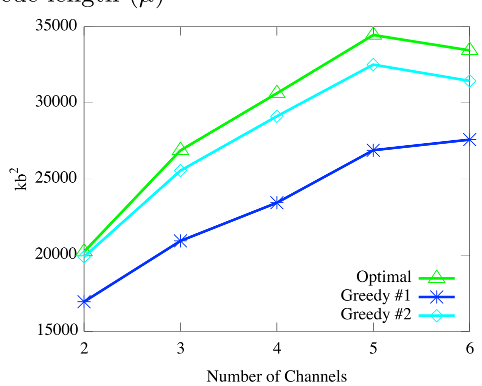


Figure 3.13: Scenario 6: Performance VS. channels per relay (K)

- Scenario 4: Vary μ, the mean subscriber queue length, in the range $\{20, 30, 40, 50, 60\}$ kb. We assume that each queue length q is drawn from the uniform distribution on $[0, 2\mu]$.
- Scenario 5: Vary l, the side length of the l by l simulation region, in the range $\{20, 30, 40, 50, 60\}$ km.
- Scenario 6: Vary K, the number of independent channels available per relay, in the range $\{2, 3, 4, 5, 6\}$.

All non-varying values were set to the median value in their respective range.

We make the following observations from simulation results, noting that overall the BSchP-Greedy2 algorithm closely tracks the optimal solution in almost all cases, while the BSchP-Greedy1 algorithm performs less well in all cases:

1) From Fig. 3.8, we see the BSchP-Greedy2 algorithm performs within 15% of the optimal solution for all cases while the BSchP-Greedy1 algorithm quickly degrades to less than 75% of the optimal.

2) Comparing Figs. 3.9, 3.11 & 3.12 vs. Figs. 3.8, 3.10 & 3.13 we see that the performance of the the proposed algorithms, specifically BSchP-Greedy1 is significantly impacted by the number of subscribers, width of the beam, and number of channels whereas BSchP-Greedy2 is affected the greatest by the width of the beam, making it much more robust.

3) From Fig. 3.12 & 3.13 we see that as the region size increases and the number of channels increases beyond 5 the effectiveness of beam scheduling is reduced reinforcing the fact that beam scheduling is most effective for denser networks with a limited number of channels.

3.3.5 Conclusions

In this paper, we have studied the beam scheduling problem for efficient communications in wireless relay networks with smart antennas. The corresponding optimization problem was formally defined as the BSchP and was shown to be NP-hard. We first presented a MILP formulation to provide optimal solutions. Then we presented two simple and fast localized greedy approachs for BSchP, one of which was shown to have an approximation ratio of $\frac{1}{2\lceil 2\pi\theta_1 \rceil}$.

It has been shown by extensive simulation results that the proposed algorithms provide performance better than 80% of optimal.

3.4 Channel Selection and Joint Routing and Channel Selection in Cognitive Radio Networks

This paper was co-authored with Drs. Mumey and Tang, and David Stearns. It has been submitted to InfoComm 2012 and is under review.

Wireless Mesh Networks (WMNs) are considered an economical method of providing robust, high-speed backbone infrastructure and broadband Internet access in large areas [86]. Mesh topology offers the advantages of alternative route selection to assure throughput and Quality of Service (QoS) requirements under dynamic load conditions. As aggregate traffic volume can be substantial on backbone links converging on gateways and mesh routers, considerations of transmission path routing and how to select channels along the path are essential to assure that a WMN can meet the QoS and throughput requirements of end-users' applications, especially real-time multimedia applications. Furthermore, range considerations and propagation characteristics demand careful attention to interference. Cognitive radios are desirable for a WMN in which a large volume of traffic is expected to be delivered since they are able to utilize available spectrum more efficiently than conventional, static channel assignment methods and therefore improve network capacity significantly [87]. However, they introduce additional complexities to resource allocation. With cognitive radios, each node can access a set of available spectrum bands which may span a wide range of frequencies. Each spectrum band may be divided into channels, and the channel bandwidths may vary from band to band. Different channels may be able to support quite different transmission ranges and data rates, both of which have a significant impact on resource allocation and interference effects. Each network link has some subset of channels available due to the activities of primary users and other traffic in the network.

In this paper, we study two hard resource allocation problems in cognitive radio mesh networks: the *Channel Selection (CS)* problem which is to choose a set of available channels on each link in a given routing path so as to maximize end-to-end throughput of the path, and the *Joint Routing and Channel Selection (JRCS)* problem where the routing path is not provided as part of the input and must be found along with a channel selection for each link on the path. We use a general and accurate approach to estimate end-to-end throughput of a path, in which channel capacities and availabilities are link specific. Our objective is to design efficient approaches to support emerging wireless applications demanding long-standing connections and high end-to-end throughput, such as real-time streaming video or bulk data transfer. This work is different from some previous works on scheduling and spectrum allocation [37, 44, 57–60] which usually dealt with the problem of scheduling and allocating channels to links for link-layer throughput maximization. Here, we focus on end-to-end performance, and consider the problem of allocating channels along a multi-hop routing path, which is a much harder problem due to the constraints related to intra-flow interference [88] (links on a common path interfere with each other if assigned the same channels) and due to the fact that in general there are an exponential number of potential paths in a mesh network connecting a pair of nodes as well as an exponential number of ways to assign channels along a path. In addition, the algorithms proposed for traditional WMNs with homogeneous channels [36,69,70] cannot be applied to solve our problems here which target at a large number of heterogeneous channels that can support different data rates and transmission ranges. In short, routing and channel selection in cognitive radio mesh networks are very challenging problems, which is why most existing works [61–67] on this topic presented heuristic algorithms that cannot provide any performance guarantees. In this work, we study the CS problem and the JRCS problem from a theoretical perspective and aim at developing theoretically well-founded and practically useful algorithms to solve them. Our major contributions are summarized as follows:

1. We present a new characterization of optimal CS solutions, which leads to an efficient dynamic programming algorithm that can optimally solve the CS problem, and if the path satisfies a certain natural *self-avoiding* criteria (defined in Section 3.4.1), in time linear in the length (hop-count) of the path. In addition, the algorithm can be easily implemented in a distributed fashion and an optimal solution can be computed in a single pass by the nodes along the path with only local information sharing.

2. We also examine the much harder problem of JRCS. We show that obtaining a $(2/3 + \epsilon)$ approximation to the JRCS problem is NP-hard for any $\epsilon > 0$, which places the JRCS problem in the complexity class of APX-hard. Despite the theoretical hardness, we present two heuristic algorithms to solve the joint problem.

3. Extensive simulation results show that the proposed joint algorithms outperform the approach using our optimal CS algorithm on shortest (minimum hop-count) paths .

The differences between this work and these related works are summarized as follows: (1) In both of our problems, the objective is to maximize end-to-end throughput, which is different from those works addressing link layer (single-hop) throughput such as [37, 44, 57–60]. (2) We obtain an optimal algorithm for the CS problem, that runs in time linear in the length of the given routing path, provided the path satisfies a natural condition. Many related works (such as [61–67]) only presented heuristic algorithms that cannot provide any performance guarantees. (3) Our optimization problems are different from those studied in [61–68]. (4) As described above, the algorithms proposed for traditional WMNs with homogeneous channels [36, 69, 70] cannot be applied to solve our problems here due to channel heterogeneity. (5) To the best of our knowledge, we are the first to establish a bound on the complexity of the JRCS problem. We show that it is NP-hard to approximate to within a factor $(2/3 + \epsilon)$ and provide effective heuristic algorithms to solve it.

3.4.1 Problem Formulation

We consider a wireless mesh backbone network $G = (V, E)$ with static mesh routers, where V is the set of nodes and E is the set of available communications links between the nodes. Each node is equipped with a cognitive radio. Similar as in [61, 63, 67], a spectrum occupancy map is assumed to be available to network nodes from a centrally-maintained spectrum database. This scenario has recently been promoted by the FCC to indicate over time and space the channel availabilities in the spectrum below 900 MHz and around 3 GHz [41]. In this case, spectrum (channel) availability between any given node pair is known. We study the problem of determining the optimal route and channel assignment for a communication session between two nodes in the network. Spectrum sensing is out of scope of this work.

We define our assumptions about the parameters of the cognitive radio network: Let m be the number of channels available in the network. In general, each link e will have only a subset of these channels available at any given time. This can be due to interference, the link distance being greater than the transmission range, or that channel being already in use on that link. We will also assume that each available channel j on link e has an associated bit rate $b_{e,j} \geq 0$. This bit rate can depend on the link distance and other factors. We assume that communication in the network is done using synchronized transmission frames. Let A_e be the set of channels available to link e during the current frame.

We adopt the following simple interference model: We assume that there is an interference distance R_j for each channel j such that a link $e = (u, v)$ *interferes* with another link $e' = (u', v')$ on channel j if and only if $|u - v'| \leq R_j$ or $|u' - v| \leq R_j$. We will also consider that the nodes in question are half-duplex. This means that nodes cannot simultaneously transmit and receive. The duplexing and interference constraints impose conditions on which link flows can be active at the same time. We will summarize these conditions in a well-known *conflict graph*, $G_c = (V_c, E_c)$, where the vertices V_c are the link-channel pairs (e, j) and the edges (undirected) indicate those link-channel pairs which cannot be simultaneously operational due to interference or duplexing constraints.

Suppose we have a routing path p from s to t and a set of active channels $J_e \subset A_e$ has been chosen to be used for each link $e \in p$. Let $G_{c,p}^{\langle J_e \rangle}$ be the conflict graph restricted to the link-channel pairs of the form (e, j) where $e \in p$ and $j \in J_e$. Let $t_{e,j}$ be the total amount of time allocated to the link-channel pair (e, j) in the transmission frame (assumed to be of length 1). Each clique C in $G_{c,p}^{\langle J_e \rangle}$ imposes the constraint

$$\sum_{(e,j) \in C} t_{e,j} \leq 1. \tag{3.10}$$

Let $m_{e,j}^{\langle J_e \rangle}$ be the size of the largest clique containing (e, j) in $G_{c,p}^{\langle J_e \rangle}$. We make a simplifying assumption that the scheduling mechanism creates a *uniform schedule* such that

$$t_{e,j} = 1/m_{e,j}^{\langle J_e \rangle}. \tag{3.11}$$

Observe that each constraint of the form (3.10) is satisfied by (3.11). We note that a uniform schedule may not be optimal but we adopt this assumption for algorithmic convenience and because it may not be possible to alter the scheduling mechanism used in a real network.

Let $G_{c,p}^j$ be the subgraph of $G_{c,p}$ consisting of the link-channel pairs that use channel j.

Definition 2. *We say that the routing path p is* **self-avoiding** *if all of the subgraphs $G_{c,p}^j$ are interval graphs such that the intervals occur in order of p.*

This means that the link-pairs in p involving channel j can be placed in order on the real number line R such that two links-pairs (e, j) and (e', j) conflict if and only if their corresponding intervals overlap. Interval graphs have a useful property that their cliques can be easily enumerated since a cliques will be represented by a set of consecutive intervals that all mutually overlap. In fact, all maximal cliques on an interval graph with n vertices can be enumerated in $O(n)$ time. We will focus on self-avoiding routing paths in this work because it is easy to find the maximal cliques in their interference graphs.

We define the *end-to-end throughput* τ of the path p and selected active channels $\langle J_e \rangle_{e \in p}$, as the minimum over all the links $e \in p$ of the effective throughput on link e. The effective throughput of an link e is sum of the bit rates on each active channel times the amount of transmission time allocated to each channel,

$$\tau(p, \langle J_e \rangle) = \min_{e \in p} \sum_{j \in J_e} b_{e,j} / m_{e,j}^{\langle J_e \rangle}. \tag{3.12}$$

We can now formalize the two computational problems considered. In addition to the source node s and destination node t, we assume the available channel sets A_e and bit rates $b_{e,j}$ are provided in the input.

Channel Selection (CS): Given a routing path p from s to t, determine active channels sets $J_e \subset A_e$ for all $e \in p$ that maximize the end-to-end throughput $\tau(p, \langle J_e \rangle)$.

Joint Routing and Channel Selection (JRCS): Find a routing path p from s to t and active channels sets $J_e \subset A_e$ for all $e \in p$ that maximizes the end-to-end throughput $\tau(p, \langle J_e \rangle)$.

Optimal Channel Selection

In this section we present an optimal algorithm for the problem of choosing the best set of channels to use for a given routing path (CS). Our proposed CS algorithm is based upon a dynamic programming approach in which the solutions to partial problems are used to assemble a solution to the full problem. To help motivate the algorithm, we provide a simple example of channel selection in Figure 3.14.

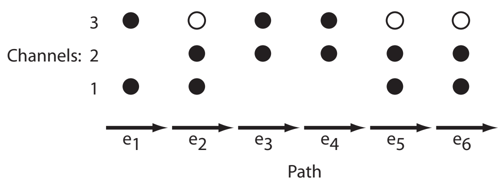


Figure 3.14: Example channel selection problem. In this example we assume that the channel availability is as shown and that each channel has a capacity of 1. We further assume that two link pairs (e_i, j) and (e_k, j) interfere if and only if $|i - k| \leq 2$. The solid circles indicate an optimal channel selection. Each selected channel participates in a clique of size 3 (due to interference and duplexing constraints). This means each selected channel provides capacity $\frac{1}{3}$ and the end-to-end capacity of the path is $\frac{2}{3}$.

Let $p = (v_0, v_1, \ldots, v_n)$ be the given routing path from the source node s to the destination node t, where $v_0 = s$ and $v_n = t$. Let $e_i = (v_{i-1}, v_i)$ be the i-th link on the path $(1 \leq i \leq n)$ and let A_i be the set of available channels on e_i. The objective is to find active channel sets $J_i \subset A_i$ for $i = 1, \ldots, n$ that maximize the end-to-end throughput $\tau(p, \langle J_i \rangle)$. For $0 < i \leq n$, we define $X_i = \{(e_i, j) | j \in A_i\}$ as the available link-pairs involving e_i. For $0 \leq l \leq n$, let $p_l = (v_0, v_1, \ldots, v_l)$ be the subpath consisting of the first l links of p. For $0 < l < n$, we define the *bridging set*,

$$B_l = \{(e_i, j), (e_{i'}, j') \mid i < l, i' > l, \\ ((e_i, j), (e_{i'}, j')) \in G_{c,p}\}. \tag{3.13}$$

We also let $B_0 = X_1$, the set of available link-channel pairs for the first link e_1 in the path. Observe that $X_{l+1} \subset B_l$ for all $0 \leq l < n$, due to the half-duplex constraint at each node. For $0 \leq l < n$, let $\langle J_i \rangle_{i=1}^{l}$ be a channel selection for the subpath p_l and let $B \subset B_l$.

Definition 3. *We say that $\langle J_i \rangle_{i=1}^{l}$ is B-**compatible**, written $\langle J_i \rangle_{i=1}^{l} \sim B$, if, for all $1 \leq i \leq l$, $(e_i, j) \in B \Rightarrow j \in J_i$ and $(e_i, j) \in B_l \setminus B \Rightarrow j \notin J_i$.*

Suppose $\langle J_i \rangle_{i=1}^{l} \sim B$. We are interested in calculating the throughput of this channel assignment for the partial path p_l. As B may contain link-channel pairs from further along in p, we will include those in the calculation, since these pairs may effect clique sizes. We will refer to this throughput as $\tau^B(p_l, \langle J_i \rangle)$. Next, let

$$\langle J_i^{l,B} \rangle_{i=1}^{l} = \underset{\langle J_i \rangle_{i=1}^{l} \sim B}{\operatorname{argmax}} \tau^B(p_l, \langle J_i \rangle),$$

be a channel selection for the subpath p_l that is B-compatible and has the maximum end-to-end throughput along the subpath p_l. The main idea of the algorithm is that the $\langle J_i^{l,B} \rangle$ can be computed by dynamic programming. In particular, suppose that the $\langle J_i^{l,B} \rangle$ are known for all $B \subset B_l$, for some $0 \leq l < n-1$. We will use these channel selections to compute the $\langle J_i^{l+1,B'} \rangle$ for all $B' \subset B_{l+1}$. Let $B' \subset B_{l+1}$ and suppose that $\langle J_i^{l+1,B'} \rangle_{i=1}^{l+1}$ be an optimal channel selection for the subpath p_{l+1} that is compatible with B'. We define

$$B_{l+1}^{prev} = B_{l+1} \cap B_l \tag{3.14}$$

and

$$B_{l+1}^{new} = B_{l+1} \setminus B_l. \tag{3.15}$$

Note that $B_{l+1} = B_{l+1}^{new} \cup B_{l+1}^{prev}$. Let

$$B = (\bigcup_{i=1}^{l+1} J_i^{l+1,B'} \cup B') \cap B_l.$$

We observe that $B \subset B_l$ and that B agrees with B' on B_{l+1}^{prev} (this means $B \cap B_{l+1}^{prev} = B' \cap B_{l+1}^{prev}$). Thus,

$$\begin{aligned}\tau^{B'}(p_l, \langle J_i^{l+1,B'} \rangle_{i=1}^{l}) &= \tau^{B}(p_l, \langle J_i^{l+1,B'} \rangle_{i=1}^{l}) \\ &\leq \tau^{B}(p_l, \langle J_i^{l,B} \rangle_{i=1}^{l}),\end{aligned} \tag{3.16}$$

since the throughput on all of the links in the subpath p_l is unchanged. We use the notation, $m_{e_{l+1},j}^{\langle J^{l+1,B'} \rangle, B'}$ to refer to the size of the largest clique containing (e_{l+1}, j) present among the link-channel pairs from $\langle J^{l+1,B'} \rangle$ and B' together. Let

$$< J^{opt} >= \langle J^{l,B} \rangle, J_{l+1}^{l+1,B'};$$

the channel assignments given by $\langle J^{l,B} \rangle$ for the subpath p_l and by $J_{l+1}^{l+1,B'}$ for link e_{l+1}. A key observation is that $m_{e_{l+1},j}^{\langle J^{l+1,B'} \rangle, B'} = m_{e_{l+1},j}^{\langle J^{opt} \rangle, B'}$ for any $(e_{l+1}, j) \in J_{l+1}^{l+1,B'}$ since both B_i and B_{i+1} will contain any link-channel pairs from p_{l+1} that conflict with it. We have,

$$\begin{aligned}&\tau^{B'}(p_{l+1}, \langle J^{l+1,B'} \rangle) \\ &\quad= \min(\tau^{B}(p_l, \langle J^{l+1,B'} \rangle_{i=1}^{l}), \\ &\qquad \sum_{j \in J_{l+1}^{l+1,B'}} b_{e_{l+1},j} / m_{e_{l+1},j}^{\langle J^{l+1,B'} \rangle, B'}) \\ &\quad\leq \min(\tau^{B}(p_l, \langle J^{l,B} \rangle_{i=1}^{l}), \\ &\qquad \sum_{j \in J_{l+1}^{l+1,B'}} b_{e_{l+1},j} / m_{e_{l+1},j}^{\langle J^{opt} \rangle, B'}) \\ &\quad= \tau^{B'}(p_{l+1}, \langle J^{opt} \rangle).\end{aligned} \tag{3.17}$$

Since $\langle J^{l+1,B'} \rangle$ was assumed optimal, we must have equality in (3.17), so we can take

$$\langle J^{l+1,B'} \rangle = \langle J^{opt} \rangle. \tag{3.18}$$

Equation (3.17) shows that the optimal channel selection for p_{l+1} and B' can be expressed in terms of an optimal channel selection for p_l and B, a smaller problem. This means that we can use dynamic programming to compute $\langle J^{l+1,B'} \rangle$. The idea is to take each $\langle J^{l,B} \rangle$ found for p_l and extend to channel assignment for p_{l+1} for all $B' \subset B_{l+1}$ such that B and B' agree on B_{l+1}^{prev}. Since B fixes which link-pairs from B_{l+1}^{prev} are included in B', we can simply enumerate all subsets $B'' \subset B_{l+1}^{new}$ and for each, form $B' = (B \cap B_{l+1}^{prev}) \cup B''$. Also, since $X_{i+1} \subset B_i$, we let B also determine all channel assignments for link e_{l+1}:

$$\langle J^{test} \rangle = \langle J^{l,B} \rangle, (B \cap X_{i+1}). \tag{3.19}$$

We then evaluate $\tau^{B'}(p_{l+1}, \langle J^{test} \rangle)$ to see if J^{test} provides a better channel assignment for p_{n+1} compatible with B'; if yes, we keep it. This evaluation is done in the same fashion as (3.17):

$$\begin{aligned}\tau^{B'}(p_{l+1}, \langle J^{test} \rangle) = \min(&\tau^{B}(p_l, \langle J^{l,B} \rangle_{i=1}^{l})), \\ &\sum_{j \in B \cap X_{i+1}} b_{e_{l+1},j} / m_{e_{l+1},j}^{\langle J^{test} \rangle, B'})\end{aligned} \tag{3.20}$$

In order to evaluate (3.20), we need to calculate the second min term since the first is already known. This is done by determining the largest clique that (e_{l+1}, j) participates in among link-channel pairs from $\langle J^{test} \rangle, B'$. If we make the assumption that the routing path p is self-avoiding, then any clique in involving (e_{l+1}, j) is either a consecutive list of link-channel pairs in $G_{c,p}^{j}$ (that all mutually overlap in the interval graph representation), or a clique involving (e_{l+1}, j) and a link-channel pair from X_l or X_{l+2} or both, using a channel other than j. Let Δ be the maximum degree of any node in any of the $G_{c,p}^{j}$ and suppose there are at most m_p channels available on any link in p. All of the clique possibilities can be checked in $O(\Delta m_p)$ time, so this is the time required to evaluate (3.20).

3.4.2 Proposed Algorithms

In this section we present two heuristic algorithms for the joint problem of routing and channel selection.

A Path Extension Algorithm

The first proposed algorithm is based on the idea of simultaneously finding good path/channel assignments from the source node s to all other nodes in the network, including the destination node t. The approach is similar to the Bellman-Ford shortest-path algorithm in that new path/channel assignments are generated by "relaxing" all the links in the network in a series of phases that continues until no better paths are discovered. Each node $u \neq s$ will store a list P_u of path/channel assignments of the form $(p_u, \langle J_e \rangle_{e \in p_u})$, where p_u is a path from s to u. When the link (u, v) is relaxed, the current path/channel assignments stored at u will be augmented by the link (u, v); for each subset $J' \subset A_{(u,v)}$ we will create a new path/channel assignment $(p'_v, \langle J_e, J' \rangle)$, where p'_v is the path p_u followed by the link (u, v). To limit the search, each node keeps a maximum of d best path/channel assignments (we chose $d = 100$). We also note that it is only necessary to augment those path/channel assignments that were created in the previous phase; we will refer to these as *new* in the algorithm. Clearly, a loop in a path can never improve the end-to-end throughput of the path, so we restrict attention to *simple* paths that never repeat a vertex. We also require that the path be self-avoiding.

Bottleneck Routing

The second approach attempts to find a single path whose links all have a high useful capacity. We make this precise as follows. We define the link capacity $c(e)$ of a link e as, $c(e) = \sum_{j \in A_e} b_{e,j}$. The link capacity provides an upper bound on the bit flow rate achievable by link e ignoring intra-path interference. In addition to link capacity, we also take into account how close the link $e = (u, v)$ to the source s and destination t. For each link $e = (u, v)$, let $d(e) = ||u-s|| + ||u-s|| + ||v-s|| + ||v-t||$. Let $d_{max} = \max_{e \in E} d(e)$ and $d_{min} = \min_{e \in E} d(e)$. An heuristic additional weighting factor on the link capacity to better estimate the *usefulness* of a link e for an s-t path. We define

$$u(e) = (1 + \frac{d_{max} - d(e)}{d_{max} - d_{min}})c(e), \quad (3.21)$$

and consider the *useful bottleneck capacity* of a path p to be

$$c(p) = \min_{e \in p} u(e).$$

Our goal is to find a path p that maximizes $c(p)$. This is a well-known problem that can be efficiently solved by computing a minimum spanning tree T on the network graph using an link weight function $w(e) = -u(e)$. The unique path in T from s to t will have maximum useful bottleneck capacity. We label this algorithm RCS-Bottleneck.

3.4.3 Simulation Results

To test our routing and channel selection algorithms we compared it against simple shortest path routing using Dijkstra's algorithm (the edge weights in this case were the physical link distances) followed by the DP-ChannelSelect algorithm to find the optimal channel selection for the shortest path. In all cases tried, the DP-ChannelSelect algorithm itself runs in under a second on a laptop computer.

For our experiments, we assumed there were three widely spaced frequency bands available for licensed and unlicensed operation and that the link throughput for each channel was the maximum available given the link distance and frequency used. The bands exhibit widely ranging propagation, transmission range and usage characteristics, highlighting the potential value of cognition in transmission scheduling. Tables 1 and 2 summarize our assumptions about the transmission rates and interference ranges of each frequency. These values are based on a scenario where each node transmits at 1W with a 2dBi antenna and the receiving antenna has a gain of 2dBi. The channel bandwidth is 10 MHz and the receiver noise figure is 5dB, and implementation losses of 3dB are assumed for each link. Path loss is calculated using line

Table 3.4: Maximum transmission distances by frequency and data rate

Transmission rate	700 Mhz	2400 Mhz	5800 Mhz
45 Mbps	15.4 km	4.5 km	1.8 km
40 Mbps	18.4 km	5.3 km	2.2 km
30 Mbps	30 km	8.6 km	3.6 km
20 Mbps	41 km	11.8 km	4.9 km
10 Mbps	68 km	20 km	8.2 km

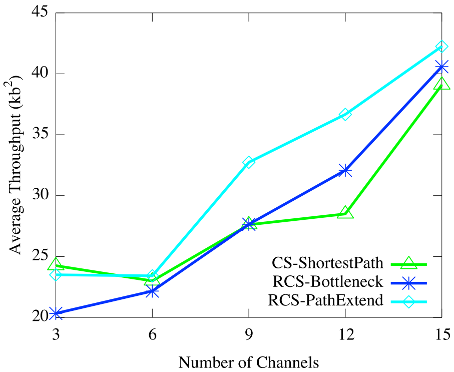


Figure 3.15: Average path end-to-end throughput versus the number of available channels.

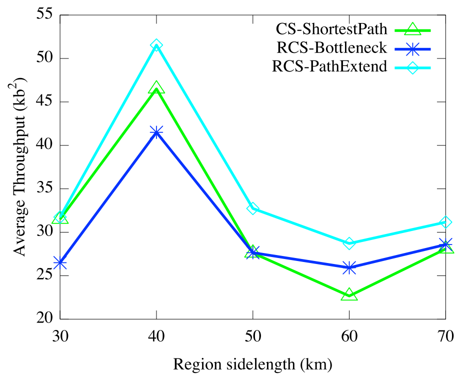


Figure 3.16: Average path end-to-end throughput versus network size. Node density was held constant at 0.01nodes/km^2.

of sight and free space characteristics. Typical IEEE 802.16 adaptive modulation and coding parameters performance parameters were used to estimate the throughput achievable as a function of CNR (carrier to noise ratio), and were then translated into the allowable path loss threshold. The maximum channel transmission rate is a function of distance and frequency (at lower frequency, the maximum distance for a given transmission rate will be greater). We assumed that each channel was available on each link with independent probability 0.5. Primary users were placed at random locations and assigned a random channel. This channel was then made unavailable to any links of cognitive radios within the interference range of the primary user.

Table 3.5: Interference ranges by frequency

Frequency	Interference range
700 Mhz	30.8 km
2400 Mhz	9 km
5800 Mhz	3.6 km

Scenario 1: Varying the number of channels available

In this scenario, the number of channels available to secondary users was varied from 3 to 15 with a step size of 3 (chosen equally from each frequency band). Ten random source-destination pairs were generated on a $50 \times 50\text{km}^2$ network with 25 nodes and 5 primary users. These pairs and the node locations were held constant for all of the experiments in this scenario. The average end-to-end transmission rate (throughput) for all routing path and channel selections is reported. The results, shown in Figure 3.15, indicate an almost linear improvement is gained by adding additional channels to the network in terms of additional throughput. The path and channel assignments found by the RCS-PathExtend were, on average, 13.23% better than those found by CS-ShortestPath, and 8.67% better than those found by RCS-Bottleneck.

Scenario 2: Varying Region Size

In this scenario, the physical region size was increased, but node density was held constant. Ten random source-destination pairs were generated on a network with 3 channels per frequency band, 5 primary users, and a constant density of 0.01nodes/km^2. The average end-to-end transmission rate for all routing path and channel selections is reported. As the region size grows, paths tend to get longer. The results, shown in Figure 3.16, indicate that the RCS-PathExtend algorithm continues to outperform the two other routing and channel assignment methods and that gap increases slightly as the region size increases. The path and channels assignments found by the RCS-PathExtend algorithm were, on average, 9.97% better than those found by CS-ShortestPath, and 20.46% better than those found by RCS-Bottleneck.

Scenario 3: Varying Node Density

In this scenario, the physical region size was held constant at $50 \times 50\text{km}^2$ and the number of nodes was increased. Ten random source-destination pairs were generated on a network with 3 channels per frequency band, 5 primary users. The average end-to-end transmission rate for all routing path and channel assignments is reported. As the network size grows, node density increases and the average number of links that a given link interferes with on a given channel increases. The effect is to increase the average vertex degree in the conflict graph G_c. The results, shown in Figure 3.17, indicate that again, the RCS-PathExtend algorithm outperforms the two other approaches across the range of node densities considered. That path and channel assignments found by the RCS-PathExtend algorithm were, on average, 8.26% better than those found by CS-ShortestPath, and 11.52% better than those found by RCS-Bottleneck.

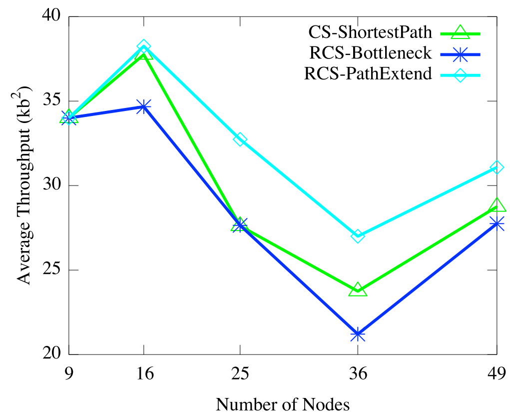


Figure 3.17: Average path end-to-end throughput versus node density. Region size fixed to $50 \times 50\text{km}^2$.

3.4.4 Conclusions

In this paper, we have examined two important problems for maximizing the end-to-end throughput for communication flows in cognitive radio mesh networks. For the channel selection problem on a known routing path, we developed an optimal algorithm and showed that for self-avoiding paths it runs in time linear in the length of the path. Furthermore, the algorithms only needs to propagate local information from source to destination and can be implemented in a distributed fashion. We also considered the joint problem of routing and channel selection and showed that it was NP-hard to approximate within a factor of $(2/3 + \epsilon)$. In addition we presented two novel heuristic algorithms for this problem and demonstrated the universal superiority of one of them, RCS-PathExtend, to simply using shortest path routing followed by optimal channel selection.

Chapter 4

Research Plan

Presented here is the plan for my research which is composed of two pieces: extending my previous work to account for topography and whitespace frequencies, enhance a sparse broadband network architecture with topology control and game theoretic algorithms to overcome challenges to connectivity and throughput in sparseness challenges in rural wireless network implementations. These two problems address the greatest challenges in providing a robust and cost-effective solution for rural wireless networking. As my research progresses it will evolve and adapt, and this plan will evolve accordingly.

4.1 Research Goals

The goal of my research is to produce an architecture with enhancements based on a set of algorithms, and a set of possible technologies (radios, frequencies, antennas, power systems) that can be used to implement sparse wireless networks where node distribution is non-uniform. To accomplish this goal we need to investigate the effects of that topography and expanded frequency spaces have on beam selection, beam scheduling and routing and channel selection. Additionally I want to verify that the existing wireless architecture deployed as part of the Buffalo Jump Technology Cooperative is the best general solution. I also want to provide enhancements that improve connectivity robustness by by avoiding single points of failure in the existing solution.

The existing wireless networking data and simulations are severely limited in their usefulness for extracting meaningful information about the connectivity (or lack thereof) among rural parts of America. I believe more measurement and simulation can significantly improve the data about existing connectivity and illuminate the most cost effective way to connect the rest of America. One of my goals is to show that by enhancing simulations to three dimensions and expanding the frequency range to include TV whitespace solutions are feasible to enfranchise a significant amount of the remaining disconnected Americans.

The second goal of my research is to show that a sparse broadband network architecture can be built using topology control to provide a robust long range wireless backbone connecting wireless meshes is a general solution to the extending broadband infrastructure to reach remote users in areas with low population density, highly varying topography or both. The artifacts of my research will include publications, a simulation toolkit, and an in situ wireless testbed.

4.2 Extensions to Current Work

4.2.1 Topography

In order to account for topographical considerations there are two additional factors that need to be added to the existing simulations. First, the simulations need to take elevation into account adding some additional computational complexity in the distance, range, and throughput computations. The addition of elevation takes the simulations from 2D to 3D, which makes them both more accurate and more realistic.

Second, natural topography also provides signal blocking that needs to be taken into account. This signal blocking significantly alters the routing and frequency selection components of the simulation.

In order to realistically simulate wireless networking implementations both of these factors need to be incorporated, resulting in updated papers for beam scheduling, beam selection and routing and channel selection. These updated papers will submitted to conferences for publication.

4.2.2 Whitespace

Additionally, with the recent moves to make TV whitespace frequencies available, and since these frequencies are in the range that can provide long range connectivity, I plan to enhance the simulations to include the ability to use TV whitespace frequencies. The addition of these frequencies could improve the performance of the simulation by providing longer range more topographically robust link options.

Again, updated publications will be produced and submitted to relevant conferences. Depending upon the outcome of the simulations the publications might combine the topographical awareness and extended frequency ranges into a single set of publications.

4.2.3 Beam Refinement

An additional problem that I am pursuing involves finding the optimal beam selection when given a transmission schedule. This comes from a problem in WiMAX networks where the two phase process of identifying nodes and scheduling the transmission via separate sub-channels provides the possibility of a multi-sector antenna to focus activate and deactivate sectors for each sub-channel in sequence. This could provide significantly more transmission power by focusing the power in the direction of the transmission for each time slice. This would require sniffing the transmission schedule packets from the WiMAX network using a protocol analyzer and solving the beam scheduling problem fast enough to activate antenna sectors for each transmission.

4.3 Future Work

All of the new work I propose is based on a wireless architecture that is made up of one or more internet gateways, a set of relay nodes and a set of subscriber nodes. The internet gateways and relay nodes provide the network backbone and are assumed to span long distances using TVWS. This subnetwork uses topology control mechanisms to maximize connectivity and throughput while minimizing interference. Subsets of one or more subscriber nodes in this network compose wireless mesh clouds, providing high bandwidth connectivity to each other. The link between these subscriber clouds and the backbone is a set of cognitive radio enhanced subscriber nodes that are periodically elected to be relay nodes routing traffic to and from the backbone. This network architecture could address the greatest resource issues that occur in sparse networks where node distribution uniformity is unknown a priori.

4.3.1 A Sparse Broadband Network Architecture

The network architecture I propose is a topology control backbone network connecting wireless mesh subnetworks. The hardware can be uniform or non-uniform as long as there are at least two cognitive radios with the same frequency capabilities as the relay nodes that connect the meshes. Referring back to Fig. 3.7, each of the subscriber stations (SS) and their associated relay station (RS) are a traditional wireless network, each with the capability of being the RS. There can be more RS's in the network that are not part of local wireless networks, providing traditional RS services as well. Each wireless cloud elects a set of one or more RS's to provide gateway services to the upper layer network of RS's that in turn route traffic through the set of internet gateways. The election of RS's within wireless networks can happen at a fixed interval or be in response to changing network conditions induced by changes in weather, usage, or hardware performance. This re-election of RS's triggers a topology control event where the upper layer can re-evaluate the topology control solution for the routing network to ensure optimal performance. The upper layer topology control network can also have a cognitive trigger with an interval to re-evaluate the topology control solution providing routing among existing (e.g. non-changing) RS's. This will have an exponential back-off integrated to avoid any loss in performance when conditions are not changing rapidly.

There are multiple aspects of this architecture that can be explored to provide the optimal implementation. Here I describe the various components of the architecture. Each of these is a possible improvement in the basic sparse broadband network architecture composed of 2.4GHz/900MHz nodes that are in place as part of the Buffalo Jump Technology Cooperative.

Topology Control Backbone Network

The topology control based routing network that provides the backbone of the architecture is characterized by the distances and topographical challenges it needs to overcome. In sparse networks, links in the routing network span long distances, from 5 to 50 miles, at these distances exercising MAC layer modifications and extended ACK timeout techniques is sufficient, however, failure is possible and the routing network still needs multiple paths to ensure durable connectivity and maximize throughput. Extending the cognitive radios in this layer with the ability to use more frequencies provides more robust, long distance network links if they are at lower frequencies — such as the TV whitespace. This routing network is ideally composed of narrow beam point-to-point or point-to-multipoint connections that can focus on other relays stations whether they are fixed as part of the routing network or changing in the subscriber clouds.

The advantages of this narrow beam, mostly fixed routing network which is dynamically reconfiguring itself to provide durable connectivity and optimum throughput come from the fact that it's a fixed infrastructure that can be deployed and configured in locations where access is limited. It is constrained only by the availability of power. Most of the locations where the RS's need to be located are higher locations where access is limited or not possible for the months of December through March.

- Topology Control

  Using a topology control approach for the backbone super network pre-computes an antenna pattern for each node such that a certain network topology can be formed for future communications. This approach is used to optimize frequency resources when scarce. Typical scarcity in frequency resources is due to over utilization in areas of high population density, however frequency resources can also be scarce when they are not able to be used by more than one pair of radios at a time – such as in TVWS where more than one pair of communicating nodes would significantly degrade the performance of the network link. I propose to investigate how many TVWS frequencies are required and what the timing constraints are on frequency switching times. Traditionally Topology Control algorithms use antenna beam switching, but I propose to use TVWS frequency switching to investigate the complexity and constraints of using TVWS frequencies for sparse network links. Compared to the alternative cross-layer approach, the major advantage to using the topology control approach is that it is purely a link layer solution that does not require any modifications to a standard MAC protocol. Hence, it can be easily implemented in a system using Commercial-Off-The-Shelf (COTS) and standard protocols. This makes it ideal for the existing testbed.

- Whitespace Frequencies

  Expanding the available frequencies to include recently freed up TV whitespace can significantly enhance the Topology Control Backbone Network by allowing the links to span much greater distances. Whitespace frequencies with longer wavelengths, provide the ability to transmit and receive over great distances, over obstacles, and through most objects that can cause interference with the shorter wavelengths of higher frequency communications systems. Although the bandwidths are lower in general radio communications at the lower frequencies in the TV whitespace region are robust, as evidenced by multiple decades of success of Television. Multiple lower frequencies could be used in parallel to improve overall performance of the long distance links when needed. The use of whitespace frequencies in sparse networks is ideal because the correlation of TV whitespace and low population density is intuitively obvious, confirmed by my tests, reports from the FCC and other independent sources.

  Using a single 6MHz channel the approximate maximum throughput is 19Mbps with a maximum range of 30km. To provide sufficient bandwidth for current usage multiple channels will need to be used together, thus the emerging 802.22 specifications assume multiple channels will be bonded to behave as a single network link. The 802.22 specifications [16] also assume the MAC layer assumes cognitive radios to do spectrum sensing — to provide the ability to sense what channels are being used and what are available. This sensing is necessary to avoid multiple radios using the same TVWS frequency causing interference and degraded performance on that channel.

- Topographic Issues

  Topographical issues need to be taken into account in the proposed network architecture and will become obvious in the topology of the backbone network. The overall wireless network will be segmented into smaller wireless mesh networks because of distance, but primarily because of topographical features that interrupt higher frequency communication systems. The purpose of integrating topographical awareness into the simulation toolkit is to provide more precise planning and analysis tools and verify them against the existing wireless BJTC wireless network.

Distributed Segmented Smart Mesh Layer

- Basic WDS Clouds extended with Cognitive Radios

  The basic implementation of the proposed network architecture involves building each layer using cognitive radios enabled with extended frequency ranges that include the TV whitespace frequencies. This solution can be immediately realized with commercial off-the-shelf (COTS) hardware, with standard frequencies (900MHz, 2.4GHz, and 5.8 GHz) and then be extended with devices that can take advantage of the lower frequencies in the TV space. This staged implementation provides an initial baseline implementation that allows for gathering data on the required hardware for deployment, connectivity, bandwidth, and usage. And then an extension to it into the TV Whitespace where the same data can be collected again for comparison. This initial COTS implementation also provides the data necessary to identify any architectural issues or components that will be prone to failure or underperformance. Then those architectural components can be investigated further based on my proposed solutions using topology control and game theory.

  Currently, the BJTC wireless network is composed of a 2.4GHz cloud in the lower Madison Valley, connected to Table Mountain where there is a 900MHz link to Three Forks, MT where the internet gateway is. There is also another 5.8GHz network that comes from Bull Mountain to Table Mountain, continues to Pony, MT then on to Whitehall, MT. I am in discussions with the connecting all of the nodes with various antenna's optimized for coverage and distance, respectively. Since the cost of radios and antennas is about equivalent and some radios are able to us more than one antenna, this implementation can be further optimized with little cost. The next phase of the implementation is to replace the link from the internet gateway to table mountain with a 900MHz point-to-point link. After that a a third 900MHz node will be deployed on the eastern side of the Madison Valley, just south of the Madison Buffalo Jump State Park. These three 900MHz nodes are accompanied by 2.4GHz nodes that provide connectivity to the wireless mesh on the valley floor.

- Game Theoretic Election of Relay Node(s)

  The critical links in the proposed architecture are the relay nodes that gateway between the local wireless networks and the backbone, providing access to other wireless networks and the internet. In order to create a robust, fault tolerant architecture one or more of these relay nodes must be allowed to fail without losing overall connectivity. This requirement will drive the need to deploy redundant hardware, which will increase cost. Therefore this requirement is a cost minimization problem where the most important constraint is no loss of connectivity given the failure of a maximum number of nodes.

  In order to accomplish this I propose that all nodes in the wireless cloud with visibility to any node outside of the cloud be identified as possible relays. Then using a game theoretic approach – one where each node makes configuration and routing choices in a selfish way – the wireless cloud can reconfigure itself to provide one or more relays at any time, maximizing throughput and guaranteeing connectivity. In order for this solution to work it is required there are at a minimum two nodes in the wireless network that can be relays at any given time. This technique is robust in the face of limited resources and in a rural network the resources are constantly changing in response to weather, foliage, and transient interfering signals. Additionally, because of the distances and varying terrain topographical constraints limit the fresnel zones of the wireless signal making entirely interference free signals too costly to consider. These limitations of the network topology create constraints that the game theoretic approach can adapt to and compensate for by through dynamic reconfiguration.

4.4 Timeline

Below is an estimated plan for my research. This plan will certainly evolve as new ideas emerge. Included below are the anticipated publications produced, which will be submitted to peer-reviewed conferences or journals to report on my results. My goal is 2-5 more papers submitted by March 2012.

- September 2011: Topographical Enhancements to existing Simulations (3 extended papers)
- October 2011: Frequency Enhancements to existing Simulations (3 extended papers)
- December 2012: Game Theoretic Relay Selection Simulation(1 new paper)
- February 2012: Sparse Broadband Network Architecture Simulation (1 new paper), begin Ph.D. dissertation
- April 2012: Complete Ph.D. dissertation
- May 2012: Defend Ph.D. dissertation

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