# EFFICIENT DESIGN OF WIMAX/802.16 MESH NETWORKS.

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# Abstract


Efficient Design of WiMAX/802.16 Mesh Networks.

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Broadband wireless networks are becoming increasingly popular due to their fast and inexpensive deployment and their capabilities of providing flexible and ubiquitous Internet access. While the majority of existing broadband wireless networks are still exclusively limited to single hop access, it is the ability of these networks to forward data frames over multi-hop wireless routes which enabled them to easily extend the network coverage area. Unfortunately, achieving good multi-hop throughput has been challenging due to several factors, such as lossy wireless links caused by interference from concurrent transmissions, and intra-path interference caused by transmissions on successive hops along a single path. A wireless mesh network WMN consists of a number of stationary wireless mesh routers, forming a wireless backbone. The wireless mesh routers serve as access points (APs) for wireless mobile devices, and some of them also act as gateways to the Internet via high speed wireless links. Several technologies are currently being considered for mesh (multi-hop) networks, including, IEEE 802.11 (both single channel and multi-channel), IEEE 802.16/WiMAX, and next generation cellular networks (LTE). In this work, we focus on the IEEE 802.16.

To maximize the network performance of mesh networks (e.g., throughput), it is essential to

consider a cross-layer design, exploiting the dependency between protocol layers such as the routing network layer and the scheduling resource allocation MAC layer. Therefore this PhD thesis considers a cross-layer design approach for designing efficient wireless mesh networks; we first develop mathematical models (link-based and path-based) for the problem of joint routing tree construction and link scheduling in WiMAX-based mesh networks with the objective of minimizing the schedule length to satisfy a set of uplink and downlink demands. This is achieved by maximizing the number of concurrent active transmissions in the network by efficiently reusing the spectrum spatially.

Second, we exploit the broadcasts nature of the wireless medium and enhance our design models by incorporating opportunistic network coding into the joint routing tree construction and link scheduling problem. Identifying coding-aware routing structures and utilizing the broadcasting feature of the wireless medium play an important role in realizing the achievable gain of network coding.

Last, the uprising mobile WiMAX (802.16e amendment) has introduced more difficulties and challenges into the network design problem; thus, ensuring larger connection lifetime and better routing stability become of greater interest for the joint routing and scheduling problem. This is addressed by augmenting the previously designed models. Throughout this thesis, we assume centralized scheduling at the base station (BS) and we develop, for the joint problems, integer linear programming (ILP) models which require the enumeration of all feasible solutions to reach the optimal solution. Given their complexities, we rely on optimization decomposition methods using column generation for solving each model in an efficient way.

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Finally, I can never forget the patience and support of my parents, my brother, my aunt, my uncle, my cousins in Canada and my relatives in Lebanon. Grand-Ma, I never got the chance to see You again, but I am sure that You are so proud of me up there in Heaven.

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# List of Acronyms

AP: Access Points

AT&T: American Telephone & Telegraph

BS: Base Station

CG: Column Generation

CGLink: Column Generation Link-based

CGPath: Column Generation Path-based

CPU: Computational

DCF: Distributed Coordination Function

DiffServ: Differentiated Services

DSL: Digital Subscriber Line

EPON: Ethernet Passive Optical Network

FTP: File Transfer Protocol

3GPP: 3rd Generation Partnership Project

GSM: Global System for Mobile communications

HTTP: Hypertext Transfer Protocol

ILP: Integer Linear Program/Programming

LAN: Local Area Networks

LOS: Line Of Sight

LP: Linear Program/Programming

LTE: Long Term Evolution

MAC: Medium Access Control

MIMO: Multiple Input Multiple Output

MinSchedLength: Minimum Scheduling Length

MaxNetStab: Maximum Network Stability

MP: Master Problem

MSH-CSCH: Mesh Centralized Scheduling

MSH-NENT: Mesh Network Entry

MSR: Maximum Spatial Reuse

MSS: Mobile Subscriber Station

MTP: Maximum Transmission Power

NC: Non Coding

NLOS: Non Line Of Sight

NP: Nondeterministic Polynomial

OFDM: Orthogonal Frequency-Division Multiplexing

OFDMA: Orthogonal Frequency-Division Multiple Access

PA: Power Aware

Physical: PHY

P2MP: Point-to-MultiPoint

QAM: Quadrature Amplitude Modulation

QoS: Quality of Service

RAM: Random Access Memory

RC: Rate Control

RF: Radio Frequency

RMP: Restricted Master Problem

RS: Relay Station

SINR: Signal-to-Interference-plus-Noise Ratio

SNMP: Simple Network Management Protocols

SRG: Spatial Reuse Gain

SS: Subscriber Station

STDMA: Spatial Time Division Multiple Access

TDMA: Time Division Multiple Access

TDD: Time Division Duplexing

VoIP: Voice over IP

WC: With Coding

WiFi: Wireless Fidelity

WiMax or WiMAX: Worldwide Interoperability for Microwave Access

WLAN: Wireless Local Area Network

WMN: Wireless Mesh Network

# Chapter 1

# Introduction

In this chapter, we start by introducing some wireless network features, and enumerate the wireless network categories. We, then, describe the broadband wireless multi-hop networks and present them in the context of WiMAX which is the selected technology for our studies done throughout the thesis. Next, we define some of the challenges to encounter (which we study throughout the thesis), in order to increase the performance (e.g., throughput) of the WiMAX multi-hop network. Finally, we provide an outline of the thesis along with its contributions/publications.

## 1.1 Wireless Network Features

Over the past years, wireless technologies have seen a tremendous success and wireless networks have now become increasingly popular due to their fast and inexpensive deployment and their capabilities of providing flexible and ubiquitous Internet access to the masses.

In these networks, the transmission and reception of a signal on a wireless link is subject to noise and interference from other ongoing transmissions. Therefore, wireless networks medium access mechanisms and protocols have quickly emerged to counter the effect of interference and to improve the network achievable data rates. One category of such mechanisms is the random access protocols such as DCF (Distributed Coordination Function) [22] of the IEEE 802.11 where nodes access the medium randomly and perform back-off once data collisions are detected. The performance of these random access protocols however remains poor for providing respectable Quality Of Service (QoS) to guarantee lower end-to-end delays and higher network throughput, especially in multi-hop wireless networks.

To provide and guarantee QoS, deterministic access protocols are inevitable and have been developed and adopted in both IEEE 802.16 and IEEE 802.11 multi-hop standards. One particular and popular deterministic radio access is the Time Division Multiple Access TDMA which assigns particular time slots to different nodes depending on their bandwidth and QoS requirements. In "normal" TDMA each node is assigned its own time slot for transmission. Since no other node is allowed to transmit in that time slot, we have a conflict-free access scheme. As long as the number of nodes not is changed, the schedule can be predefined and no updates are needed. Because of its simplicity, normal TDMA is a commonly used scheme in many wireless systems [55]. Note however that the efficiency of TDMA based scheduling methods can be improved both in terms of delay guarantees as well as achieving higher capacities by allowing the TDMA time slots to be shared by simultaneous transmissions that are geographically separated while ensuring the required transmission quality; this scheme is termed as spatial-TDMA (STDMA) [65].

To further enhance their resource utilization, and therefore network throughput, recent emerging wireless technologies, are expected to utilize more complex and efficient radio access technologies, which involve both time and frequency multiplexing. Such multiplexing strategy enables a time slot to be further separated into several frequencies, where neighboring links can be active at the same time without corrupting each others transmission, given that they are using different frequencies or sub-carriers. One popular time-frequency multiplexing radio access strategy used in the IEEE 802.16e [6] standard is the OFDMA (Orthogonal Frequency Division Multiple Access) protocol which is a combination of both TDMA and OFDM. In such a case, a time slot is divided into several sub-carriers (up to 16 sub-carriers) allowing more spatial spectrum reuse flexibility.

Not only does the flexibility of wireless network benefit from its capability to reuse the spectrum spatially, but it also benefits from their abilities to provide Internet access even in harsh environments. For instance, in rural cities where infrastructures are far apart from each other, cable or fiber deployment to connect users to an Internet access point (or central office) are not possible and their cost of deployment is high, a wireless Internet access network emerges as a smart affordable solution.

Wireless technologies are also used in major cities where fiber/cable deployment may become a bottleneck. Instead of increasing the fiber/cable deployment in a city, an alternative approach would be to use wireless backhaul networks to provide Internet access to new users. Moreover, one can benefit from this alternative to have an interaction between existing fiber networks and wireless networks in a city, where the highly bandwidth consuming connections are routed to the fiber networks and the low bandwidth consuming connections transit through wireless backhaul networks.

Finally, one of the most important feature of a wireless network, which distinguishes it from all other types of networks, is its ability of enabling mobility (mobile users). Whether users are in a train, in a car or in a plane, wireless networks are the sole mean of communication. Another important feature of a wireless network, is its self-healing and self-configuration against network faults which is enabled through clustering where the wireless network is separated into clusters. In each cluster a cluster-head node is selected to perform and coordinate routing and resource allocation of the other nodes part of the cluster [75].

## 1.2 Wireless Categories of Networks

Several types of wireless networks exist. Starting from the elementary point-to-point single-hop wireless network, ALOHA [75], developed in the early 1970's, many wireless protocols and wireless technologies have emerged, with much higher complexity and performance. Among these, we distinguish three important categories:

- Ad hoc wireless networks,
- Cellular wireless networks,
- Broadband wireless multi-hop networks.

Ad hoc wireless networks belong to the category of wireless networks that utilize multi-hop relaying and are capable of operating without the support of any centralized fixed infrastructure; hence, they are referred to as infrastructure-less [75] technologies. Since there is no centralized node to provide, e.g., routing information, each node must therefore maintain some routing information, with a complexity level depending on the type of involved routing (proactive [83], reactive [62], or hybrid [57]); this makes the routing issue a quite hard problem to solve, especially when dealing with mobility and frequent path breaks may occur. For establishing a connection in ad hoc networks between two radio units, the transmitting radio unit checks if the SINR is satisfied at the receiving radio unit. Two nodes which are not neighbors may communicate, if the intermediate hosts or hops are participating in the ad hoc network and are willing to forward packets for them; this is well recognized as which the multi-hop relaying functionality [24] of ad hoc networks.

Cellular wireless networks, on the other hand, are fixed infrastructure-based, single-hop networks, where a fixed centralized node (called Base Station denoted BS), provides connectivity between client nodes. Hence, the only radio frequency links (referred in the sequel by RF-links) are between the BS and the client nodes with no direct RF-links between client nodes. Thus, a cellular network is a Point-to-Multipoint (PtoMP) network, where the BS provides communication between nodes that are within its range and no routing is involved; therefore, a cellular network is by far much simpler to design when compared to ad hoc networks. An example of cellular networks, is the GSM [72] network widely used in Europe. Given its single-hop limitation, a cellular network consisting of one centralized node and several client nodes is sometimes not enough to cover a given metropolitan area, and hence several centralized BS nodes are required which can drastically increase the network deployment cost and requires frequent BS-to-BS interactions especially when a client node is moving from the coverage range of one BS to another, also known as handover.

Broadband wireless multi-hop networks, also called wireless mesh networks (WMN)s [14], are networks which are formed to provide an alternate Internet communication infrastructure for mobile or fixed nodes/users [75]. These wireless networks enable multi-hop sessions that are generated (destined) by (to) a fixed node, the BS. Hence, the BS in wireless mesh networks provides much larger area reachability than that of a cellular network due to the multi-hop property which is lacking in cellular networks. The BS (in centralized configuration network set up) is responsible for gathering and transmitting control messages in order to perform adequate routing and scheduling of client-end connections. Through its multi-hop, multi-relay property, WMNs not only extend the network covering range but also enable connectivity at distant nodes that are Not in the Line of Sight NLOS of the BS. Furthermore, a WMN network provides reliability through its multiple routes feature between source and destination nodes therefore ensuring high network availability when node or link failures occur or when channel conditions become poor owed to surrounding increased interference. Such reliability is ubiquitous and crucial for achieving QoS of real-time voice and video traffic [26].

## 1.3 Broadband Wireless Multi-hop Networks

While the majority of existing wireless networks are still exclusively confined to a single hop access, it is the ability of these networks to forward packets over multi-hop wireless paths which enabled them to easily extend the coverage area [23]. As more users depend on such networks for their primary source for Internet access, there is an increasing expectation that these networks should provide reliable and high end-to-end throughput [34]. Moreover, given their robustness against link and node failures, owed to their multi-path and multi-hop features, these type of networks are incontestably the best candidates for deployment in an environment condemned with frequent failures.

Unfortunately, achieving good multi-hop throughput has been challenging due to factors, such as lossy wireless links caused by interference from concurrent transmissions, and intra-path interference caused by transmissions on successive hops along a single path [23, 34]. This lack of good throughput has been a major reason why citywide deployments of, for instance, wireless mesh networks (WMNs) [91], have not yet gained enough momentum in spite of the financial investment of commercial companies.

A broadband wireless multi-hop network or WMN is the intermediate segment that separates the wired (e.g., optical) backbone network from the Internet clients, which are located in residential and business areas. It is also referred to as the last mile access backhaul network [26]. To provide Internet connectivity, a broadband wireless multi-hop network is attached to the edge of the backbone network (e.g., optical metro network or longhaul) through gateways or wireless access points, which can also act as relay nodes, are deployed near residential and business areas where the end-users are located (see Figure 1.1 for an illustration). Hence, a broadband wireless multi-hop network or WMN [14] consists of wireless mesh routers, forming a wireless backhaul network . Several technologies are currently being considered for mesh networks, including, IEEE 802.11 (both single channel and multi-channel), IEEE 802.16/WiMAX, and next generation cellular networks. In this thesis we focus on IEEE 802.16.

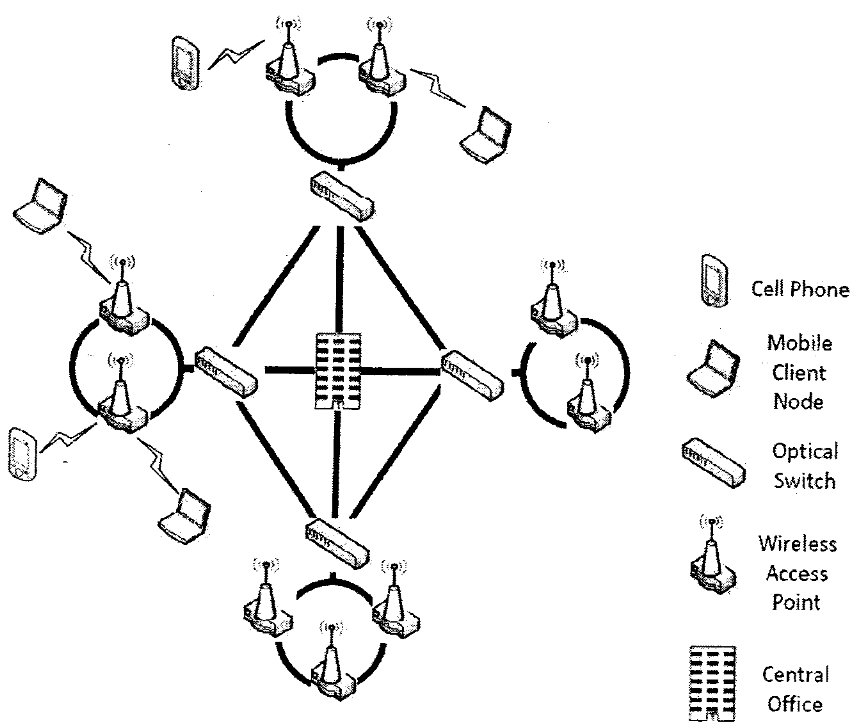


Figure 1.1: Optical to wireless network, taken from [51]

## 1.4 WiMAX

The IEEE WiMAX/802.16 2004 [3] [4] has become the most popular and cost-effective broadband wireless technology due to its capability in providing high throughput over long distances as well as its suitability for Quality of Service (QoS) support. Given this, WiMAX/802.16 has emerged as a serious competitor to other last-mile access technologies (e.g., optical access and cable access). The IEEE WiMAX/802.16 is mainly used under a spectrum of 2-11 GHz. In such spectrum, both licensed and unlicensed frequencies exist. This property of WiMAX/802.16 to offer unlicensed frequencies enables it to attract small and private industries that can deploy a WiMAX network (for several ends) in a fast and easy manner without having to pay for a licensed frequency and have it approved by the government. However, some drawbacks of unlicensed frequencies, are: (i) the limited bandwidth (when compared with licensed frequencies) and (ii) the possible frequency overlap with other networks (technologies).

We distinguish between two types of nodes in WiMAX/802.16. Subscriber Station (SS) nodes, e.g., WiFi APs, and the Base Station (BS) which performs centralized routing and scheduling decisions to the network traffic and acts as the gateway to the wired network. As a centralized node, the BS forwards the Internet traffic from the optical backbone network to the corresponding SS nodes, and it also aggregates the received data (uplink traffic) from SSs and forwards them to the Internet. On the other hand, the SS nodes serve as Internet access points (APs) for end-customers which may be using wireless mobile devices or laptops; these APs can also act as relay/sponsor nodes to other SS nodes which are out of reach of the BS coverage range therefore forming multi-hop routing paths.

The IEEE WiMAX/802.16 supports both point-to-multipoint (P2MP) and multipoint-to-multipoint (mesh) modes. In mesh mode, SSs can communicate with the BS and with each other through multi-hop routes via other intermediate (sponsor/relay nodes) SSs. The main advantages of WiMAX/802.16 mesh mode (over the WiMAX/802.16 P2MP mode) include extending the BS network coverage and providing high bandwidth assignment to end clients (even distant ones) located at SSs which are not necessarily in the line of sight (LOS) of the BS, i.e., compatibility with non-LOS (NLOS) environments.

The IEEE WiMAX/802.16 mesh mode of operation uses Time Division Multiple Access (TDMA) technology as a MAC layer access where each scheduling frame is divided into 256 time slots. The first 16 time slots form the control subframe and the others define the data subframe. Within a TDMA time slot, sub-channelization could be used where the available spectrum is subdivided into multiple orthogonal sub-carriers (WiMAX uses OFDM as a modulation method and supports sub-channelization in units of 1, 2, 4, 8, or 16 OFDM sub-carriers) [77]. However augmenting the number of sub-carriers increases the complexity of the MAC layer access algorithm and the complexity of the control messages which include additional sub-carrier assignment information associated with SS nodes. Two types of scheduling exist for WiMAX/802.16 mesh mode: (i) centralized scheduling, and (ii) distributed scheduling. In this thesis, we focus on centralized scheduling, where the BS collects the unicast connections from all its SSs through the mesh centralized scheduling (MSH-CSCH) request messages, and then performs appropriate RF-links activation at each time slot to route the granted connections. Scheduling decisions are propagated by the BS to all SSs through MSH-CSCH grant messages. It is to be noted, that in centralized scheduling, the BS and SSs form a routing tree, where the BS is the root node and the SSs form the leaf and the relay nodes.

Recently, the IEEE 802.16 standard for WiMAX technology has been extended to provide mobile broadband access through the 802.16e amendment [6]; this includes component to support P2MP, mesh modes and seamless handover operations [105] [104]. This technological uprising is now becoming a fast growing popular access technology which enables low-cost mobile Internet applications and realizes the convergence of mobile and fixed broadband access in a single air interface and network architecture [47]. Accordingly, SS nodes need no longer be stationary, with some of them subject to mobility (up to a vehicular speed), referred to as mobile subscriber stations MSSs. However, Mobile WiMAX will face new challenges (such as mobility aware resource allocation) and dealing with them is inevitable.

In May and June 2009, the IEEE 802.16-2009 standard (May 2009) [11] and the IEEE 802.16j-2009 (June 2009) [12] (amendment 1: Multiple relay specification) were published. The IEEE 802.16-2009 and IEEE 802.16j standards are a revision of the IEEE 802.16 2004 [3] and 802.16e [6]. Also, the main feature of the IEEE 802.16j-2009 when compared with the IEEE 802.16 2004 mesh mode, is the incorporation of relay stations (RS)s. Therefore data relay is only possible through the RSs which can communicate with each other and with the BS, as the SS nodes are only limited to either connect with a RS node or with the BS. The routing tree topology remains almost the same in the IEEE 802.16j-2009 when compared with the IEEE 802.16 2004 mesh: The root node is still the BS, however the relay nodes are the RSs (SS nodes can no longer be relay nodes as they were in the IEEE 802.16 2004 mesh) and the leaf nodes are SSs. In our thesis, we have assumed the IEEE 802.16 2004 standard, however our work can be easily adapted with the IEEE 802.16j-2009 (e.g., by replacing the SS nodes by RS nodes (at relay nodes) along with adequate traffic patterns).

## 1.5 Problem Definitions & Thesis Outline

### 1.5.1 Cross-layer Design and Optimization

Cross-layer design has been introduced to take the most benefits of the scarce radio resources available for wireless networks. Ad hoc networks and data packet transmission opened the myriad of transmission possibilities, and motivated to break the barriers imposed by the layered transmissions [33]. Cross layer design is defined in [88] as a protocol design that exploits some of the dependency and interaction between protocol layers to enhance the network performance gains. Such approach provides a huge improvement to the biased layering where the protocols at the different layers [33] are designed independently and hence do not exploit an efficient use of the network resources.

In wireless backhaul multi-hop networks, the system throughput can improve drastically if a cross-layer approach is adopted to coordinate the network layer routing, MAC and physical layer operations [26]. Given that wireless links are interdependent in a wireless multi-hop network and that the interference level (which directly affects the MAC scheduling decisions) varies from the selection of a routing path to another, network layer routing and MAC/PHY layer scheduling become tightly coupled [26]. Indeed, a particular selection of routing paths at the network layer, can provide a reduced level of cumulative interference at receiving nodes, and as a result more transmissions can be activated simultaneously (while adjusting their power and rate accordingly) at the MAC and PHY layer, therefore utilizing efficiently the limited available resources and increasing the network throughput.

To deal with cross-layer implementations, tools such as optimization [24], game theory [79, 80, 81] have been consolidated as important tools to formulate and solve the most of the cross-layer problems [33]. In our thesis, we use column generation [53] (one of most advanced optimization tool) to design and solve our cross-layer joint routing-scheduling models. By exploiting its decomposition property of the joint optimization problem into subproblems, column generation does not require exploring explicitly all possible solutions and therefore can converge to optimality with reduced CPU time. Moreover, its subproblems information exchange and interaction is well suited for cross-layer design where for instance each subproblem can correspond to a particular layer (e.g., MAC layer). We present the principles of the column generation method in Chapter 3.

Several studies have adopted a cross-layer design for optimizing network resource utilization, in the following we present some of them, while the other related works are discussed in Chapters 4, 5 and 6 where our contributions based on a cross-layer design approach are presented. Bjorklund *et al.* [24] addressed the problem of resource allocation in ad hoc networks providing a cross-layer design for minimizing the schedule length of a frame, through activating concurrently wireless links assuming STDMA MAC layer access, and considering the physical layer SINR interference model. Capone *et al.* [27] have further improved the model of [24] by incorporating in their cross layer design optimization models, power control and transmission rate adaptation according to the SINR requirement. These works [24, 27] have showed how cross-layer design can achieve a better network resource utilization and are being currently used as references for several other works see, e.g., [28] [65].

### 1.5.2 Problem Definitions and Contributions

The problem of scheduling and routing tree construction in WiMAX/802.16 based mesh [3] networks is not defined in the standard and has thus been the subject to extensive research. Moreover, in contrast to the simple single-hop P2MP architecture, the network operations and radio resource allocation problem are much more complicated for multi-hop WiMAX mesh networks and that may hold them from fulfilling their promises in achieving the same services (e.g., higher throughput and quality of service (QoS) guarantees) provided by their counterpart.

We consider in Chapter 4 the problem of joint routing and scheduling in WiMAX-based wireless mesh multi-hop network, with the objective of determining a minimum schedule period that satisfies a given (uplink/downlink) end-to-end traffic demand. Minimizing the length of a schedule amounts to maximizing the spectrum spatial reuse by activating concurrently as many links on the same channel. Therefore our model which consists into minimizing the schedule's length is referred to as maximum spatial reuse (MSR). We define a transmission configuration as the set of wireless links that can simultaneously transmit on the same channel without violating the signal-to-interference-plus-noise ratio (SINR) requirement. We assume centralized scheduling at the base station (BS) and attempt to maximize the system throughput through appropriate routing tree selection while achieving efficient spectrum reuse through opportunistic link scheduling. We present an integer linear programming ILP optimization model for the joint problem, which relies on the enumeration of all possible link schedules. Given its complexity, we decompose the problem using a column generation (CG) approach. We present two formulations for modeling MSR, namely the link-based (CGLink) and the path-based (CGPath) formulation. These two formulations differ mainly in the number of routing decision variables. Our numerical results indicate that the path-based formulation needs much less computational (CPU) time than the link-based formulation in order to determine the same solution with the same spatial reuse gain. In addition, our approach is useful for determining the theoretical-capacity of these networks and could be adopted as a traffic engineering methodology, given that the traffic flow varies occasionally.

Instead of using simple forwarding at relay nodes (which is done in Chapter 4), a technique known as network coding which uses opportunistic broadcasting (at particular relay nodes), initially proposed by [13] in the context of multi-cast communication, has shown to substantially improve the network performance. Recently, a new approach has been developed for improving the (unicast) throughput in multi-hop wireless networks (COPE) [63]. This framework (COPE) exploits the broadcast nature of the wireless medium; here, intermediate relay nodes may perform opportunistic coding and broadcasting, rather than simple forwarding. Opportunistic coding and broadcasting refers to the situation where two connections are transiting (are routed) through an intermediate node B but in opposite directions (refer to Figure 1.2), and instead of using simple forwarding at different point of times to transmit the data packets of the two different connections, the intermediate node B can code the packets of the two connections into one packet, and broadcast it to the intended receivers (which can decode the code packet once received) at the same time. From its definition, enabling network coding (identifying and exploiting those routing structures where opportunistic coding is possible, coding the data packets and broadcasting them to the intended receivers) requires a cross-layer design between the MAC/PHY layer (where the coded transmissions are being scheduled and broadcasted based on some SINR threshold requirements) and the network layer where the connections routing algorithm is present.

This technique, known as network coding [13] [63], has received a lot of attention over the past few years due to its potential in improving the network performance. Therefore, enabling network coding for routing and scheduling connections in broadband wireless multi-hop networks can further increase the network's bandwidth capacity, admitting more user sessions to the network.

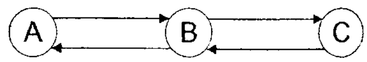


Figure 1.2: Opportunistic coding structure.

Incorporating this strategy in WiMAX multi-hop "mesh" networks is the focus of our work in Chapter 5. To achieve our goal, we propose a cross-layer design framework (based on a column generation approach) for the joint problem of coding-aware routing and scheduling in WiMAX-based mesh networks with unicast sessions. Our coding-aware model attempts to maximize the system throughput by exploiting opportunistic coding opportunities through appropriate routing and achieving efficient spectrum reuse through appropriate link scheduling. We assume centralized scheduling at the base station (BS), and focus on minimizing the total schedule length to satisfy a certain traffic demand. Minimizing the schedule length is equivalent to maximizing the system throughput. We present an integer linear programming ILP optimization model for the joint problem. Our numerical results show that significant gains may be achieved when network coding is incorporated into the design. We compare the performance to that of a joint coding-oblivious model with and without power control.

Mobility has recently been considered through the IEEE 802.16e amendment which includes component to support P2MP, mesh modes and seamless handover operations [105] [104]. Thus, nodes in the wireless mesh are no longer stationary, and some of them are subject to mobility (up to a vehicular speed), referred to as mobile subscriber stations MSSs. Such mobility uprising must be addressed in the network dimensioning and design problems, otherwise the network operation would become erroneous. Indeed, the first problem that faces a mobile WiMAX mesh network is its frequent RF-link breakages which makes some of its routing paths no longer available (rerouting becomes inevitable). Another issue that faces mobile WiMAX is that some mobile nodes that were transmitting concurrently in a time slot (given that they were outside the interference range of each other), could move towards each other and start interfering with one another when transmitting simultaneously. Thus, the predetermined link activation schedule (before mobility occurs) is no longer valid and schedule reconfiguration is required. Given the frequent RF-link failures (leading to routing path failures) and frequent topology changes, where new links are created and some transmitting nodes become close enough to interfere on each other's transmissions, MAC layer link scheduling and network layer routing must be interconnected and designed jointly to yield a correct network operation.

In Chapter 6, we consider joint routing and scheduling in a WiMAX-based mobile multi-hop network. We assume that nodes are not necessarily stationary, but rather mobile with a mobility that may yield to frequent topology changes (e.g., failure of existing links and creation of new transmission links). We model the joint routing and scheduling as an optimization problem (based on a column generation approach) whose objective is either to determine a minimum length schedule by maximizing spectrum spatial reuse or maximizing the network lifetime by routing around the less stable RF-links, while satisfying a set of (uplink/downlink) end-to-end demands. While solving the problem with the two objectives, we study the trade-offs between these two objectives. We show that minimizing the schedule length forces the joint routing and scheduling problem to generate a routing tree and feasible transmission configurations which favor higher spectrum spatial reuse (and hence higher system throughput), irrespective of the robustness of the selected transmission links. In addition, we show that maximizing the network stability or lifetime yields the selection of different routing trees and slot assignments which do not necessarily result in shorter schedule length. We perform numerical experiences where we compare the performances of our proposed models with respect to the network stability and resource spatial reuse. The CPU time, to solve this mobility aware model (i.e., maximizing the network stability), is reasonable in the context of a

2-hop mobile WiMAX network.

Throughout this thesis, we assume that the channel conditions do not vary and thus channel parameters are constant, the traffic demands do not change over a small period of time and nodes are fixed to their locations. In Chapter 6, we extend our work to consider mobile nodes. We also point out that the nodes are synchronized with the BS under the assumption that the control messages are correctly flooded without any error. It entails that the BS has a precise and accurate clock [9].

### 1.5.3 Thesis Outline

Here is the thesis structure and organization. In Chapter 2, we present and discuss the IEEE 802.16 standard and evolution, starting from the IEEE 802.16a which was introduced in 2003 to the recently approved IEEE 802.16j published in May 2009. Then, in Chapter 3, we introduce the column generation optimization strategy, provide an example for a better understanding of this method and present strategies for solving efficiently the ILP based on the optimal LP solution obtained by the column generation. We note that column generation is one of the most advanced optimization tools, and is known for solving efficiently large scale optimization models. Such approach is adopted in our thesis to solve optimally our cross-layer designed models. As mentioned earlier, we study in Chapter 4, the problem of joint routing and scheduling in 802.16-based wireless mesh multi-hop networks, with the objective of determining a minimum length schedule that satisfies a given end-to-end traffic demand. Next, in Chapter 5, we introduce network coding for WiMAX/802.16-based mesh networks to further improve the network resource utilization; we redesign and reformulate our mathematical models to be able to identify the opportunistic coded data at intermediate nodes and to broadcast it to the corresponding receiving nodes (that can correctly decode the coded transmissions to retrieve their corresponding data packets). The objective is to maximize the network resource utilization by determining the minimum length schedule in presence of both unicast and broadcast (coded) transmissions. In Chapter 6, we develop a joint routing-scheduling algorithm that considers mobility of the nodes with an objective of determining the most stable RF-links so that the frequency of rerouting and rescheduling is reduced and more data is delivered for a particular routing-scheduling algorithm. Finally, in Chapter 7, we conclude our thesis and present future work and directions that we shall investigate.

## 1.6 Publications

We summarize our contributions in the following:

- Jad El-Najjar, Chadi Assi, Brigitte Jaumard, "A Maximum Network Stability Model for Mobile WiMAX Networks", Journal on Mobile Networks and Applications (MONET), Springer/ACM May, 2009 [40].

- Jad El-Najjar, Chadi Assi, Brigitte Jaumard, "Joint Routing and Scheduling in WiMAX-based Mesh Networks", Submitted to IEEE Journal of Transaction on Wireless Communications, 2009. [38].

- Jad El-Najjar, Chadi Assi, Brigitte Jaumard, "Joint Routing and Scheduling in WiMAX-based mesh networks: A Column Generation Approach" The 10th IEEE International Symposium on a World of Wireless, Mobile and Multimedia Networks, WOWMOM 2009, 1- 10 [39].

- Jad El-Najjar, Brigitte Jaumard, Chadi Assi, "Minimizing Interference in WiMax/802.16 based Mesh Networks with Centralized Scheduling" in IEEE global telecommunication conference Globecom, Wireless Network Symposium, 2008, 1-6 [44].

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- Lehan Meng, Jad-El-Najjar, Hamed Alazemi, Chadi Assi, "A Joint Transmission Grant Scheduling and Wavelength Assignment in Multichannel SG-EPON", IEEE/OSA Journal of Lightwave Technology 2009, 4781-4792 [73].

- Lehan Meng, Jad-El-Najjar, Hamed Alazemi, Chadi Assi,"A Joint Transmission Grant Scheduling and Wavelength Assignment in Multichannel SG-EPON", in the 21st International Teletraffic Congress ITC, 2009, Paris, France, 1-8 [74].

# Chapter 2

# Literature Review and background on WiMAX

In this Chapter, we give an overview of the WiMAX standard where we present its evolution starting from 2003 till 2009 and describe its main features namely the mesh mode which appeared in IEEE 802.16 2004 [3] standard and which was updated in the IEEE 802.16j 2009 [12] (amendment 1: Multiple relay specification) and the mobile WiMAX which was introduced in the IEEE 802.16e [6]. In addition, we present some relevant work done on WiMAX such as routing and resource allocation and show how these studies differ from our contributions.

## 2.1 WiMAX Standard Evolution & Timeline

The IEEE 802.16 [3] [11] standard defines the Wireless MAN (Metropolitan Area Network) air interface specification. This wireless broadband access standard provides one of the missing puzzle piece for the last mile connection in wireless metropolitan area networks. In this section we present the IEEE 802.16 standard specifications and features starting from 2001 till 2009.

### 2.1.1 WiMAX Uprising

The IEEE 802.16 first appeared in 2001 and operated in the 10-66 GHz spectrum and it specified the physical layer (PHY) and medium access control layer (MAC) of the air interface Broadband Wireless Access systems. At 10-66 GHz range, transmissions required Line-of-Sight (LOS). Note that, the physical layer (ranging from 10-66 GHz) was found unsuitable for non-line-of-sight (NLOS) which operated using lower frequencies. Therefore, the IEEE published 802.16a [2] amendment which accommodated NLOS connections in April 2003. This 802.16a [2] amendment operated for both licensed and unlicensed frequencies between 2 GHz and 11 GHz, and it was a first extension of the IEEE 802.16 standard. In the following year (2004), the IEEE 802.16 Working Group task created and published a new amendment, referred to as WiMAX [3], for last mile Internet access at high speed and low cost equipments, which is easy to deploy, and which provides a scalable solution for extension of a, for example, a fiber backbone. In this amendment, WiMAX BSs offer greater wireless coverage which can reach 5 miles, within a network bandwidth variating from 70 Mbps to 150 Mbps. The 802.16 2004 [3] air interface standard covered also non-line of sight (NLOS) applications in licensed and unlicensed bands in the sub 11 GHz frequency range and provided two modes: (i) P2MP single hop sessions and (ii) the mesh multi-hop sessions.

Moreover, WiMAX is widely supported by companies, including Intel, Dell, Motorola, Fujitsu, AT&T, British Telecom, France Telecom, Reliance Infocomm, Siemens, Sify, PriceWatehouseCoopers and Tata Teleservices, all forming an alliance called WiMAX Forum [1]. Being deployed between Wireless LANs (local area networks) such as WiFi and wide area networks (backbone networks) such as optical ring networks, WiMAX offers a cost-effective wireless alternative to conventional wire-line DSL and EPON (Ethernet Passive Optical Network) segments in areas where those technologies are not readily available. More importantly, the WiMAX technology can provide a cost-effective broadband access solution in areas beyond the reach of DSL and fiber (environment constraint free). The still evolving IEEE 802.16 standard is expected to address mobile applications therefore enabling broadband Internet high speed access directly to WiMAX-enabled portable devices ranging from iphones and blackberries to laptop computers [5] [1].

### 2.1.2 WiMAX Mesh

The IEEE 802.16 WiMAX (2004) [3] [4] standard provides a mechanism for creating multi-hop (multi-relay) mesh network, which can be deployed as a high speed metro area wireless network [98]. Here the "mesh" terminology refers to multi-hop wireless routing paths starting at the centralized base station BS node and ending at subscriber station SS nodes where Internet customers are present. Note that only one routing path is used from the BS to reach a particular SS node, therefore the WiMAX mesh topology is in reality a routing tree topology where the root node is the BS and the relay/leaf nodes are the SS nodes.

WiMAX technology may provide a single last hop Internet high speed access to residential areas, business companies and broadband (Internet Service Provider) ISP. However, through its multi-hop feature, WiMAX can be also used for creating a long reach, city size wireless metropolitan area backhaul network. When a IEEE 802.16 (2004) WiMAX is deployed in "mesh" multi-hop mode, it not only increases the wireless network coverage, but it also provides features such as lower backhaul deployment cost, rapid deployment, and NLOS users reachability through multi-hopping [98]. WiMAX deployment scenarios and strategies are basically aimed for metropolitan citywide wireless high speed Internet coverage, backhaul for connecting 3G cellular base stations as well as

WiFi gateways, and fiber to wireless connectivity. In addition to the single-hop IEEE 802.16 P2MP (point-to-multipoint) operation which was first introduced in the IEEE 802.16a amendment, the IEEE 802.16 WiMAX defined the basic signaling flows and message formats to establish a mesh network connection [98] as well as the mesh mode specifications which were integrated into the IEEE 802.16-2004 [3].

Even though single hop (P2MP) WiMAX is highly flexible into attaining Quality of Service QoS guarantees in terms of network throughput and end-to-end connection's delay, achieving the same performance in multi-hop multi-relay WiMAX (mesh) is challenging [98]. One major problem is dealing with the interference (asynchronous and synchronous) from ongoing transmissions of the neighboring WiMAX nodes. Cross-layer design and optimization is a key approach to improve the performance of these wireless multi-hop communication networks. Interference in wireless mesh networks is one of the most significant issues that limit the network capacity and scalability [98]. New ways are being investigated to improve the coverage of base stations. One of them is through multi-hop networking which enables data to hop from point to point, circumventing obstacles such as hills. It is to be noted that only a small amount of meshing (multi-hopping), e.g., 3-hops paths, is required to see a large improvement in the coverage of a single base station [14].

When comparing both IEEE 802.11 WiFi and IEEE 802.16 based mesh networks, 802.16-based WiMAX mesh network provides various advantages such as increased range and higher bandwidth. The TDMA based scheduling (OFDMA when sub-channelization involving several orthogonal sub-carriers is considered within a TDMA time slot) of radio access in WiMAX-based multi-hop multi-relay system provides also a fine deterministic granularity radio resource access control which can encounter synchronous interference such as data collisions without requiring any back-off algorithms. Such TDMA based scheduling mechanism, where each frame is divided into 256 slots (16 of them forming a control subframe and the remaining 240 slots defining the data subframe), allows centralized/distributed slot allocation, which combined with appropriate algorithms and optimization designs and techniques, provides overall efficient resource utilization suitable for both fixed and mobile wireless backhaul networks. However, interference still remains a major issue for multi hop WiMAX mesh networks; to provide high spectral usage, an efficient algorithm for time slot allocation (TDMA) and sub-carrier allocation (OFDMA) is needed, so as to maximize the concurrent transmissions of data in the mesh therefore reducing the TDMA scheduling length. The level of interference depends upon how the data is routed, scheduled and transmitted in the WiMAX mesh network [98].

In IEEE 802.16 Mesh mode, a base station (BS) provides backbone Internet connectivity of the mesh network and controls one or more subscriber stations (SS) [98]. When centralized scheduling scheme is used, the BS is responsible for collecting bandwidth request from subscriber stations (SS)s and for managing routing and resource allocation (deterministic scheduling). It is also interesting to point out that in centralized scheduling, the BS keeps a routing tree topology, where it acts as the root node and its connected SSs (part of the mesh) as leafs and relay nodes.

Now, we describe, the network entry procedure (where a new node wants to join the network) in IEEE 802.16 WiMAX Mesh mode. The Mesh Network Configuration (MSH-NCFG) and Mesh Network Entry (MSH-NENT) messages are used for advertisement of the mesh network and for allowing easily new nodes to synchronize and to join the mesh network [98]. Active nodes within the mesh periodically forward from the BS, MSH-NCFG messages with Network Descriptor, which outlines the basic network configuration information such as BS ID number, the channel current resource allocation and the routing tree formation [97]. A new node that plans to join an active mesh network searches for active nodes and listens to MSH-NCFG message. The new node establishes synchronization and starts the network entry procedure based on the information given by MSH-NCFG [97] [3]. Among all possible neighboring nodes, the joining node (which is called Candidate Node in the 802.16 Mesh mode terminology) selects, based on the BS advertisement control messages (all the NSH-NCFG messages are originated from the BS) a potential Sponsoring Node referred to as Parent node (since the WiMAX multi-hop mesh has a tree topology) to connect to. Afterwards, Mesh Network Entry message (MSH-NENT) with NetEntryRequest information is then sent by the Candidate Node to join the mesh [98].

The IEEE 802.16 Mesh mode MAC supports both centralized scheduling and distributed scheduling. Centralized mesh scheme is used to establish high-speed Internet connections to end customers located at residential and business areas where SS nodes are deployed. In this scheme, the BS is the only node responsible for coordinating the radio resource allocation within the mesh multi-hop network. In addition, every SS sends its resource request to the BS, and then the BS computes and advertise the amount of granted resources for each link [98]. The request and grant procedures utilize the Mesh Centralized Scheduling (MSH-CSCH) message type. A Subscriber Station's capacity request is sent using the MSH-CSCH:Request message to the Subscriber Stations parent node and so on to reach the BS. Thereafter, the BS determines the resource allocation results, and propagates the MSH-CSCH:Grant along the route from the Mesh BS. To make available the scheduling tree configuration information to all participants within the mesh network, a Mesh Centralized Scheduling Configuration (MSH-CSCF) message is broadcasted by the Mesh BS and then re-broadcasted by intermediate relay nodes [98].

### 2.1.3 Mobile WiMAX

The WiMAX technology, based on the IEEE 802.16-2004 [3] [4] Air Interface Standard has rapidly proven itself as a key role technology in fixed broadband wireless metropolitan area networks (WMAN). The first certification lab, established at Cetecom Labs in Malaga, Spain was fully operational in 2006 and more than 150 WiMAX trials are present or underway in Europe, Asia, Africa and North and South America [8]. In December 2005, the IEEE approved and ratified the 802.16e amendment [6] to the 802.16 standard. This amendment added the features, specifications and attributes to the standard that are necessary to support mobility. Mobile WiMAX [6] is a wireless metropolitan area technology that enables convergence of both mobile and fixed high speed Internet access networks through a common area broadband wireless access protocol and a flexible network architecture. The Mobile WiMAX Air Interface adopts TDMA and Orthogonal Frequency Division Multiple (commonly known as OFDMA) for improved multi-path performance in non-line-of-sight environments. Such MAC layer feature allows radio resource allocation in both time and frequency domain. That is, in a TDMA time slot, several neighboring users, can transmit simultaneously, interference free, while using different orthogonal frequencies or sub-carriers (1, 2, 4, 8 and 16 sub-carriers are supported by WiMAX) [77].

Some of the key features supported by Mobile WiMAX are:

- High Data Rates. The inclusion of sub-channelization (OFDM sub-carriers) schemes, along with advanced physical layer coding and modulation (64-Quadratic Amplitude Modulation) all enable the Mobile WiMAX technology to reach high peaks data rates up to 63 Mbps per sector in a 10 MHz channel. Depending on the company budget deploying the network, a BS can possess several sectors with, however, an increased cost.

- Quality of Service (QoS). The fundamental purpose of the IEEE 802.16 MAC architecture is QoS. It defines Service Flows which can map to DiffServ code points that enable end-to-end IP based QoS traffic (e.g., VoIP video streaming and best effort). In addition, sub-channelization provides a flexible mechanism for optimal scheduling of space, frequency and time resources over the air interface on a frame-by-frame basis [8].

- Spectrum Scalability. It is well known that spectrum resource allocation for wireless is still quite a sensitive and crucial issue into achieving high data rates. Mobile WiMAX technology through its OFDMA radio access, is designed to be able to scale in both time and frequency domains (through its multiple sub-carriers) therefore achieving spectrum harmonization. However, using multiple sub-carriers within a TDMA time slot introduces more control overheads and increases the resource allocation complexity which involves both time slot and channel assignment.

- Diversity: Mobile WiMAX is the perfect broadband technology that is diverse in its offerings. It can provide Internet access in rural settings as well as enhancing the capacity of mobile broadband access in metro and suburban areas [8].

- Mobility: Mobile components for both mesh and P2MP topologies have been introduced in the 802.16e standard [6]. In addition Mobile WiMAX supports optimized handover schemes with latencies less than 50 milliseconds ensuring that real-time applications such as VoIP perform smoothly without any service degradation. Secured private key (based on Data Encryption Standard DES) management schemes insures that security is maintained during handover. [8]

Challenges associated with these key features are ubiquitous and need to be overcome. For instance, an important issue in Mobile WiMAX is its mobility; it leads to frequent link failures and topology changes. Both routing and scheduling algorithms must be aware of these changes, through maintaining mobility information, so as to reconfigure and to perform updates based on these changes. In order to reduce the frequency of reconfiguration (recomputing) of both routing and scheduling algorithms, optimization tools are crucial for searching stable long lasting topologies that are somewhat resilient to frequent failures and topology changes.

### 2.1.4 WiMAX vs WiFi

WiMAX and WiFi are two technologies that, lately, have seen tremendous attention by industries and researchers. Both technologies provide multi-hopping multi-relaying (mesh networks) and operate on a similar principle which is to forward data from one device to another via radio signals, in order to reach a particular destination node. Although, at first glance, both technologies appear to be similar, and thus subject to competition, WiMAX is, in fact, intended to provide the last mile access of metropolitan users to the backbone fiber network, whereas WiFi is limited to providing connectivity between users that are close to each other (in the same room or on the same floor or in the same house). Hence WiMAX is a Wireless Metropolitan Area Network standard and WiFi is a Wireless Local Area Network (WLAN) standard.

From a performance (network throughput) point of view, WiFi can currently reach a 54 Mbps throughput under ideal conditions, WiMAX can easily achieve a network throughput of 100 Mbps [3]. The biggest difference between these two technologies is not the connection's speed, it is the network coverage. WiMAX outdistances WiFi by far. While WiFi's range is about 50 meters, WiMAX BS range is 5 miles and when multi-hopping is used, WiMAX network coverage range can explode reaching up to a radius of 30 miles. Of course, at a farther distance (several miles), environment constraints such as buildings, hills, trees and even weather can reduce the network coverage range and the network throughput but nonetheless WiMAX has the potential to cover huge urban and rural areas.

Moreover, when investigating the frequency spectrum, the first WiMAX amendment (IEEE 802.16) proposed the usage of 10-66 GHz frequency spectrum for WiMAX connections, which is well above the WiFi spectrum range (up to 5 GHz maximum). But in the 802.16a amendment, support for 2-11 GHz frequency was introduced to provide NLOS services which required lower range frequencies. Therefore there is some frequency spectrum overlap between WiMAX and WiFi which requires adequate network planning attention when coexisting in the same area.

In summary, WiMAX is not intended to contend with WiFi, but to coexist and even to provide Internet connectivity to WiFi users. For instance, a WiFi gateway can be connected to a WiMAX SS node as a client. That SS will provide, via a WiMAX BS, Internet bandwidth access to the WiFi gateway which then divides and distributes it into smaller Internet granularities to its WiFi users. Hence, in that scenario, the WiFi gateway acts as a client in the WiMAX network.

### 2.1.5 WiMAX Evolution

The IEEE 802.16 2004 [3] [4] standard defined both P2MP and Mesh topologies. Ranging, control messages exchange, MAC and physical layer specifications were all discussed in details in the IEEE 802.16 2004 standard. Moreover, this amendment introduced, for the mesh topology, the concept of a multi-hop tree where the root node was the BS and the SS nodes were leafs and relay nodes. However, how this tree is constructed and designed are left for researchers and network designers to implement based on their needs and objectives. Moreover, centralized and distributed scheduling control messages exchange (between the BS and the SSs) were also defined in this standard, but again how the BS would allocate its radio resources was kept undefined in centralized scheduling. For distributed scheduling, where in this case, each SS is responsible for allocating its own resources based on its neighboring SSs behaviors, it was suggested that a 2-hop neighboring SSs information was enough to provide a smooth distributed scheduling interference free. But still no distributed scheduling algorithms were provided. It is to be noted that TDMA single carrier is the basic MAC layer access adopted in the IEEE 802.16 2004 standard, however refinements were added such as enabling a TDMA slot to possess multiple sub-carriers allowing a SS to transmit/receive simultaneously on different sub-carriers. This refinement where a multiplexing between time (TDMA) and frequency (OFDM) domains is being done was referred to as OFDMA. OFDMA could easily scale in the single-hop P2MP topology where only scheduling and sub-carrier assignment are being performed by the BS, however for the mesh multi-hop topology where in addition routing is required, increasing the number of sub-carriers would lead to increased BS complexity and overhead control messages as the BS needs to perform scheduling (time slot assignment), sub-carrier frequency assignment and routing. Note that in OFDMA, WiMAX can have 1-2-4-8 or 16 sub-carriers.

In 2005, the IEEE 802.16e [6] amendment was completed and approved by the IEEE standard committee. In this amendment, mobility was enabled for the first time in WiMAX. The IEEE 802.16e which is also referred to as Mobile WiMAX included components to support mobility for both P2MP and mesh modes. Handover control messages exchange (between BS and a mobile station) was also defined in this standard, allowing seamless soft handover which is crucial when facing VoIP traffic with high QoS requirements. The MAC layer access technology used in mobile WiMAX is OFDMA. Moreover several power saving modes classes were also defined including a sleep mode, given that energy consumption is a crucial factor in Mobile WiMAX which impacts on the lifetime of a node and its transmitting power, its transmitting rate and its receiving sensitivity capabilities.

In September 2005, the IEEE 802.16f [7] amendment was approved. This amendment provides enhancements to the IEEE 802.16-2004 [3] standard to define a management information base (MIB) for the MAC and physical layer and associated management procedures. The MIB's purpose is to enable management information exchange between SS nodes and the BS using management protocols such as simple network management protocols (SNMP). Following 802.16f, the IEEE 802.16g [10] was approved in September 2007. The IEEE 802.16g [10] completed the IEEE 802.16f [7] amendment by adding standardized procedures and interfaces for the management of conformant IEEE 802.16 2004 devices. It included: (i) The enhancements of the radio interface MAC management messages, (ii) The enhancements of the radio interface data plane capabilities, (iii) The introduction of a set of control and management primitives for the IEEE 802.16 2004 entities, as a specification for the design of protocols for control and management of a WiMAX/802.16 network and (iv) the introduction of services to enable inter-operable and efficient management of network resources, mobility, and spectrum in IEEE 802.16 fixed and mobile devices.

Just recently, in May 2009, the IEEE 802.16-2009 [11] standard was approved. This standard specifies the air interface, including the medium access control layer (MAC) and physical layer (PHY), of combined fixed and mobile point-to-multipoint (P2MP) WiMAX topology. The MAC is structured to support multiple physical layer (PHY) specifications (such as single carrier and OFDM multiple sub-carrier channels, time division duplexing (TDD) and several types of modulation techniques including 64-QAM), each suited to a particular operational environment. The

IEEE 802.16-2009 [11] standard enables rapid worldwide deployment of innovative, cost effective, and inter-operable multi-vendor broadband wireless access products. It helps achieving a competing environment in broadband access by providing alternative solutions to cable and fiber broadband access, encourages consistent worldwide spectrum allocations through its licensed frequency bands, and accelerates the commercialization of broadband wireless access systems. The standard is a revision of IEEEE Std 802.16-2004, and consolidates material from IEEE Std 802.16e-2005, IEEE 802.16f-2005, and IEEE 802.16g-2007, along with additional maintenance items and enhancements to the management information base specifications. It is worth pointing out that the WiMAX mesh topology was not addressed in the 802.16-2009 [11] standard and its dedicated section was quoted as reserved.

As expected, the IEEE 802.16 Working Group was not to limit WiMAX to the single-hop P2MP topology. In the following month of the IEEE 802.16-2009 standard (May 2009) [11], the IEEE 802.16j-2009 [12] (amendment 1: Multiple relay specification) was published. This amendment specifies OFDMA physical layer and medium access control layer enhancements to IEEE 802.16-2009 for licensed bands to enable the operation of multi-hopping through relay stations (RS). Similar to the IEEE 802.16-2004 [3] mesh topology, the multi-hop tree topology from the BS (root node) to reach all the SS leaf nodes (via the RS when multi-hopping was needed) was adopted in the IEEE 802.16j [12]. The tree construction (routing path computing) along with resource allocation were not addressed in this amendment and are subject to extensive research to come up with efficient designs and implementations. In addition, it is worth pointing out that as the IEEE 802.16-2004 mesh topology, the IEEE 802.16j [12] defines both centralized and distributed scheduling control messages exchange. Components to allow mobility support in the multi-hop relay 802.16j [12] are defined as well.

Finally in 2010, the IEEE 802.16 Working Group is expected to release the IEEE 802.16m, which includes many innovative features such as increasing the WiMAX bandwidth capacity to reach 1 Gbps.

## 2.2 Literature Review

The IEEE 802.16 2004 WiMAX [3] standard provides a mechanism for creating a multi-hop mesh network, which can be deployed as a high speed broadband wireless access network. The network topology is a tree rooted at BS with SS nodes acting as either leafs or relay nodes. Issues which were kept undefined in the IEEE 802.16 2004 standard are determining the routing and link scheduling (radio resource allocation and temporal axis TDMA slot assignment) for the tree, either jointly or separately. The network throughput of a WiMAX mesh network increases drastically if an efficient design of multi-hop routing and scheduling is adopted. The purpose of this section is to present some important routing and scheduling algorithms proposed by various authors for the IEEE 802.16 multi-hop mesh [3] network. We discuss and scheme these algorithms which were studied and designed for throughput enhancement, minimizing interference, providing QoS, achieving spatial reuse, bounding the end-to-end delay, etc .

### 2.2.1 Radio Resource Allocation and Scheduling Definitions

Radio resource allocation has for a longtime been considered as scheduling in most of the literature. However, there are some distinctions and differentiations between these two concepts which need to be highlighted. Radio resource allocation is done at the MAC sublayer and aims to distribute the available resources among the users based on their bandwidth requirements and priorities. Scheduling on the other hand, also called radio resource management [33], regroups two MAC functionalities: (i) Radio resource allocation which was previously defined and (ii) time slot allocation order whose purpose is to identify which user's resources are to be delivered first/last (assigned to time slots at the beginning/end of a scheduling period) to guarantee delay and QoS requirements.

For example in a TDMA MAC access system, the radio resource allocation is composed of the number of slots identified (which represents also the amount of bandwidth granted) to a particular user to transmit in, the power/rate control allocations and the sub-carrier frequency (in presence of multiple OFDM sub-carriers). Whereas, the scheduling operation contains, in addition to the radio resource allocation, the time slot allocation order that tells which user gets to transmit at each discrete point of time in a scheduling period so to handle delay and QoS requirements.

It is to be noted that, in the process of network planning, radio resource allocation (with joint routing if a multi-hop environment is considered) is enough to identify, the network's bandwidth capacity, its robustness in high traffic loads in order to overcome bottleneck nodes and its maximum spectrum spatial reuse (where simultaneous transmissions are not subject to interferences).

### 2.2.2 Related Work for WiMAX Mesh

Wei *et al.* [98] proposed a novel interference-aware routing algorithm and a centralized scheduling scheme, which is a centralized radio resource allocation algorithm. The framework of [98] is based on a single carrier centralized scheduling which is managed by the BS. In addition, a routing tree topology, with the BS as its root node, is considered to provide connectivity to the SS leaf and relay nodes. To take care of interference, Wei *et al.* [98] define the blocking metric of a node as the number of neighboring nodes and the blocking value of a path as the summation of the blocking values of the nodes part of the path. This blocking value of a node based on its number of neighbors is very approximate and does not give an accurate estimation of interference since even some non-transmitting neighbors are considered in this metric.

Du *et al.* [37] designed a centralized scheduling for WiMAX mesh with multi-channel capabilities. This framework introduced the concept of primary interference where a node is trying to do more than one action in a time slot (i.e., transmitting and receiving) and secondary interference where a node $v$ is receiving from an adjacent transmitting node $v'$ and another adjacent node $v''$ (within the interference range of node $v$) is transmitting at the same time. Through appropriate separate scheduling (here scheduling refers to identifying the set of simultaneous, interference free, active links in a slot along with the total number of slots to satisfy the demands) and channel assignment algorithms, Du *et al.* [37], try to efficiently allocate the network resources so to reduce the schedule length. It is to be noted that in this work, the routing tree was provided as an input.

Narlikar *et al.* [77] presented separate routing and scheduling (proper sense of scheduling based on Section 2.2.1 which considers the time axis to assign a departure time for each user's generated packet also defined as slot allocation order in the time axis) algorithms for designing a multi-hop wireless backhaul (i.e., WiMAX mesh) network with delay guarantees. The WiMAX mesh network was based on TDMA scheduling with multiple OFDM sub-carriers. In such MAC layer access technology, multiple separate data streams can be received in the same time slot over separate sub-carriers at nearby receivers with no interference and a node can receive in the same time slot from 3 different transmitting nodes given that they all transmit on different sub-carries. The scheduling was based on an odd-even link activation in such a way that two links within interference range and using the same sub-carrier would be activated in alternate time slots. However, this odd-even link activation did not consider the accumulated interference (which is measured with the SINR metric) from links transmitting in the same parity time slot.

Han *et al.* [59] designed a TDMA collision-free centralized scheduling (in its proper sense based on Section 2.2.1) algorithm for IEEE 802.16 based Wireless Mesh Networks (WMN) to provide high-quality wireless multimedia services. Their study included a relay strategy for the mesh nodes in a transmission tree, taking special considerations on fairness, channel utilization and transmission delay. Han *et al.* [59] used metrics such as the length of scheduling, channel utilization ratio and transmission delay to evaluate the performance of the proposed scheduling algorithm. Their simulation results showed that giving higher priority to the nodes nearer to the BS will reduce the length of scheduling and transmission delay and improve the channel utilization ratio. Note that, in this work [59] the interference model did not consider the accumulated interference (which is measured with the SINR metric) at a particular receiver, moreover power and rate control transmissions which can further improve the channel utilization were not addressed in this centralized scheduling scheme.

Other works [94] [50] [52] [30] done on WiMAX mesh, were also published. All tried to come up with either efficient scheduling or efficient routing and sometimes both separately, but none considered the design approach of constructing a joint routing-scheduling algorithm.

## 2.3 Mobile WiMAX Literature Review

### 2.3.1 Mobile WiMAX Challenges

Recently, the IEEE 802.16 standard for WiMAX technology has addressed mobility through the 802.16e amendment [6], which includes component to support P2MP, mesh modes and seamless handover operations [105] [104]. This technological uprising is now becoming a fast growing popular access technology which enables low-cost mobile Internet applications and realizes the convergence of mobile and fixed broadband access in a single air interface and network architecture [47]. Accordingly, SS nodes need no longer be stationary, with some of them subject to mobility (up to a vehicular speed), referred to as mobile subscriber stations MSSs. However, Mobile WiMAX will face new challenges and dealing with them is inevitable. Some of these arising problems are handover when a mobile node moves from one mesh to another, frequent RF-link breaks, resulting in path breaks and therefore an invalid routing algorithm, due to mobility of the corresponding end-nodes as well as end-nodes batteries depletion, and finally topology changes which can lead to unavailable and erroneous scheduling/resource allocation algorithms. A key aspect to deal with such problems is to consider mobility in both routing and scheduling searching for long lasting topologies and routes (maximum network stability) so to reduce the frequent recomputations of both routing and scheduling.

### 2.3.2 Related Work on Mobile WiMAX

Few work on Mobile WiMAX have appeared in the literature lately [47, 96, 49, 82, 31, 92, 84]; however, given its novelty, its recent introduction to the Telecom industry, and its close to be finalized amendments (e.g., 802.16m [47]), most of the work focused on presenting an overview of Mobile WiMAX, its performance and evolution in order to stimulate and attract researchers from both academia and industries to invest in this technology. A summary is presented next. Etemad of [47] provided a high-level overview of Mobile WiMAX and its map evolution from both radio and network perspectives; a summary of the protocol structure as well as key MAC/PHY features of the air interface are also presented. Moreover, in [47], Etemad underlined the importance of this next generation mobile technology by its ability to support flexible deployment solutions such as integrated multihop relaying (mesh) and femtocells. In [96], Wang *et al.* presented an overview of mobile WiMAX system and summarized its coverage and performance under various channel conditions and for different types of MIMO (Multiple Input Multiple Output) schemes. Several hints on the performance of VoIP over Mobile WiMAX through simulations were given and they showed how Mobile WiMAX can support more delay-insensitive services (HTTP or FTP) without affecting the VoIP capacity. Fong *et al.* [49] presented several features and solutions used in mobile WiMAX and the 802.16 standard to optimize the support for VoIP traffic. VoIP capacity is considered as a key indicator of system efficiency in next-generation mobile broadband networks even though mobile-Internet services are expected to be the primary applications that create the majority of the traffic in these networks. Results showed that 15% of the overall VoIP capacity is increased in the WiMAX Release 1.5 (dynamic scheduling) when compared with the WiMAX Release 1.0 (persistent scheduling). Furthermore, the work presented in [82] discussed the usage of Femto access points (AP) as a deployment approach to improve indoor coverage, user throughput, scalability and lower backhaul cost in mobile WiMAX deployment. Also, [82] addressed the technical challenges associated with WiMAX Femto-AP deployments and presented a summary on the industrial activities on femtocells. It is to be noted that femtocells system solutions are identified by many mobile operators as a complementary approach to macrocell deployment for faster and lower cost service rollout. Finally, a key characteristic of Mobile WiMAX is its ability to support integrated approaches to provide 3GPP services in the same network infrastructure, thereby making its adoption quicker and easier by most established mobile operators. Given that, Taaghol *et al.* [92] described how Mobile WiMAX can be seamlessly integrated into legacy 3GPP/UMTS systems.

They provided an appropriate authentication infrastructure, optimize the handover interruption, preserve the QoS as the mobile device moves between mobile WiMAX and 3GPP access technologies, and enable inter-operator roaming.

# Chapter 3

# Large Scale Optimization Methods

In this chapter, we discuss how to solve large scale optimization Integer Linear Programming ILP models efficiently, using a technique commonly known as column generation. We first remind the main issues that are present in large scale optimization models. Then, we discuss the reasons and motivations that made us use the column generation strategy in our models. We next present the LP column generation processing in details throughout an example. Finally, we discuss some techniques used to obtain an ILP solution from the column generation LP optimal solution and describe the column generation in the context of wireless cross-layer designs.

## 3.1 Introduction

Integer linear programming ILP large scale optimization models are quite difficult to solve. One method, which relies on linear programming LP relaxation (assuming real fractional variables instead of integer variables for the same model) can be used to first find the optimal LP solution and then to extract the ILP solution given the LP solution.

However, two main problems are encountered in such a method, the first is how to deal with the huge number of (real) variables to come up with the LP optimal solution with a fast and efficient way; the second is how to pass from a real fractional optimal value to an integer optimal solution knowing that in most cases these two solutions are very often not identical and not necessarily close to each other. Clearly, for the first problem, a strategy is required so as not to explicitly explore all possible solutions but instead explore some of them (with increased optimality value), in order to implicitly explore all possible solutions or columns. For the second problem, we are required to have a technique that can pass from the fractional optimal solution $z^*_{LP}$ (for the relaxed LP model) to an integer solution $z_{ILP}$ (associated with the original ILP), with a small GAP. The GAP (associated with a min objective) is defined as the distance that separates $z_{ILP}$ from the optimal solution $z^*_{LP}$ (associated with the LP model) when provided the fractional or real optimal solution $z^*_{LP}$ (associated with the relaxed LP model). The relative GAP can be formulated as $\frac{z_{ILP}-z^*_{LP}}{z^*_{LP}}$. Recall that the relaxed LP model is similar to the original ILP model (same constraints and objective) but with a difference where its variables can take real values instead of integer values only.

A method was derived for dealing with the first problem. This method was presented by P.C. Gilmore and R.E. Gomory [53] and consisted to work with only few patterns at a time and to generate new patterns (or columns) when they are really needed, that is, when they can improve the current solution to reach the optimal one. This technique is called column generation and is presented in subsequent Section 3.3.

A technique based on branch-and-price [19] exists for dealing with the second problem. However, simpler approaches such as rounding the fractional optimum solution are quite satisfactory for typical problems arising in the paper industry [32] [85].

We mention that most work that studied column generation were closely related to the context of the applications and problems that were considered. No recent work was done to explain solely and thoroughly the concept of column generation in a generalized form. This is one of the reasons that motivated us to include this chapter.

## 3.2 Motivations

Modeling and solving large scale ILP optimization models are ubiquitous in both academic and industrial environments. Indeed, computing the optimal solution or finding the GAP between the obtained solution (provided for example by an algorithm or heuristic) and the optimal one is a major hint to analyze the performance of a given algorithm. Moreover, in environments where finding a good and accurate solution is a must, given that it leads to major reduced financial costs and drastically increased resource savings, scalability and computational execution (CPU) time to retrieve the optimal solution or a near optimal solution (i.e., a solution with a small GAP), are major issues to be dealt with. In such contexts, column generation, used to retrieve the LP optimal solution, associated with an ILP method (based on the LP optimal solution) to compute the optimal or near optimal ILP solution is one good approach that can be adopted.

In a wireless environment, column generation becomes an interesting and very promising tool for cross layer design and network optimization. Given the huge number of variables involved in cross layer optimization models, such approach was for longtime kept aside and not even discussed. Indeed, for the past two decades, layers were kept separated, where each layer was involved with a specific operation: For instance the network layer was involved in routing demands along multi-hop paths and the data link, more specifically the MAC layer was involved in the resource allocation and scheduling of the demands (which user gets to access the medium at a point of time or "frequency" without having conflicts and in an ordered manner). Researchers and engineers were, at that point of time, involved with a particular layer and dealing with both of them was out of the question. Recently, the idea of having a cross layer design (for wireless networks) became possible given the emergence of highly powerful and scalable optimization tools (e.g., column generation). Therefore, more researchers started to adopt a cross layer design approach especially when they realized that it was, by far, more efficient than an isolated layer design. For instance, it was quite obvious that when having a joint routing and scheduling design, the crucial wireless resources were utilized more effectively than a separated routing and scheduling design (assuming that we have adequate tools to solve the joint design efficiently). However, one particular drawback of such a cross-layer design is that it involves more complex models with a larger number of variables and parameters.

## 3.3 LP Relaxation Column Generation

Column generation originally presented in [53] [54], is an optimization technique that decomposes a Linear Program (LP) into a master problem and a pricing problem. Instead of having all columns or possible solutions inserted in the master problem, the master problem is initialized with a subset of columns referred as restricted master problem. The pricing problem is a column generator that keeps generating and adding columns as long as there exists one that can improve the LP solution of the restricted master problem. Given the augmenting property of the pricing problem, where a column is generated only to improve the restricted master problem solution, a tiny fraction of such columns is usually enough to reach optimality which corresponds to the optimal LP solution of the master problem (if it is fed with all possible columns). Therefore, as opposed to the classical

LP simplex algorithm in which all the columns are inserted at the same time before solving it in order to obtain the optimal solution, a column generation technique alternates between the master problem and the pricing problem, until the former contains the necessary columns required to find the optimal solution of the original LP [24].

Let us examine more in details the LP column generation's master and pricing problem interaction. The restricted master problem is initialized with a feasible solution (subset of columns) or alternatively artificial columns could be introduced just to initiate and to allow the column generation interaction to take place. When the restricted master problem is solved, the dual variables of the binding constraints are recuperated and are provided as inputs to the pricing problem (coefficients or multipliers in the pricing problem's objective). Afterwards, the pricing problem is solved and a column based on its solution is generated. If the reduced cost associated with the pricing problem solution (or generated column) is negative, than the restricted master problem solution is not optimal and therefore can be ameliorated, otherwise (positive reduced cost) no improvement can be done on the restricted master problem's solution which is in that case the optimal LP solution of the master problem if fed with all possible columns (i.e., column generation interaction finishes). In the case of a negative reduced cost, the generated column by the pricing problem is added to the set of already existing columns in the restricted master problem, and the restricted master problem is solved again with the new set of columns. The column generation process continues in a similar fashion until a positive reduced cost is obtained indicating that the optimal LP master problem solution is reached.

We present the column generation technique throughout the following example in order to high-light its main steps which were discussed previously. Consider the following ILP model:

$$z^*_{ILP} = \min \sum_{j \in J} c_j x_j \tag{3.1}$$

subject to:

$$\sum_{j \in J} a_{ij} x_j \geq b_i \quad i \in I \tag{3.2}$$

$x_j \in Z^+_n, j \in J.$

Note that $J$ represents the set of all columns associated with the model, and $I$ the set of rows.

We define the master problem (MP) as the linear program model but where the variables $x_j$ are relaxed and can take any real positive value:

$$z^*_{LP} = \min \sum_{j \in J} c_j x_j \tag{3.3}$$

subject to:

$$\sum_{j \in J} a_{ij} x_j \geq b_i \quad i \in I \tag{3.4}$$

$x_j \geq 0, j \in J.$

We assume that all possible columns $a_j, j \in J$ are given as elements of a set $A \neq 0$.

Therefore, the restricted master problem (RMP) corresponds to the MP but without considering all possible columns $|J|$. Instead, the RMP is solved with a subset $J' \subseteq J$ of columns. Since the master problem contains all possible columns $J$ and that the restricted master problem contains a subset of columns $J'$, $z^*_{LP} \leq z_{LP}$. The column generation procedure consists in selecting the adequate subset $J'$ such that $z^*_{LP} = z_{LP}$. The RMP objective and constraints become:

$$z_{LP} = \min \sum_{j \in J'} c_j x_j \tag{3.5}$$

subject to:

$$\sum_{j \in J'} a_{ij} x_j \geq b_i \quad i \in I \tag{3.6}$$

$x_j \geq 0, j \in J'$.

The column generation begins by solving the RMP which contains an initial subset of columns $J'$. Once, the RMP solved, the obtained values of $x_{LP}$, in particular, the dual values $u_{LP}$ associated with constraints (3.6) are used as coefficients in the pricing problem to calculate the reduced cost. The pricing problem correspond to :

$$c^* = \min\{c(a) - u^T a \ : \ a \in A\} \tag{3.7}$$

where $u^T$ is the transpose vector of $u$. Note that $a$ is a variable in the pricing problem, which purpose is to generate a new column with coefficients $a^{new}$ that is eventually added to the RMP in order to improve its solution.

After solving the pricing problem, the column generation procedure checks if $c^* \geq 0$. If it is so, no reduced coefficient $\bar{c}_j$ is negative and the previously obtained values of $x_{LP}$ optimally solve the MP problem, i.e., $z^*_{LP} = z_{LP}$ and $x_{LP} = x^*_{LP}$ (column generation procedure stops). Otherwise, if $c^* < 0$, add to the RMP a new column with coefficients $a^{new}$ (the obtained values after solving the pricing problem), and resolve the RMP and the pricing problem (repeat the previously described column generation iteration).

We give an illustration of the column generation procedure in the following Figure 3.1.

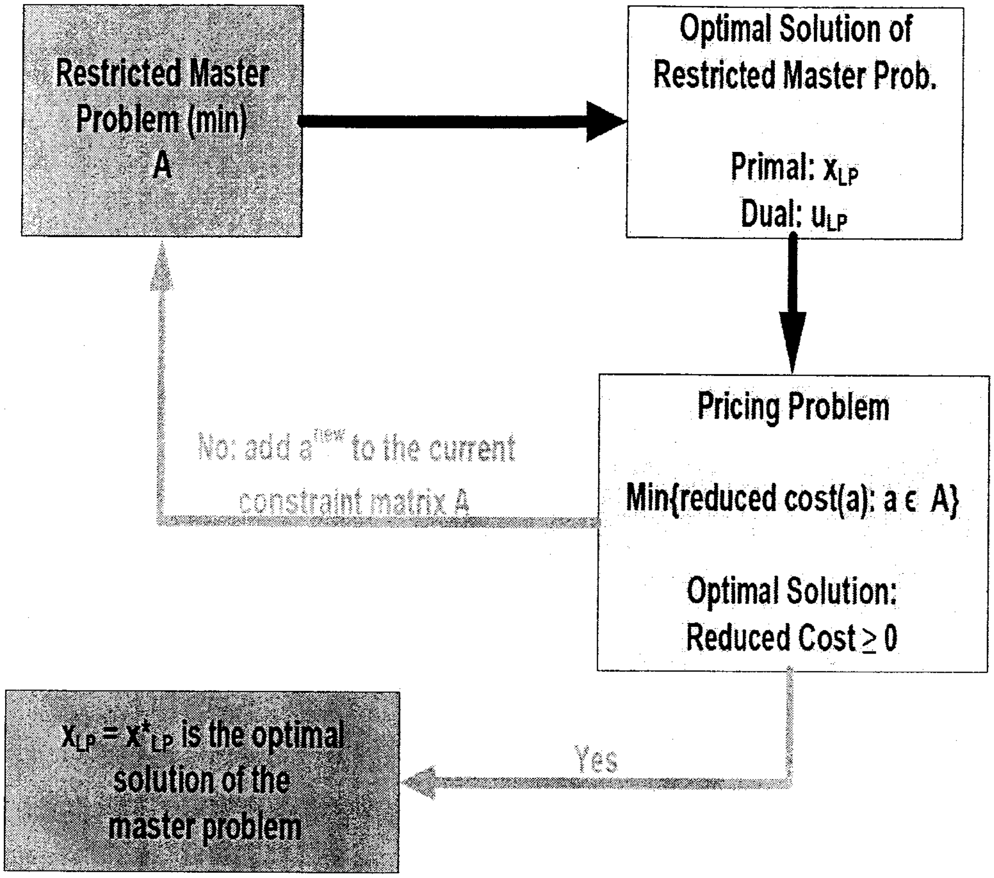


Figure 3.1: Column Generation Procedure [61]

## 3.4 ILP Solutions

Once the LP relaxed optimal solution and its associated generated columns are obtained by the column generation procedure, two possible non-exact scalable strategies can be used to recuperate the ILP solution, namely (1)-the ILP method provided by for instance, a software such as CPLEX [35] or (2)- a self-implemented heuristic ILP. The first consists into solving the master model (with CPLEX [35]), using the generated columns from the column generation procedure along with integer variables (i.e., $x_j \in Z_n^+$ in Section 3.3). However this method is only possible when the set of the generated columns is not too large, which is quite often the case. The second (ILP heuristic) method is used when the set of generated columns becomes to large to be solved by the CPLEX package, and in such case a heuristic can be developed to recuperate an ILP solution based on the generated columns. In both strategies the optimal ILP solution or a near ILP optimal solution (with a small GAP) can be obtained. As formulated in Section 3.1, the distance between the lower bound (the optimal relaxed LP solution) and the upper bound (the recuperated ILP solution) of the ILP optimal solution defines the optimality GAP.

To solve exactly (obtain the ILP optimal solution) large scale Integer Linear Programming (ILP), column generation technique [32] combined with a branch-and-bound method, also called a branch-and-price method [19], is the optimization technique to use. However due to its complexity, and that the previously described strategies provide satisfactory near optimal solutions, they are favored at its expense.

Indeed, although ILPs arising in practice are very often NP-complete, the ILP method based on column generation combined with CPLEX [35] (when the number of generated columns is not too large) is computationally highly scalable due to the augmenting property of the pricing that usually requires generating only a tiny fraction of the set of columns before reaching optimality.
Moreover, when the set of columns associated with the optimal LP becomes very large, an ILP heuristic approach for solving the ILP near to optimality based on the rounding off technique, can be easily implemented. Such technique consists into rounding (to the closest integer) the fractional values of the variables associated with the generated columns of the LP optimal solution [32]. This technique is scalable since no additional computational effort is required.

Finally, a round robin approach for solving the ILP using CPLEX [35], in presence of a large set of generated columns, was presented recently by [85]. This technique consists into solving a portion of the generated set of columns of the optimal LP solution, using CPLEX [35], and adding the obtained values with another portion of the set of columns and solving again. This procedure is repeated until the whole set of columns of the optimal LP solution has been solved (covered). It was shown in [85] that this method is very efficient into providing a near optimal ILP solution (small GAP) for large sets of columns associated with the optimal LP solution.

## 3.5 Column Generation for Cross-layer Designs

In this section, we start by presenting some of the existing works which adopted a column generation approach in their wireless cross-layer designs. Then we describe our column generation design approach and some novel points introduced in it.

### 3.5.1 Literature Review

Column generation for wireless cross-layer designs was firstly introduced by Bjorklund *et al.* [24]. Therein, the authors addressed the problem of resource allocation with spatial TDMA (STDMA) as the access control scheme while satisfying the SINR constraint at all receiving nodes. For that matter, they developed mathematical models for both node-oriented and link-oriented allocation strategies where the objective is to minimize the length of the STDMA frame. The authors of [24] showed that both allocation strategies are NP-hard and they presented for the first time a column generation approach for formulating and solving the resource allocation problem under the SINR constraint. They showed that such optimization approach reduced drastically the CPU time to obtain the LP solution when compared with the classical LP simplex method. Instead of solving the resource allocation problem with all possible transmission configuration set as variables to obtain the optimal LP solution, column generation provides the same result while exploring only a small subset of transmission configurations. Indeed transmission configurations are generated one at a time by the pricing problem and fed to the master problem, such that they always improve the current resource allocation (master problem) LP solution.

Based on [24], which was considered as a turning point for using column generation optimization models in order to enable cross layer designs, Capone *et al.* [27] improved it by allowing power and rate controlled transmissions while satisfying the SINR constraints.

### 3.5.2 Our Contributions

In our column generation approach, the master problem consists into joint routing and scheduling the uplink and downlink connections of the WiMAX mesh network, while the pricing problem serves as the transmission configuration generation. At each column generation iteration, the master problem is fed with a transmission configuration from the pricing problem so that to improve the master's objective. If no more improvement can be done, the master's objective is LP optimal.

We mention that one of the novel features that are integrated in our column generation design approach, is the path-based and the link-based master problem formulations done in Chapter 4. Another novel feature, which is to incorporate power-aware broadcasts in the pricing problem, is studied in Chapter 5. More details on the master's objective and formulation as well as the pricing's transmission configuration generation, along with the other contributions, are provided in Chapter 4, 5 and 6.

## 3.6 Conclusions

In this chapter, we reminded the concept of large scale optimization methods and showed how these can lead to efficient wireless cross layer designs. The strength of column generation relies on the fact that it explores implicitly all possible columns (transmission configurations) resulting in drastically reduced CPU time to obtain the LP optimal solution, which is a must in a cross layer design approach given its complexity. Moreover, when solving the ILP (using a non-exact method), based on the generated columns from the relaxed LP column generation optimal solution, we obtain the GAP between the current recuperated ILP solution and the optimal ILP solution. Therefore column generation, provides always a hint on the optimal ILP solution when it is not obtained, based on the previously defined GAP. We note that most of the time, if the ILP optimal solution was not obtained, an ILP solution with a GAP of less than 3% was provided.

# Chapter 4

# Maximizing Spatial Reuse in WiMAX-based mesh networks

In this Chapter, we design a joint routing-scheduling model that maximizes special reuse in WiMAX based-mesh networks. For that purpose, we use a column generation approach which reduces the CPU time for solving the model and increases the scalability. Two formulations are proposed for designing the joint model, basically the link-based CGLink and the path-based CGPath. While CGLink do not require any path information to compute the joint routing-scheduling solution, CG-Path requires a set of potential paths between each couple of source destination node (BS, SS) as an input. However CGPath is more flexible and scalable than CGLink, since it allows users to select the number of potential paths between each (BS,SS) to be fed as an input to the model therefore reducing the CPU time when compared with the CGLink, at the expense of having a less efficient solution (when the number of potential paths is not enough to determine the optimal solution). Finally, in this Chapter, we enable power and rate control transmissions along with sub-carrier allocation when generating a feasible transmission configuration (a set of RF-links that can be active simultaneously).

## 4.1 Introduction

To enhance the throughput of multi-hop wireless mesh networks, it is expected that these networks employ several advanced physical layer techniques, such as MIMO and OFDM, adaptive modulation, etc., and adopt broadband access technologies, such as next generation cellular networks and IEEE 802.16/WiMAX [3] systems. The multi-hop nature of such networks will enables access points to use shorter backhaul links which yields an increase in the network throughput due to lower path loss and better spectrum spatial reuse [77]. However, these networks still face several serious challenges which may hold them from fulfilling their promises in achieving the same services (e.g., higher throughput and quality of service (QoS) guarantees) provided by their wired counterpart. For instance, factors such as lossy wireless links caused by interference from concurrent transmissions on neighboring links, and intra-path interference caused by transmissions on successive hops along a single path [23] are still serious challenges that these network have to deal with. Managing interference in these networks require proper links activation at each time slot (which henceforth we refer to by scheduling) such that neighboring links in the mesh, which mat interfere with each other, are not active simultaneously. Therefore, in this chapter we address the problem of joint routing and scheduling in wireless mesh networks and we assume 802.16 based wireless links in the network. WiMAX technology has emerged as the technology of choice for wireless backhaul due to their higher data rates and their capabilities of achieving communication over long distances and providing QoS guarantees.

We assume centralized scheduling where the base station constructs the routing tree for uplink/downlink traffic from/to their clients. The objective of our formulation is to satisfy a given traffic demand using the minimum system scheduling time. Minimizing the schedule length amounts to maximizing the spectrum spatial reuse by concurrently transmitting on as many links as possible, which we refer to as a transmission configuration (a group of RF-links that can simultaneously transmit without violating the signal-to-interference-plus-noise ratio (SINR) requirement); our model is hence referred to as maximum spatial reuse (MSR) model. We assume opportunistic scheduling (rate control) where nodes in the mesh network exploits the time-varying link conditions to achieve better system throughput. We further assume that a node can select a suitable transmission power to reach its immediate "receiving" next hop and we refer to this scheme as power-aware scheme (MSR-PA). Our approach is useful for determining the theoretical-capacity of these networks and could be adopted as a traffic engineering methodology, given that the traffic flow varies occasionally. Since this problem is a combinatorially complex one, we adopt a decomposition approach using column generation (CG) [53]. We present two formulations for modeling MSR, namely the link-based (CGLink) and the path-based (CGPath) formulations. These two formulations mainly differ in the number of routing decision variables. Unlike previous work on routing in wireless mesh networks which use link-based formulation, the CGPath presented in this chapter is much more scalable, since it involves a small number of routing variables and provides solutions that are very close or the same as the optimal provided by the time consuming link-based formulation. The remainder of the chapter is organized as follows. Section 4.2 presents the related work and some motivations. Section 4.3 presents the network communication model and assumptions. Section 4.4 defines the problem through an illustrative example. In Section 4.5, the transmission configuration generation problem is formulated, then in Section 4.6 the joint routing-scheduling problem is presented. Section 4.7 presents a column generation based formulation of the problem. In Section 4.9, the numerical results are discussed. Finally conclusions are drawn in Section 4.10.

## 4.2 Related Work

Recently, the problem of jointly controlling routing and transmission scheduling in STDMA-based multi-hop wireless networks is presented in [65]; the authors presented a cross-layer formulation which incorporates multi-path routing and the generation of the set of links that can be simultaneously active without violating the SINR requirement. Routing and scheduling optimization in WMNs with nodes equipped with directional antennas is studied by Capone *et al.* [28] and a CG approach is used to determine a lower bound on the objective (minimum length schedule).

Nahle *et al.* [76] presented a joint routing and scheduling for improving the performance of WiMAX-based mesh networks. The routing selects high end-to-end data rate routes and the scheduling ensures resource allocation (channels and slots) that yields maximum utilization and fairness. The proposed heuristic has shown, through a simulation study, to improve the system capacity. This work however differs from our current work in that we are presenting an optimal design method for the joint routing and scheduling. Further, our work considers the feedback from physical layer (i.e., SINR) when performing MAC scheduling to determine the proper link activation schedule. The work done in [76] did not consider interference in their heuristic. Ali *et al.* [15] presented another heuristic for centralized scheduling and routing in WiMAX based mesh networks. Their method however decomposes the scheduling and routing problems and solve them separately and do not consider the realistic physical layer model to capture interference in the network. Similarly, Tao *et al.* [94] have studied throughput enhancement in WiMAX/802.16 mesh networks by constructing also separate heuristics for routing and scheduling. The work of [76], [15] and [94] did not, however, consider power control transmissions neither rate control which can further improve the throughput (efficiency) of the mesh network.

## 4.3 Network Communication Model

We consider a directed graph $G(V, L)$ which represents the WiMAX/802.16 mesh network. $V$ denotes the set of nodes (BS and SS) and $L$ represents the set of RF-links that are available between nodes. Note that a RF-link exists if its receiving node is within the coverage range of its transmitting node. We assume that all nodes have the same maximum covering range $D$ and therefore if a link exists in a particular direction, its corresponding link in the opposite direction exists too. Moreover, denote by $V_i^+$ the set of neighbors of $i$ such that $j \in V_i^+$ iff $(i, j) \in L$. Similarly, $V_i^-$ represents the set of neighbors of $i$ such that $j \in V_i^-$ iff $(j, i) \in L$. Finally, $V_i = V_i^- \cup V_i^+$ denotes the set of all neighbors of node $i$.

We consider the physical model [56], which captures the effect of cumulative interference. The physical model, also known as the capture model [56], considers the SINR constraints at the receiver for correct reception; a signal is correctly received and decoded at a receiving node $j$ if the SINR at the receiver is greater than a threshold $\Gamma_r$, where $r$ is the physical data rate used to transmit the signal. The following constraint reflects such property and should be satisfied for every active transmitting link $(i, j)$:

$$SINR_{ij} = \frac{p_{ij} G_{ij}}{\eta + \sum\limits_{(l,m) \neq (i,j)} p_{lm} G_{lj}} \geq \Gamma_r \tag{4.1}$$

where $\eta$ is the thermal noise, $p_{ij}$ is the transmitting power of node $i$ used to communicate with node

$j$ and $G_{ij}$ is the environment or channel gain between nodes $i$ and $j$. Note that $G_{ij} = d_{ij}^{-\alpha}$ where $d_{ij}$ represents the distance between $i$ and $j$ and $\alpha$ the path loss factor. The denominator of expression (4.1) represents the background thermal noise and the asynchronous interference generated by other transmissions taking place when link $(i, j)$ is active.

We distinguish between two types of nodes in WiMAX/802.16. Subscriber Station (SS) nodes, e.g., WiFi APs, and the Base Station (BS) which performs centralized routing and scheduling decisions. The IEEE WiMAX/802.16 supports both point-to-multipoint (P2MP) and multipoint-to-multipoint modes. In mesh mode, SSs can communicate with the BS and with each other through multi-hop routes via other intermediate (sponsor/relay nodes) SSs. The main advantages of WiMAX/802.16 mesh mode includes extending the network coverage and providing high bandwidth assignment to end clients (even distant ones) located at SSs which are not necessarily in the line of sight (LOS) of the BS. The IEEE WiMAX/802.16 mesh mode of operation uses Time Division Multiple Access (TDMA) technology [25] [37] where a scheduling period is divided into time slots. We further assume sub-channelization (sub-carrier allocation) within a time slot; sub-channelization divides the spectrum into multiple orthogonal sub-channels (e.g., OFDM technology). This sub-channelization allows multiple data streams to be successfully received concurrently either at the same node or at neighboring nodes.

## 4.4 Problem Statement

Our objective is to find the minimum scheduling length which satisfies all the upling/downlink demands. To achieve our objective, we jointly optimize the routing (tree construction) and link scheduling for traffic delivery. We note that to maximize spatial reuse (under interference constraints), many links (with enough spatial separation) should be activated simultaneously (we refer to such group of links as transmission configuration). Consider the network shown in Figure 4.1 for illustration where bidirectional edges represent the feasible transmission links (we assume a single channel and a single sub-carrier in the network). Two uplink sessions of one unit demand each are to be established between nodes N1, N2 and the BS. We assume time is divided into slots (of one unit demand capacity each) and we need to determine a link activation schedule to satisfy the traffic demands. To deliver traffic from N1 and N2 to the BS, we consider the following 3 possible trees that might be chosen (see Figure 4.2): $T_1$ =(N1-N3-BS, N2-N4-BS), $T_2$ =(N1-N3-BS, N2-N4-N3-BS), $T_3$ =(N1-N3-N4-BS, N2-N4-BS), (other trees are also possible but excluded). Assume $T_1$ is selected, traffic from N1 to BS must be routed through N3. Due to intra-path interference and single radio constraint at node N3, both links (N1-N3) and (N3-BS) cannot be active during the same time slot. A similar argument is made for (N2-N4-BS). One feasible non-optimal solution for the problem is to use 4 time slots, each for activating one link. However, by exploiting the spectrum spatial reuse, we can activate both links (N1-N3) and (N4-BS) at the same time, assuming that the activation of (N4-BS) does not corrupt the reception on (N1-N3) (i.e., $SINR_{13} \geq \Gamma$). Similarly, (N2-N4) and (N3-BS) can be active simultaneously in one time slot ($SINR_{24} \geq \Gamma$). This results in scheduling two transmission configurations ($g_1, g_2$), each configuration consists of a set of links that can be concurrently active, and thereby forming a routing tree ($T_1$) for uplink demands. It can be easily verified that the other trees will require more time slots for delivering the two uplink demands. We further note that, transmission configurations could be repeatedly assigned to several time slots.

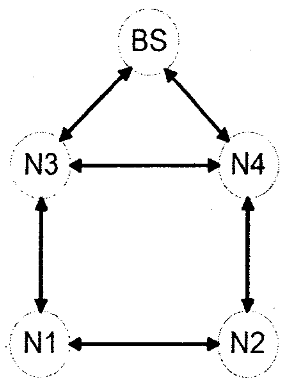


Figure 4.1: WiMAX Mesh network example.

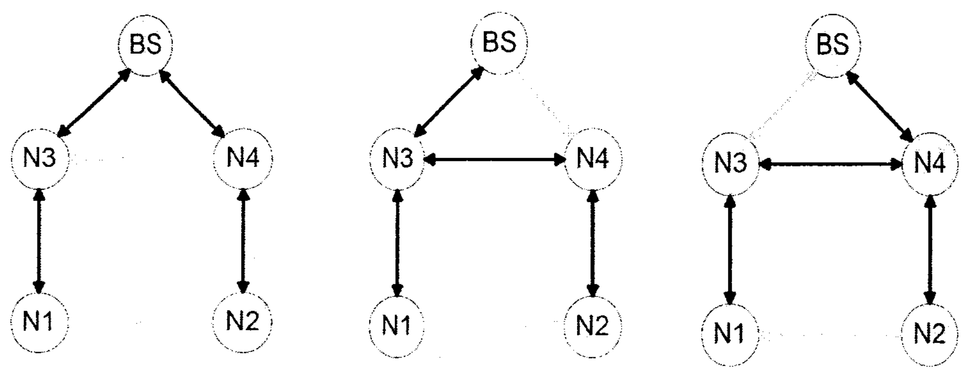


Figure 4.2: left: $T_1$; middle: $T_2$; right: $T_3$

## 4.5 Transmission Configuration Generation Problem

The fundamental issue is to determine a set of links that can be active concurrently in the same time slot while respecting the SINR condition at the corresponding receivers. We assume opportunistic scheduling where a sender selects a transmission rate on its selected subchannel (subcarrier) which depends on the distance to its receiver and the spectrum conditions. Each time a link is active, we need to determine which subchannel(s) is/are allocated to carry the traffic routed through the link. Let $R$ denotes the set of feasible rates available for selection, $C$ denotes the set of available orthogonal subchannels and $S$ denotes the set of all feasible configurations (transmission configurations). A configuration (transmission configuration) is hence the set of links, their rates, transmission power and corresponding subchannels. We first formulate the problem assuming fixed transmission power and rate and then extend the formulation to make them variables.

### 4.5.1 Subcarrier Allocation

Define binary variables $t_{ij}^{s,c}$, where $s \in S$, $c \in C$ and $(i,j) \in L$. $t_{ij}^{s,c} = 1$ if $(i,j)$ is active in transmission configuration $s$ and a subcarrier $c$ is allocated to it, and 0 otherwise. Constraints (4.2) allow a node $i$ to transmit on only one subcarrier $c \in C$ (and to a particular neighbor $j$) in one transmission configuration $s$ ($V$ is the set of nodes). Constraints (4.3) ensure that a node $i$ cannot transmit and receive in the same time slot (associated with transmission configuration $s$). $V_i$ is the set of neighbors of node $i \in V$. Constraints (4.4) avoid collisions at receiving node $i$ when neighboring nodes are transmitting using the same subchannel $c$ to node $i$. Moreover constraints (4.4) implicitly allow a node $i$ to receive multiple data streams at the same time slot on different subcarriers; thus, a node cannot receive from more than $|C|$ neighboring nodes at the same time slot.

$$\sum_{j:(i,j)\in L} \sum_{c\in C} t_{ij}^{s,c} \leq 1 \qquad i \in V. \tag{4.2}$$

$$\sum_{c\in C} t_{ji}^{s,c} + \sum_{c\in C} t_{ij}^{s,c} \leq 1 \quad i \in V\ , j \in V_i. \tag{4.3}$$

$$\sum_{j:(j,i)\in L} t_{ji}^{s,c} \leq 1 \qquad i \in V\ , c \in C. \tag{4.4}$$

Constraint (4.5) ensures that the SINR threshold $\Gamma$ is satisfied at a receiving node $j$ for correct frame reception; here, $i$ is the transmitting node on a particular subcarrier $c$. We point out that (4.5) is a linear relaxed form of the SINR expression (4.1) [27]. As formulated in (4.5), if link $(i, j)$ is active in subcarrier $c$ within transmission configuration $s$ (i.e., $t_{ij}^{s,c} = 1$), then, from constraint (4.5), $P_{\max} G_{ij} \geq \Gamma \left( \eta + \sum_{(h,m) \in L; h \neq i} P_{\max} G_{hj} t_{hm}^{s,c} \right)$, otherwise (i.e., $t_{ij}^{s,c} = 0$) therefore constraint (4.5) is always satisfied and thus $P_{\max} G_{ij} + M_{ij}^{c} \geq \Gamma \left( \eta + \sum_{(h,m) \in L; h \neq i} P_{\max} G_{hj} t_{hm}^{s,c} \right)$ given that $M_{ij}^{c}$ is always greater than the right-side part of the constraint (4.5).

$$P_{\max} G_{ij} + M_{ij}^{c}(1 - t_{ij}^{s,c}) \geq \Gamma \left( \eta + \sum_{(h,m) \in L; h \neq i} P_{\max} G_{hj} t_{hm}^{s,c} \right) \quad i \in V,\ j \in V_i,\ c \in C \quad (4.5)$$

where $M_{ij}^{c} \geq (\eta + \sum_{(h,m) \in L; h \neq i} P_{\max} G_{hj} t_{hm}^{s,c})\ (i, j) \in L$,

$\Gamma$ is the SINR threshold, $\eta$ is the background thermal noise and $P_{\max}$ is the maximum transmission power.

### 4.5.2 Power Aware, Multi-Rate Mesh Network

Now as the environment conditions vary (due to fading, shadowing and other effects), network nodes should opportunistically schedule their transmissions and select appropriate transmission rate and power on their outgoing links to overcome the link dynamics. Thus, we extend our model above accordingly. We denote by $t_{ij}^{s,c,r}$ the new binary variables for determining the transmission configurations, where $r$ stands for the transmission rate selected. $\Gamma_r$ is the SINR threshold needed for correct frame reception at transmission rate $r$. Constraints (4.2)-(4.4) are replaced with the following constraints:

$$\sum_{j:(i,j)\in L}\sum_{c\in C}\sum_{r\in R} t_{ij}^{s,c,r} \leq 1 \qquad i \in V. \tag{4.6}$$

$$\sum_{c\in C}\sum_{r\in R} t_{ji}^{s,c,r} + \sum_{c\in C}\sum_{r\in R} t_{ij}^{s,c,r} \leq 1 \quad i \in V\ , j \in V_i. \tag{4.7}$$

$$\sum_{j:(j,i)\in L}\sum_{r\in R} t_{ji}^{s,c,r} \leq 1 \qquad i \in V\ , c \in C. \tag{4.8}$$

For example (4.6) ensures that in one configuration $s$, a node $i$ transmits to its neighbor $j$ on only one subcarrier $c$ and using one particular rate $r$ ($r$ is selected from the set of available rates $R$). The other constraints are straightforward. (4.9) ensures that for a successful transmission between node $i$ (using rate $r$ and on subcarrier $c$) and node $j$, the SINR threshold $\Gamma_r$ must be met.

$$P_{\max} G_{ij} + M_{ij}^{c,r}(1 - t_{ij}^{s,c,r}) \geq \Gamma_r \left( \eta + \sum_{(h,m)\in L; h\neq i} P_{\max} G_{hj} (\sum_{r\in R} t_{hm}^{s,c,r}) \right) \tag{4.9}$$

where $i \in V,\ j \in V_i,\ c \in C,\ r \in R$ and

$M_{ij}^{c,r} \geq (\eta + \sum_{(h,m)\in L; h\neq i} P_{\max} G_{hj} t_{hm}^{s,c,r})\ (i,j) \in L.$

Constraint (4.9) assumes that all nodes use the same maximum transmission power $P_{\max}$ (MSR-MTP model). When transmission power is adaptively chosen (MSR-PA), (4.9) changes to the following:

$$p_{ij}^{s,c} G_{ij} + M_{ij}^{c,r}(1 - t_{ij}^{s,c,r}) \geq \Gamma_r \left( \eta + \sum_{(h,m)\in L; h\neq i} p_{hm}^{s,c} G_{hj} \right) \tag{4.10}$$

where $p_{ij}^{s,c}$ is a real variable ($p_{ij}^{s,c} \in [0, P_{max}]$) denoting the transmit power required on link $(i,j)$ to meet the SINR requirement which is proportional to the amount of accumulative interference at $j$

| | Type | | Definition |
|---|---|---|---|
| Term | Par | Var | |
| $t_{ij}^{s,c,r}$ | | X | $(i,j)$ is active within sub carrier $c$ @ rate $r$ |
| $M_{ij}^{s,c,r}$ | X | | large value associated with $(i,j)$ when active within $c$ at rate $r$ |
| $G_{ij}$ | X | | the environment gain between nodes $i$ and $j$ |
| $\Gamma_r$ | X | | the SINR threshold associated with rate $r$ |
| $\eta$ | X | | the background thermal noise |
| $\varepsilon$ | X | | a very small number |
| $P_{\max}$ | X | | maximum transmission power |
| $p_{ij}^{s,c}$ | | X | variable transmission power of link $(i,j)$ |

Table 4.1: Parameters and variables used in the transmission configuration generation.

from nodes transmitting concurrently on the same subcarrier $c$. Note that the correctness of $p_{ij}^{s,c}$ is ensured by adding the following constraints:

$$p_{ij}^{s,c} \geq \varepsilon \sum_{r\in R} t_{ij}^{s,c,r}; \qquad p_{ij}^{s,c} \leq P_{\max} \sum_{r\in R} t_{ij}^{s,c,r} \tag{4.11}$$

where $\varepsilon$ is a very small real number. Hence, if $(i,j)$ is active at any rate and and assigned subchannel $c$ ($\sum\limits_{r\in R} t_{ij}^{s,c,r} = 1$), then $p_{ij}^{s,c} > 0$. Otherwise if $(i,j)$ is not using subchannel $c$ and for any rate ($\sum\limits_{r\in R} t_{ij}^{s,c,r} = 0$), then $p_{ij}^{s,c} = 0$. We point out that in a transmission configuration $s$, given constraint (4.6), only one subchannel $c$ can have $p_{ij}^{s,c} > 0$, and thus the transmission power on link $(i,j)$ becomes $p_{ij}^{s,c}$.

We summarize the parameters (Par) and variables (Var) used in the transmission configuration generation problem, in Table 4.1.

## 4.6 Joint Routing-Scheduling Problem

We first define some parameters and variables that are commonly used in our formulations. Let $S$ be the set of possible transmission configurations. In addition, an integer variable $\lambda_s$ is associated

| | Type | | Formulation | | Definition |
|---|---|---|---|---|---|
| Term | Par | Var | Link | Path | |
| $\lambda_s$ | | X | X | X | number of times configuration $s$ is used |
| $t_{ij}^{s,c,r}$ | X | | X | X | $(i,j)$ active link in $s$ within sub carrier $c$ @ rate $r$ |
| $W_{ij}^{s,c,r}$ | X | | X | X | time slot $s$ size in bits when $(i,j)$ within $c$ at rate $r$ |
| $W$ | X | | X | X | large value |
| $R_{\text{SS}}^{\text{UL}}$ | X | | X | X | uplink demand in bits to satisfy at an SS |
| $R_{\text{SS}}^{\text{DL}}$ | X | | X | X | downlink demand in bits to satisfy at an SS |
| $y_{ij}^{\text{UL}}$ | | X | X | X | link $(i,j)$ active for uplink |
| $y_{ij}^{\text{DL}}$ | | X | X | X | link $(i,j)$ active for downlink |
| $w_{ij}^{\text{SS}+}$ | | X | X | | flow routed on $(i,j)$ for SS uplink |
| $w_{ij}^{\text{SS}-}$ | | X | X | | flow routed on $(i,j)$ for SS downlink |
| $w_{p}^{\text{SS}+}$ | | X | | X | flow routed on path $p$ for SS uplink |
| $w_{p}^{\text{SS}-}$ | | X | | X | flow routed on path $p$ for SS downlink |
| $x_{p}^{\text{SS}+}$ | | X | | X | path $p$ routes SS uplink |
| $x_{p}^{\text{SS}-}$ | | X | | X | path $p$ routes SS downlink |
| $\delta_p^{ij}$ | X | | | X | link $(i,j)$ belongs to path $p$ |

Table 4.2: Parameters and variables used in the joint problem.

with each transmission configuration $s \in S$ that is equal the number of times $s$ is used throughout a TDMA scheduling period (i.e., number of times $s$ is assigned to time slots in the scheduling period). In addition the following variables $y_{ij}^{\text{UL}}$ ($y_{ij}^{\text{DL}}$) are introduced to identify whether or not link $(i,j)$ is active for uplink (or downlink) transmission in a scheduling period. These variables will come in handy when constructing the routing tree associated with the centralized scheduling. $y_{ij}^{\text{UL}} = 1$, if $(i,j)$ is active for uplink transmission, 0 otherwise. Similarly $y_{ij}^{\text{DL}} = 1$, if $(i,j)$ is active for downlink transmission, 0 otherwise. Moreover, we define $t_{ij}^{s,c,r}$ as a parameter in the joint routing-scheduling problem such that: $t_{ij}^{s,c,r} = 1$ if $(i,j)$ is active in transmission configuration $s$ within subcarrier $c \in C$ and at rate $r \in R$, and 0 otherwise. We summarize in Table 4.2 the parameters and variables that are used throughout our model.

### 4.6.1 Link-based Formulation

We define first the routing variables. $w_{ij}^{\text{SS}^+}$ is a real variable that represents the amount of uplink traffic of node SS $\in V$ routed through link $(i,j) \in L$. $w_{ij}^{\text{SS}^-}$ is a real variable that represents the amount of downlink traffic of node SS $\in V$ routed through link $(i,j) \in L$. Hence the overall number of routing variables is $2(|V|-1) \times |L|$. For example, in a mesh network of 23 nodes and 116 links, the overall number of routing variables is $2(23-1) \times 116 = 5104$. Our objective is to minimize the overall number of time slots (or schedule's length):

**Objective:**

$$\min \sum_{s \in S} \lambda_s \tag{4.12}$$

**Subject to:**

The flow conservation for uplink demands are (for a given SS node):

$$\sum_{j \in V_i^-} w_{ji}^{\text{SS}^+} - \sum_{j \in V_i^+} w_{ij}^{\text{SS}^+} = \begin{cases} 0 & \text{if } i \in V \setminus \{\text{SS}, \text{BS}\} \\ -R_{\text{SS}}^{\text{UL}} & \text{if } i = \text{SS} \\ R_{\text{SS}}^{\text{UL}} & \text{if } i = \text{BS} \end{cases} \qquad i \in V,\ \text{SS} \in V/\{\text{BS}\}. \tag{4.13}$$

where $R_{\text{SS}}^{\text{UL}}$ is the uplink demand to be satisfied for a Subscriber Station SS.

Similarly, flow conservation constraints must also be enforced for downlink demands (for a given SS node).

$$\sum_{j\in V_i^-} w_{ji}^{\mathrm{SS}^-} - \sum_{j\in V_i^+} w_{ij}^{\mathrm{SS}^-} = \begin{cases} 0 & \text{if } i \in V \setminus \{\mathrm{SS}, \mathrm{BS}\} \\ R_{\mathrm{SS}}^{\mathrm{DL}} & \text{if } i = \mathrm{SS} \\ -R_{\mathrm{SS}}^{\mathrm{DL}} & \text{if } i = \mathrm{BS} \end{cases} \qquad i \in V,\ SS \in V/\{\mathrm{BS}\}. \quad (4.14)$$

where $R_{\mathrm{SS}}^{\mathrm{DL}}$ is the downlink demand to be satisfied for a Subscriber Station SS. Now, in order to satisfy the definitions of $y_{ij}^{\mathrm{UL}}$ and $y_{ij}^{\mathrm{DL}}$, we formulate the following constraints :

$$\frac{w_{ij}^{\mathrm{SS}^+}}{W} \leq y_{ij}^{\mathrm{UL}}; \quad \mathrm{SS} \in V/\{\mathrm{BS}\},\ (i,j) \in L \qquad (4.15)$$

$$\frac{w_{ij}^{SS^-}}{W} \leq y_{ij}^{\mathrm{DL}} \quad \mathrm{SS} \in V/\{\mathrm{BS}\},\ (i,j) \in L \qquad (4.16)$$

where $W$ is a large value. To ensure the routing tree structure property, (4.17) and (4.18) are used for both uplink and downlink connections respectively:

$$\sum_{j\in V_i^+} y_{ij}^{\mathrm{UL}} \leq 1 \quad i \in V \qquad (4.17)$$

$$\sum_{j\in V_i^-} y_{ji}^{\mathrm{DL}} \leq 1 \quad i \in V \qquad (4.18)$$

Finally, (4.19) represents the bandwidth constraint.

$$\sum_{s\in S}\sum_{c\in C}\sum_{r\in R} t_{ij}^{s,c,r} W_{ij}^{s,c,r} \lambda_s \geq \sum_{\mathrm{SS}\in V/\{\mathrm{BS}\}} (w_{ij}^{\mathrm{SS}^+} + w_{ij}^{\mathrm{SS}^-}) \quad (i,j) \in L \qquad (4.19)$$

where $W_{ij}^{s,c,r}$ is the transport capacity of link $(i,j) \in L$ that is active during configuration $s$ on subcarrier $c \in C$ and operating at a rate $r \in R$.

### 4.6.2 Path-based Formulation

Here, each SS is assigned with a predetermined set of potential routing paths to the BS (for uplink connections) denoted by $P_{\text{SS}^+}$ and the BS is assigned with a set of routing paths ($P_{\text{SS}^-}$) to each SS (for downlink connections). The following variables and parameters are used: $w_p^{\text{SS}^+}$ represents the amount of uplink traffic that is being routed on path $p \in P_{\text{SS}^+}$. $x_p^{\text{SS}^+}$ is 1, if $w_p^{\text{SS}^+} > 0$; 0 otherwise. $w_p^{\text{SS}^-}$ represents the amount of downlink traffic which is routed on path $p \in P_{\text{SS}^-}$. $x_p^{\text{SS}^-}$ is 1 if $w_p^{\text{SS}^-} > 0$, and 0 otherwise. We also define the parameter $\delta_p^{ij}$ which is equal 1 if $(i, j)$ belongs to path $p$, 0 otherwise. Note that, under this formulation, and considering 3 potential paths between each SS node and the BS, the overall number of routing variables in a mesh of 23 nodes and 116 links is $4(V - 1) \times 3 = 264$, which is much smaller than the 5104 variables of the link-based formulation. In addition, we point out that, unlike link-based formulation which explores all possible paths (which exponentially grow with the size of the network), the path-based formulation considers only a subset of predetermined paths to construct the routing tree. Our objective is the same as (4.12) with the following constraints. A direct relationship exists between $x_p^{\text{SS}^+}$ ($x_p^{\text{SS}^-}$) and $w_p^{\text{SS}^+}$ ($w_p^{\text{SS}^-}$), which requires constraints (4.20) and (4.21). Constraints (4.22) and (4.23) ensure that one path among the potential paths is selected to route respectively the uplink/downlink traffic. (4.24) presents the uplink flow conservation constraint (a similar one for downlink is derived). In order to satisfy the definitions of $y_{ij}^{\text{UL}}$ and $y_{ij}^{\text{DL}}$, we formulate constraints (4.25) and (4.26) respectively. (4.17) and (4.18) (refer to Section 4.6.1) are introduced to preserve the rooted tree property. Finally, (4.27) defines the bandwidth constraint at each link $(i, j) \in L$.

$$x_p^{\mathrm{SS}^+} \geq \frac{w_p^{\mathrm{SS}^+}}{W} \quad p \in P_{\mathrm{SS}^+}; \quad \mathrm{SS} \in V \tag{4.20}$$

$$x_p^{\mathrm{SS}^-} \geq \frac{w_p^{\mathrm{SS}^-}}{W} \quad p \in P_{\mathrm{SS}^-}; \quad \mathrm{SS} \in V \tag{4.21}$$

$$\sum_{p \in P_{\mathrm{SS}+}} x_p^{\mathrm{SS}^+} \leq 1; \qquad \mathrm{SS} \in V/\{\mathrm{BS}\} \tag{4.22}$$

$$\sum_{p \in P_{\mathrm{SS}-}} x_p^{\mathrm{SS}^-} \leq 1 \qquad \mathrm{SS} \in V/\{\mathrm{BS}\} \tag{4.23}$$

$$\sum_{j \in V_i^-} \sum_{p \in P_{\mathrm{SS}+}} \delta_p^{ji} w_p^{\mathrm{SS}^+} - \sum_{j \in V_i^+} \sum_{p \in P_{\mathrm{SS}+}} \delta_p^{ij} w_p^{\mathrm{SS}^+} = \begin{cases} 0 & \text{if } i \in V \setminus \{\mathrm{SS}, \mathrm{BS}\} \\ -R_{\mathrm{SS}}^{\mathrm{UL}} & \text{if } i = \mathrm{SS} \\ R_{\mathrm{SS}}^{\mathrm{UL}} & \text{if } i = \mathrm{BS} \end{cases} \tag{4.24}$$

$$\sum_{p \in P_{\mathrm{SS}+}} x_p^{\mathrm{SS}^+} \delta_p^{ij} \leq y_{ij}^{\mathrm{UL}}; \quad \mathrm{SS} \in V/\{\mathrm{BS}\}, (i,j) \in L \tag{4.25}$$

$$\sum_{p \in P_{\mathrm{SS}-}} x_p^{\mathrm{SS}^-} \delta_p^{ij} \leq y_{ij}^{\mathrm{DL}} \quad \mathrm{SS} \in V/\{\mathrm{BS}\}, (i,j) \in L \tag{4.26}$$

$$\sum_{s\in S}\sum_{c\in C}\sum_{r\in R} t_{ij}^{s,c,r} W_{ij}^{s,c,r} \lambda_s \geq \sum_{\mathrm{SS}\in V/\{\mathrm{BS}\}} \left( \sum_{p\in P_{\mathrm{SS}+}} w_p^{\mathrm{SS}^+} \delta_p^{ij} + \sum_{p\in P_{\mathrm{SS}-}} w_p^{\mathrm{SS}^-} \delta_p^{ij} \right) \quad (i,j)\in L \tag{4.27}$$

## 4.7 A Column Generation Approach

Clearly, enumerating all possible feasible transmission configurations for solving the LP problem is not feasible, and additionally most of these configurations will not be used in the optimal solution. To reduce this complexity we use a primal-dual column generation approach (described in Chapter 3), for decomposing the problem into subproblems. Column generation, originally presented in [53], [54] is an optimization technique that decomposes the linear program (LP) into a master model (joint routing and scheduling problem) and a pricing model (transmission configuration generation problem). The master model is initialized with a subset of columns $S_0$ of the LP. The pricing problem, which is a separate model for the dual LP, is a column generator that keeps generating and adding columns as long as there exists one that can improve the LP solution of the master problem. Given the augmenting property of the pricing problem, where a transmission configuration is generated only to improve the master problem solution, a tiny fraction of such groups is usually enough to reach optimality (a proof of optimality of the solution is given in [32]).

### 4.7.1 Master Problem

Given that the master problem, which corresponds to the joint routing scheduling problem, contains only a subset $S_0$ of transmission configurations, we write the objective of the master problem for the as follows:

$$\min \sum_{s \in S_0} \lambda_s \tag{4.28}$$

**Subject to:** (in the case of link-based formulation) Constraints (4.13) to (4.18), and

$$\sum_{s \in S_0} \sum_{c \in C} \sum_{r \in R} t_{ij}^{s,c,r} W_{ij}^{s,c,r} \lambda_s \geq \sum_{\text{SS} \in V/\{\text{BS}\}} (w_{ij}^{\text{SS}^+} + w_{ij}^{\text{SS}^-}) \quad (i,j) \in L \tag{4.29}$$

And **subject to:** (in the case of path-based formulation) Constraints (4.20) - (4.26), (4.17) (4.18), and

$$\sum_{s \in S0} \sum_{c \in C} \sum_{r \in R} t_{ij}^{s,c,r} W_{ij}^{s,c,r} \lambda_s \geq \sum_{\text{SS} \in V/\{\text{BS}\}} ( \sum_{p \in P_{\text{SS}^+}} w_p^{\text{SS}^+} \delta_p^{ij} + \sum_{p \in P_{\text{SS}^-}} w_p^{\text{SS}^-} \delta_p^{ij}) \tag{4.30}$$

### 4.7.2 Pricing Problem: On-line Transmission Configuration Generation

The pricing objective is defined by the reduced cost of the $\lambda_s$ variables, a classical optimality metric in linear programming theory [32]. Using that theory, we can claim that any transmission configuration with a negative reduced cost is an augmented one, i.e., a configuration whose addition improves the LP value of the objective of the master problem. The expression of the reduced cost can be written as follows: $(1 - \sum_{c \in C} \sum_{r \in R} \sum_{(i,j) \in L} t_{ij}^{s,c,r} \sigma_{ij})$, where $\sigma_{ij}$ is the dual variable associated with: (i) constraint (4.29), if link-based formulation is considered, (ii) constraint (6.25), if path-based formulation is considered. To solve the pricing problem, we must look for a transmission configuration $s$ (associated with variables $t_{ij}^{s,c,r}$), where $\sum_{c \in C} \sum_{r \in R} \sum_{(i,j) \in L} \sigma_{ij} t_{ij}^{s,c,r}$ is maximum. If $\max\{\sum_{c \in C} \sum_{r \in R} \sum_{(i,j) \in L} \sigma_{ij} t_{ij}^{s,c,r}\} \geq 1$ (negative reduced cost), the column associated with $s$ is added to the master problem (to $S_0$). Otherwise, no further improvement of the master problem objective is possible and therefore optimality is reached. The pricing problem objective and constraints are written as follows:

$$\max \quad \sum_{c \in C} \sum_{r \in R} \sum_{(i,j) \in L} t_{ij}^{s,c,r} \sigma_{ij} \tag{4.31}$$

**Subject to:**

(4.6)-(4.8)

and (4.9) if (MSR-MTP)

or (4.10) if (MSR-PA)

### 4.7.3 Solution Scheme

In order to solve the joint routing-scheduling ILP problem, we first solve the LP relaxation of the master problem using the column generation technique, where $\lambda_s$ take real values. Note that the theoretical convergence is guaranteed for the LP solution under the same assumptions of convergence of the simplex algorithm (classical LP solution scheme), see, e.g., Chvatal [32].

Once the optimal LP solution has been solved, we solve the ILP problem, called ILP0, defined by the set of explicitly generated columns, where $\lambda_s$ are now integer variables. The optimal solution of the LP relaxation defines a lower bound on the optimal ILP solution, while the the optimal solution of the ILP0 problem defines an upper bound. Difference between the two bounds provides the so-called optimality gap, i.e., the precision of the ILP0 optimal solution with respect to the optimal solution of the joint routing-scheduling ILP problem.

## 4.8 Optimality of the Path-based Formulation

### 4.8.1 The path formulation is not exact

The path formulation is not exact as, from mathematical point of view, we do not examine all possible paths, whether explicitly or implicitly. It is true that it is unlikely that we may miss the optimal solution if we take, e.g., the first 5 shortest paths, taking into account that the transmission network must be a routing tree, where the base station is located at the root of the tree. Note also that, when dealing with optimality, we mean the optimality of the solution of the linear relaxation. In terms of the optimality of the ILP model, there is no guarantee even if we solve the ILP model (made of the columns generated in order to reach the continuous optimal solution) using an exact ILP solver (such as CPLEX). There is no theoretical guarantee that those columns are enough in order to get the optimal ILP solution. One needs to implement a branch-and-cut method in order to guarantee reaching the optimal ILP solution.

### 4.8.2 Required additions in order to make the path formulation exact

There are at least two different ways to modify the current model or solution algorithm in order to guarantee the optimality of the solution.

#### 4.8.2.1 Add another pricing problem

A first way is to add a second pricing problem, in charge of generating routing paths, either downlink or uplink paths. We can still use the current path model with an initial set of routing paths providing by, e.g., a $k$-shortest path algorithm. Once we cannot find any new transmission configuration with a negative reduced cost, we solve the second pricing problem and see if we can generate a new route (uplink or downlink) with a negative reduced cost. Note that the costs and the reduced costs of the path configurations and the transmission configurations are not the same. If we succeed finding such a route, we go back iterating with the first pricing problem, in order to generate new augmenting transmission configurations (some of which will use the latest generated route).

#### 4.8.2.2 Re-using the link formulation

A second way is to re-use the link formulation. As soon as we cannot generate any new transmission configuration with the path formulation, save the current solution and embed it in the link formulation. Either the link formulation will conclude that the solution is indeed optimal (if no new transmission configuration can be generated), or will generate a new transmission configuration which will be use a new route, which does not belong to the initial set of routes.

## 4.9 Numerical Results

We implemented CGLink CGPath MSR models using CPLEX Concert Technology adapted for C++ (version 9.1.3) [35]. The models are then solved on a 64-bit Linux powered machine at 3GHz and 4GB of RAM.

### 4.9.1 Network and Parameters

We consider a random real-like WiMAX/802.16 mesh network (depicted in Figure 4.3), with a single base station (BS) and 22 access points or SS nodes. We assume 58 bidirectional radio links (116 unidirectional links) between some pairs of nodes within transmission range of each other. We mention that the nodes in Figure 4.3 are generated in a random fashion, where each node has a pair of $(x, y)$ coordinates. Hence, to calculate the Euclidean distance $d_{ij}$ between nodes $(x_i, y_i)$ and $(x_j, y_j)$, we use the following expression: $d_{ij} = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}$.

We assume a total spectrum of $B = 56MHz$ and high capacity links with transmission data rates of $r_1 = 50Mbps$, $r_2 = 75Mbps$ and $r_3 = 100Mbps$; their corresponding SINR thresholds $(\Gamma_r)$ are respectively 0.9, 1.6 and 2.5 derived using the Shannon capacity theorem and assuming a Gaussian channel. The Shannon capacity theorem is given by:

$$r = B \log_2(1 + \Gamma_r) \tag{4.32}$$

therefore,

$$\Gamma_r = 2^{\frac{r}{B}} - 1 \tag{4.33}$$

These different rates are used by the base station to opportunistically schedule links in the network. The length of a scheduling period is 100ms and consists of 2400 slots [25] (10 frames of 240 slots with a 10ms duration each). Hence, depending on the selected transmission rate, the number of bits transported per time slot on a particular link varies. For example, at a rate of 100Mbps and assuming a 100ms schedule the transport capacity of a time slot is $W_{ij}^{s,c,r_3} = 4,166.6$bits. We assume one single subcarrier in the spectrum. We further set the thermal noise $\eta = 10^{-6}mW$, the path loss factor $\alpha = 2$ and a maximum transmission power $P_{\max} = 0.6$ Watt. For the power-aware models, the node selects its power from $[0, P_{\max} = 0.6]$ Watt. The traffic demands for uplink/downlink sessions are selected from the set $0.5, 0.75, 1, 1.25, 1.5, 1.75, 2$Mbits per second and we assume each SS has an uplink/downlink session. Finally, in the CGPath, we considered $k = 3$ shortest paths computed using [46] between each SS and the BS.

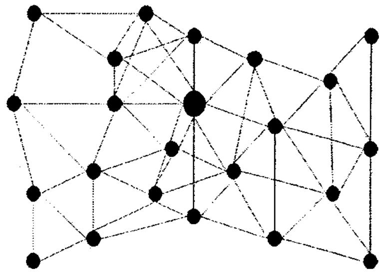

Figure 4.3: 23-Node WiMAX/802.16 Centralized Mesh Network

### 4.9.2 CGPath Vs CGLink

We start by comparing the performance (schedule length and CPU time) of both link-based and path-based formulations; we first assume a fixed transmission rate of 100Mbps per link and we numerically solve the two models MSR-MTP and MSR-PA and we show the results (schedule length and CPU time) in Tables 4.3 and 4.5. We observe (from Table 4.3) that the link-based and path-based formulations achieve the same schedule length for satisfying the end user demands (both for fixed transmission power and dynamic transmission power). However, as shown in Table 4.5, the CPU time of the path-based model is much smaller than that of the link-based model to achieve the optimal solution. For example, for 22 uplink and 22 downlink demands of 0.5Mbits, the MSR-MTP (path) model requires a CPU time of 4.2s and the MSR-MTP (link) model requires a CPU time of 38.4s to reach the optimal solution of 936 time slots (i.e., 9 times faster). We also observe from Table 4.5 that the path-based model (MTP and PA) maintains almost the same computation complexity as the size of the demands to satisfy in the network increases as opposed to the link-based models. In the link-based method, as the size of the demands increases and more time slots are required to satisfy the demands, the combinatorial complexity of the method substantially increases.

In the context of the planning of WiMAX networks, those CPU times are fully acceptable and they will remain so, even if we increase the number of nodes, e.g., to 50 nodes, which is already a very large number of nodes taking into account the current size of WiMAX networks.

Next, we study the benefits of performing power control in WiMAX based mesh networks. In Table 4.3 we see that PA methods (for both path and link based) consistently require less time slots (i.e., shorter scheduling period) to route all the demands in the network. For example when demands are of size 1Mbits, MTP methods require 1872 slots whereas PA methods require 1224 slots, a reduction of 34.6% in the schedule length (which is a direct result from the improved spectrum spatial reuse that power aware methods yield). This gain (referred to as the spatial reuse gain, SRG) is nonetheless obtained at the expense of larger computation time as shown in Table 4.5. One final observation about the results in Table 4.3 is that in some instances, the solution returned by the solver exceeds the total schedule length (2400 slots/cycle). For those instances, the network should admit more traffic than the available capacity. For example, when the traffic load per SS is 1.5Mbits, the network has reached its saturation point under the MTP models whereas the saturation point for the PA models is at 2Mbits. This shows another gain we may achieve from spatial reuse, which is the capability of carrying more traffic using the same network resources.
In addition, as shown in Table 4.4, more configurations are required to obtain the solution associated with Table 4.3 when PA methods are assumed instead of MTP.

We next study the benefits of multi-path routing by varying $k$, $k = 1, 2, 3$ in the path-based model for both MSR-MTP and MSR-PA methods. The results are shown in Tables 4.6 and 4.7. As $k$ increases, different alternatives are explored for constructing the routing trees. The gains are shown for the PA-method; for the MTP method, diversifying the route selection does not yield any benefits since there is no efficient reuse of the spectrum. However, in the PA method, using larger values for $k$ (3) does achieve to the optimal solution obtained by the link-based and smaller values of $k$ results in longer schedule lengths.

It is worth noticing that when all nodes are transmitting using the maximum power, both link and path based models achieve the same performance and varying $k$ in the path based does not yield any benefits. This is due to the fact that under maximum transmit power, the spectrum is not efficiently (spatially) utilized, and when the traffic demand increases the BS becomes the bottlneck, yielding to a schedule length exceeding the maximum schedule period.

| | Number of time slots | | | | | | |
|---|---|---|---|---|---|---|---|
| | Demand per SS (in Mbits) | | | | | | |
| | 0.5 | 0.75 | 1 | 1.25 | 1.5 | 1.75 | 2 |
| CGPath MSR-MTP | 936 | 1,404 | 1,872 | 2,340 | 2,808* | 3,276* | 3,744* |
| CGPath MSR-PA | 612 | 918 | 1,224 | 1,530 | 1,836 | 2,142 | 2,448* |
| CGLink MSR-MTP | 936 | 1,404 | 1,872 | 2,340 | 2,808* | 3,276* | 3,744* |
| CGLink MSR-PA | 612 | 918 | 1,224 | 1,530 | 1,836 | 2,142 | 2,448* |
| SRG (%) | 34.6 | 34.6 | 34.6 | 34.6 | 34.6 | 34.6 | 34.6 |

* denotes that the length of the schedule exceeds the 2400 slots available.

Table 4.3: Number of required time slots in order to satisfy the demand per SS

### 4.9.3 Separate vs. Joint Uplink/Downlink Routing

In this section we consider separate and joint scheduling of both uplink/downlink demands in the mesh network and study the impact on the network performance. The results are shown in Table 4.8; it is clear that by jointly considering uplink and downlink demands, better network performance

| Number of Configurations | |
|---|---|
| Scheme | Number of Configurations used |
| CGPath MSR-MTP | 44 |
| CGPath MSR-PA | 68 |
| CGLink MSR-MTP | 44 |
| CGLink MSR-PA | 68 |

Table 4.4: Number of configuration used per schedule associated with the schedule lengths shown in Table 4.3

| | CPU time (in seconds) | | | | | | |
|---|---|---|---|---|---|---|---|
| | Demand per SS (in Mbits) | | | | | | |
| | 0.5 | 0.75 | 1 | 1.25 | 1.5 | 1.75 | 2 |
| CGPath MSR-MTP | 4.2 | 4.2 | 4.8 | 4.2 | 4.2 | 4.2 | 4.2 |
| CGPath MSR-PA | 32.4 | 31.8 | 33 | 31.8 | 31.8 | 32.4 | 32.4 |
| CGLink MSR-MTP | 38.4 | 43.8 | 52 | 61.2 | 101 | 127 | 149 |
| CGLink MSR-PA | 106.0 | 135 | 156 | 169 | 177 | 199 | 208 |

Table 4.5: CPU time required to obtain a solution.

| | MSR-MTP Scheme | | | MSR-PA Scheme | | |
|---|---|---|---|---|---|---|
| | Demand / SS (Mbits) | | | Demand / SS (Mbits) | | |
| | 0.5 | 1 | 1.5 | 0.5 | 1 | 1.5 |
| CGPath 1-shortest path | 936 | 1,872 | 2,808* | 654 | 1,308 | 1,962 |
| CGPath 2-shortest paths | 936 | 1,872 | 2,808* | 630 | 1,260 | 1,890 |
| CGPath 3-shortest paths | 936 | 1,872 | 2,808* | 612 | 1,224 | 1,836 |
| CGLink | 936 | 1,872 | 2,808* | 612 | 1,224 | 1,836 |

* denotes that the length of the schedule exceeds the 2400 slots available.

Table 4.6: Number of time slots required to satisfy the demands.

(e.g., shorter schedule length) is achieved which results from the higher spectrum spatial reuse. This higher spatial reuse of the spectrum is attributed to the fact that the scheduler jointly selects the uplink and downlink routing trees such that more links may be scheduled concurrently while maintaining the required transmission quality for successfully delivering the traffic. When considering the demands separately, each uplink and downlink routing trees are selected separately by the BS, and it is clear that smaller CPU time is obtained (since smaller number of routing and decision

| | MSR-MTP Scheme | | | MSR-PA Scheme | | |
|---|---|---|---|---|---|---|
| | Demand / SS (in Mbits) | | | Demand / SS (in Mbits) | | |
| | 0.5 | 1 | 1.5 | 0.5 | 1 | 1.5 |
| CGPath 1-shortest path | 2 | 1.8 | 1.8 | 23 | 23 | 23 |
| CGPath 2-shortest paths | 3 | 3 | 3 | 29 | 29 | 28 |
| CGPath 3-shortest paths | 4.2 | 4.8 | 4.2 | 32 | 33 | 32 |
| CGLink | 38.4 | 52 | 101 | 106 | 156 | 177 |

Table 4.7: Computing times (in seconds) required to obtain a solution.

| CGPath MSR-PA | | | | | | | |
|---|---|---|---|---|---|---|---|
| | Number of Slots | | | | CPU time in seconds | | |
| Scheme | Demand/SS (in Mbits) | | | | Demand/SS (in Mbits) | | |
| | 0.25 | 0.5 | 1 | | 0.25 | 0.5 | 1 |
| Uplink alone | 180 | 360 | 720 | | 12 | 11 | 12 |
| Downlink alone | 186 | 372 | 744 | | 15 | 14 | 14 |
| Uplink alone + Downlink alone | 386 | 732 | 1464 | | 27 | 25 | 26 |
| Joint Uplink & Downlink | 306 | 612 | 1224 | | 33 | 32 | 32 |

Table 4.8: Number of time slots required to satisfy the demands and associated CPU time.

variables are involved), but clearly more time slots are required (hence less network throughput) to carry the demands.

### 4.9.4 56-Node Mesh Network

We now use a 56-node (540 links), depicted in [41], wireless mesh network and perform similar experiments to the previous ones. We assume the same transmission rate (100Mbps) per each link and the scheduling frame is divided into 2400 time slots as explained earlier. We compare the performance of our methods (MTP/PA link based and path based) using the same metrics as before. Table 4.9 shows the number of time slots required to satisfy the demands for both MSR-MTP and MSR-PA schemes. We observe first that in the MSR-MTP scheme, 1-shortest path per SS (single path routing) in the CGPath formulation yields the same solution (optimal one) as the CGLink formulation. Increasing the number of paths ($k > 1$) gives the same result as the single path routing, but however this increases the CPU time as observed in Table 4.10. Note also that the CGLink formulation has the largest CPU time and achieves the same optimal solution (refer to Table 4.10). These same observations were noticed too for the 23-node network.

Now, unlike the MSR-MTP method, in MSR-PA, increasing the number of paths per SS ($k = 1, 2, 3$), in the CGPath formulation, leads to a better spectrum spatial reuse (see Table 4.9) which is

| | MSR-MTP Scheme | | | MSR-PA Scheme | | |
|---|---|---|---|---|---|---|
| | Demand / SS (in Mbits) | | | Demand / SS (in Mbits) | | |
| | 0.25 | 0.5 | 0.75 | 0.25 | 0.5 | 0.75 |
| CGPath 1-shortest path | 1,296 | 2,592* | 3,888* | 984 | 1,968 | 2,952* |
| CGPath 2-shortest paths | 1,296 | 2,592* | 3,888* | 922 | 1,844 | 2,766* |
| CGPath 3-shortest paths | 1,296 | 2,592* | 3,888* | 895 | 1,790 | 2,685* |
| CGLink | 1,296 | 2,592* | 3,888* | - | - | - |

* denotes that the length of the schedule exceeds the 2400 slots available.

Table 4.9: Number of required slots in order to satisfy the demands

evident from the shorter schedule length required to route the demands. However, the trade-off is that the CPU time increases drastically (given the large scale of the network) when the number of paths per SS node increases, as observed in Table 4.10. The explanation behind such observation is that, under the power aware scheme, an increased number of paths per SS node in the CGPath formulation, leads to a better selection and construction of the routing tree thereby allowing more links to transmit concurrently using adequate transmission power. It is worth pointing out that for the CGLink MSR-PA, the optimal solution was not found after 4 days of running time, and this is owed to the highly increased computation complexity of such formulation under large scale networks. In addition to these previous observations, we also compare the performance of MSR-MTP and MSR-PA for the CGPath formulation with respect to the minimum length schedule (number of slots) and the CPU time to obtain the solution (Table 4.9 and Table 4.10 respectively). For a particular set of bandwidth demands and same number of shortest paths per each SS, it is clear that MSR-PA provides a shorter length schedule than MSR-MTP (see Table 4.9), at the expense of increased CPU time as it is shown in Table 4.10.

| | MSR-MTP Scheme | | | MSR-PA Scheme | | |
|---|---|---|---|---|---|---|
| | Demand / SS (Mbits) | | | Demand / SS (Mbits) | | |
| | 0.5 | 1 | 1.5 | 0.5 | 1 | 1.5 |
| CGPath 1-shortest path | 228 | 222 | 225 | 28,123 | 28,146 | 28,104 |
| CGPath 2-shortest paths | 269 | 276 | 274 | 64,427 | 64,446 | 64,603 |
| CGPath 3-shortest paths | 636 | 632 | 639 | 141,722 | 141,795 | 141,901 |
| CGLink | 3,002 | 4,566 | 7,053 | - | - | - |

Table 4.10: Computing times (in seconds)

### 4.9.5 Performance with Rate Control

Now we study the performance of our models considering opportunistic scheduling where transmission rate on the wireless links are chosen according to the channel environment and the level of interference in the network. In other words, three transmission rates are considered, namely, 50Mbps, 75Mbps and 100Mbps. Each transmission rate has its corresponding SINR requirement for successful packet delivery as we mentioned earlier. Links are scheduled and their transmission rates are selected to increase the spectrum spatial reuse. We consider the two models, link-based and path-based ($k = 3$), and we consider (1)MTP, (2)PA and (3)PA with Rate Control (RC) in our study. In the 23-node network, traffic demands (uplink and downlink) per subscriber stations are selected randomly between [1, 1.5]Mbits. The metrics used in the comparisons are the schedule length, the CPU time and the network throughput which is defined as the total amount of the demands delivered over a scheduling period: $\frac{\sum \text{demands (bits)}}{\sum\limits_{s \in S_0} \lambda_s \text{ (seconds)}}$. The results are shown in Table 4.11 and Figure 4.4. First both link-based and path-based methods achieve the same optimal solution and hence performance for the same reasons discussed earlier. MSR-MTP requires a schedule length of 2270 slots to carry all the demands, followed by MSR-PA with 1728 slots (a spatial reuse gain of 23.8%) and then followed by MSR-PA RC with 1404 times lots and a spatial reuse gain of 38.19%. This shows that opportunistic scheduling indeed yields additional benefits in terms of improved utilization, and this

| Random demand per SS between [1, 1.5]Mbits uplink, downlink | | | | |
|---|---|---|---|---|
| | CGPath k=3 | | CGLink | |
| | Schedule length | CPU time | Schedule length | CPU time |
| MSR-MTP | 2270 | 4.5 | 2270 | 58.3 |
| MSR-PA | 1728 | 30.1 | 1728 | 179 |
| MSR-PA RC | 1404 | 105 | 1404 | 467 |

Table 4.11: 23-node: Schedule length (number of slots) and CPU time (in seconds).

is shown in Figure 4.4 where we show the system throughput achieved in the network. The figure shows that almost 60% increase in the system throughput is obtained when both transmission power and rate (MSR-PA RC) are incorporated into our model as variables as opposed to 30% increase in the case where only variable power is considered. Clearly, the drawback however is the added computation complexity (in the pricing model of the colum generation formulation) which is shown in the increase of CPU time needed to find the optimal solution.

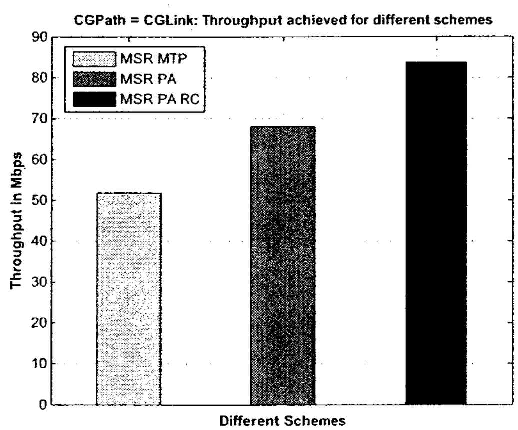


Figure 4.4: Throughput achieved by the schemes CGPath = CGLink: 23-node network.

We finally consider a larger network (56-node network) and solve the same models for both link-based and path-based methods. Traffic demands per SS are selected randomly between [0.25, 0.5]Mbits. Due to its complexity (PA and PA RC methods), we only solve the path-based model for $k = 1$. MSR-PA RC model yields a spatial reuse gain of 35.87% over MTP and MSR-PA yields a

| Random demand per SS between [0.25, 0.5] Mbits uplink, downlink | | | | |
|---|---|---|---|---|
| | CGPath k=1 | | CGLink | |
| | Schedule length | CPU time | Schedule length | CPU time |
| MSR-MTP | 2436 | 219 | 2436 | 3205 |
| MSR-PA | 1910 | 27859 | - | - |
| MSR-PA RC | 1562 | 75498 | - | - |

Table 4.12: 56-node: Schedule length (number of slots) and CPU time (in seconds).

gain of 21.5% over MTP. As we explained before, it is clear that opportunistic scheduling indeed results in substantial reduction in the length of the schedule required to route the demands in the network and this ultimately results in improving the system throughput as shown in Figure 4.5. It is to be noted here that the CPU time for this large network becomes excessively large as shown in Table 4.12 and when using the link-based model, the solver did not return the optimal solution after more than three days of running time.

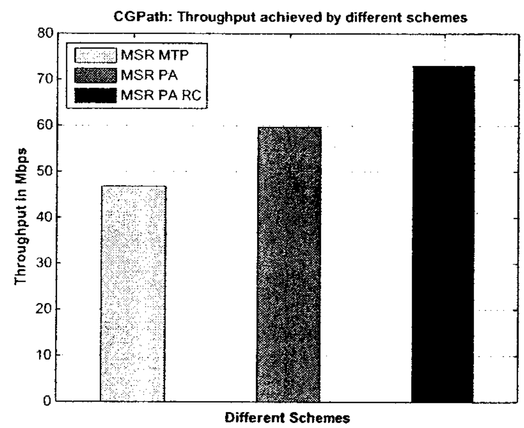


Figure 4.5: Throughput achieved by the different schemes CGPath: 56-node mesh network.

## 4.10 Conclusion

This chapter presented two formulations for joint routing-scheduling in WiMAX/802.16 mesh centralized networks. These two formulations are : (i) Column Generation Link-based CGLink and

(ii) Column Generation Path-based CGPath. In both CGPath and CGLink formulations, Maximum Transmission Power scheme MSR-MTP, Power Aware scheme MSR-PA, and MSR-PA with rate control (RC) were implemented and their performance is investigated. Since fewer routing variables are needed in the CGPath formulation when compared with the CGLink formulation, less CPU time is needed in the former to obtain the same optimal solution (for both MSR-PA and MSR-MTP schemes). This shows a better scalability of our CGPath formulation, which is practical for dimensioning WiMAX-based mesh networks. Another revealed advantage of our CGPath formulation is that its CPU time required to obtain the optimal solution remains the same even when increasing the size of the demand to satisfy per SS node. Finally, the benefits (better network spatial reuse and higher accepted demand per SS node) of using MSR-PA and MSR-PA RC schemes over the MSR-MTP scheme (in both CGPath and CGLink) were evaluated and substantial spatial reuse gain and hence system throughput are observed. However the MSR-PA and the MSR-PA RC schemes required more CPU time to determine the optimal solution, and in some instances the computation time becomes excessively high.

# Chapter 5

# Coding Aware Routing-Scheduling in WiMAX multi-hop networks

In this chapter, we design a cross-layer design framework (based on a column generation approach) for the joint problem of coding-aware routing and scheduling in WiMAX-based mesh networks with unicast sessions. The model attempts to maximize the system throughput by exploiting opportunistic coding opportunities through appropriate routing (tree construction) and achieving efficient spectrum reuse through appropriate link scheduling. Identifying coding-aware routing structures and utilizing the broadcasting feature of the wireless medium play an important role in realizing the achievable gain of network coding. Moreover, unlike all previous work which consider the interference-graph model (or protocol model) to enable (coded data) broadcasts, we consider the physical model to enable such broadcasts based on the SINR requirements at all receiving nodes part of the broadcast. Such assumption (physical model) allows us to further extend our work to include power aware (coded) broadcasts.

## 5.1 Introduction

Recently, a new approach is developed for improving the (unicast) throughput in multi-hop wireless networks (COPE) [63]. This framework (COPE) exploits the broadcast nature of the wireless medium; here, intermediate nodes may perform opportunistic coding, rather than simple forwarding. This technique, known as network coding [13] [63], has received a lot of attention over the past few years due to its potential in improving the network performance. Nevertheless, there are two fundamental limitations in COPE [63] [68], as we describe them as follows. The first limitation is that coding opportunity is crucially dependent on traffic pattern [68]. In other word, network coding is possible only when different flows form certain coding structures [63] [68] which are described in Section 5.3. The other limitation of COPE is that it limits the entire coding scenario within a two-hop region [63] [68].

Currently, the IEEE 802.16 standard [3] [4], commonly known as WiMAX, is targeted for broadband wireless access and is best suited for multi-hop wireless backhaul. It enables high speed multimedia applications, extended service coverage and supports high data rates. The WiMAX mesh mode of operation is also specified in the standard, where the data channel is divided into time slots and TDMA scheduling is employed for slot allocation. WiMAX supports both centralized and distributed scheduling. In this chapter, we assume a WiMAX-based wireless mesh network with centralized scheduling and we focus on capacity optimization of such network.

In this chapter, we investigate the achievable performance gains of network coding in a WiMAX-based WMN with unicast traffic. We develop a joint coding-aware routing and resource scheduling for WiMAX-based WMN. In a WiMAX-based WMN with centralized scheduling, a scheduling tree for uplink traffic (and for downlink traffic) is constructed by the Base Station (BS) to route the end-users demands located at (Subscriber Stations) SSs. We exploit this property in our work to construct uplink/downlink scheduling trees that maximize the opportunities of network coding and hence achieve better throughput performance. Given a set of unicast sessions, our objective is to determine routes and feasible link schedules (slot assignment) using the minimum schedule length. Here, a feasible link schedule is the set of links in the network (routing trees) which may be active in parallel. We refer to this set of links as a transmission configuration. We formulate the joint problem as an integer linear program (ILP). Finding the optimal solution for the ILP requires the enumeration of all feasible transmission configurations, which is not practical for moderate and large size networks. We adopt a primal-dual approach for solving the problem using column generation framework.

The remainder of the chapter is organized as follows. Section 5.2 presents the related work and some motivations. Next, in Section 5.3, we present the existing network coding approaches (structures) in the literature and provide for each an illustrative example showing its benefits. Moreover Section 5.4 defines the problem through an illustrative example. In Section 5.5, the transmission configuration generation problem is formulated, then in Section 5.6 the coding aware joint routing-scheduling problem is presented based on the path formulation. Section 5.7 discusses the reason of using the column generation optimization approach and the wise interaction that it provides between the coding aware joint routing-scheduling problem and the transmission configuration generation problem. In Section 5.8, the numerical results are discussed. Finally conclusions are drawn in Section 5.9.

## 5.2 Related Work

Resource optimization for improving the throughput of wireless mesh networks has received a lot of attention from the community during the past few years. Several frameworks have been presented with a focus on routing, scheduling and resource allocation in the context of single channel [27, 28, 24, 65, 20, 36], multi-channel [100, 16, 64, 93], multi-antenna (MIMO) [58, 21] and WiMAX-based mesh networks [39, 37]. All such previous studies have focused on the traditional forwarding architecture.

Instead of using simple forwarding, a technique known as network coding, initially proposed by [13] in the context of multi-cast communication, has shown to substantially improve the network performance. Following the work of [13], several researchers have explored efficient construction of network codes (e.g., [70]). Network coding for multi-hop wireless showed significant performance gains as well. The authors of [63] used the simplest form of network coding (XOR) and designed COPE, a forwarding framework, which exploits the broadcasting nature of the wireless medium to improve the throughput of the unicast multi-hop traffic. COPE has two attractive properties, the opportunistic coding and the opportunistic listening.

Moreover, Le *et al.* [67] established fundamental understanding on how a coding scheme works under a realistic physical layer and practical link-scheduling algorithms. For that matter, they presented three potential coding scenario structures, namely: (a) the coding scenario with opportunistic listening, (b) coding scenario without opportunistic listening and (c) the hybrid scenario. Based on these three coding scenario structure, Le *et al.* proposed DCAR [68], the first distributed coding-aware routing system for wireless networks. DCAR [68] incorporates potential coding opportunity structures into route selection using the "Coding+Routing Discovery" and (Coding-aware Routing

Metric). DCAR [68] adopts a more generalized coding scheme by eliminating the two-hop limitation in COPE [63]. Argyriou [18] also proposed distributed MAC protocols and mechanisms that allowed the efficient realization of network coding for increasing the system throughput. These protocols and mechanisms [18] exploit to the fullest opportunistic listening by allowing nodes to decode overheard transmissions of both data packets and acknowledgments.

Chaporkar and Proutiere [29] studied the issue of joint scheduling and COPE-like coding. They presented a XOR-Sym, a new scheme that achieves a lower implementation complexity than that of COPE [63], while providing similar throughput gains [29]. Since the opportunistic nature of COPE [63] leaves it at the mercy of higher and lower layer protocols to create coding opportunities spontaneously, Scheuermann *et al.* [86] created coding opportunities in a more deterministic, yet still practical way. For that matter, they proposed a cross-layer scheme noCoCo that integrates per-hop packet scheduling, network coding, and congestion control in a novel way [86]. Extensive simulations showed that noCoCo [86] significantly outperforms standard non-coding approaches as well as COPE [63] in terms of network throughput, delay and transmission overhead.

A linear optimization model to achieve network coding for unicast sessions is presented in [95]. For code construction, the authors used a poison-antidote approach to search for particular topologies (e.g., "X" shape) which favor network coding. Sengupta *et al.* [87] designed a mathematical model which jointly optimizes the routing and XOR network coding. Using the coding approach developed by [63] (opportunistic coding/listening), they formulated the coding-aware routing as a multi-commodity flow problem. They showed that the joint design significantly improves the network throughput performance.

The benefits of network coding in multi-channel WMNs are studied in [103] and the authors showed that network coding results in capacity increase for these networks. Here ([103]), a joint optimization for routing, channel assignment and network coding is formulated.

Su and Zhang [89] proposed a linear programming/optimization technique for the joint network coding and routing, with the objective of maximizing the network throughput for ad hoc networks. Once the optimal flows/paths for each link and network coding links combination are obtained, a link scheduling and channel assignment algorithm, based on the solution to the linear program, is executed to approximately attain the optimal throughput. Furthermore, Zhang *et al.* [102] proposed a coding-aware routing theoretical linear optimization formulation to calculate the maximal throughput of unicast traffic that can be achieved with cooperative network coding in a multi-rate wireless networks. Note that both opportunistic coding and opportunistic listening were studied in [102].

A cross-layer design with network coding is studied in [69] for multi-hop multi-radio WMNs. The network code construction is based on the poison-antidote approach and a joint routing and MAC scheduling is presented. Finally, coding at different layers (XOR-based coding and physical layer superposition coding) is studied in [17] and an algorithm is presented for packet mixing. A throughput gain of 30% is acheived over simple XOR-based coding.

Our efforts in this chapter are related to the work discussed earlier; we develop a linear optimization model for the joint code-aware routing and scheduling in WiMAX-based mesh networks. We assume a WiMAX-based WMN with centralized scheduling where the BS constructs the scheduling trees for both uplink and downlink traffic. Our work is based on opportunistic coding of packets on both uplink and downlink sessions. Our formulation constructs scheduling trees that exploit the coding opportunities to route uplink and downlink sessions using the minimum system activation time (minimum schedule length). To achieve a minimum schedule length, as many links are activated concurrently to maximize the spectrum spatial reuse; this further results in additional performance gains.

Our work differs from that of [87] [89] [102] [103] in that we consider joint coding-aware routing with link scheduling based on a column generation approach. Our work, also differs from [69] [95] in that we, unlike [69] [95] where the poison-antidote coding approach is adopted, assume opportunistic coding for code construction. It is to be noted that the poison-antidote method is not applicable to WiMAX-based mesh networks because of the routing tree property requirement of WiMAX mesh with centralized scheduling. Moreover, unlike all previous work which consider the interference-graph model (or protocol model) to enable (coded data) broadcasts, we consider the physical model to enable such broadcasts based on the SINR requirements at all receiving nodes part of the broadcast. Such assumption (physical model) allows us to further extend our work to include power aware (coded) broadcasts.

## 5.3 Network Coding Existing Approaches

Several network coding approaches were presented in the literature [63, 87, 69, 67]. We discuss these approaches in the following subsections and discuss their respective characteristics.

### 5.3.1 Opportunistic Coding

The key property of opportunistic coding is what packets to code together to maximize throughput. An intermediate relay node may have multiple options, but it should aim to maximize the number of native packets (i.e., original received packets) delivered in a single coded broadcasted transmission, while ensuring that each intended next hop receiver has enough information to decode its native packet [63]. Note that each wireless node uses only packets in its local queues for coding [87].

Therefore, in such approach, intermediate relay nodes may perform opportunistic coding and broadcasting, rather than simple forwarding. Opportunistic coding and broadcasting occurs in the context where two connections are transiting (are routed) through an intermediate node B but in opposite directions (refer to Figure 5.1), and instead of using simple forwarding at different point of times to transmit the data packets of the two different connections, the intermediate node B can code the packets of the two connections into one packet, and broadcast it to the intended receivers (which can decode the code packet once received) at the same time. We adopt such approach in our cross-layer network coding design.

Assume simple XOR operation for information coding in the wireless medium. Figure 5.1 illustrates a coding scenario where both nodes A (with packet "x") and C (with packet "y") have one packet each to exchange and node B acts as intermediate hop for forwarding these packets. We assume that a node can either transmit or receive at a time (half duplex) and that it can only receive from a particular node (to avoid packet collision). Clearly, 4 time slots (A-B, C-B, B-A, B-C) are needed to complete the packet exchange, in the absence of network coding. In the presence of network coding, only 3 slots are required for completing this exchange: (A-B), (C-B) and (B-A, B-C). We refer to (A-B) and (C-B) transmissions as unicast transmissions that are active in two different time slots, and to (B-A, B-C) transmission as a broadcast transmission active in a time slot. In a broadcast transmission, node B (broadcasting node) performs a XOR operation on the two packets received from A and C, respectively packets "x" and "y". Upon broadcasting the resultant packet denoted by "z", A (and C) can decode it intended packet by XORing the received packet "z" with "x" (and "y").

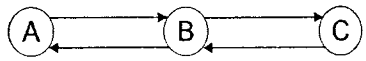


Figure 5.1: Opportunistic coding structure.

### 5.3.2 Opportunistic Listening

Wireless is a broadcast medium, creating many opportunities for nodes to overhear packets when they are equipped with omni-directional antennae. Here the nodes are set in a promiscuous mode, which allows them to snoop on all communications over the wireless medium and store the overheard packets for a limited period [63]. The snooped packets are used in coding decisions [87].

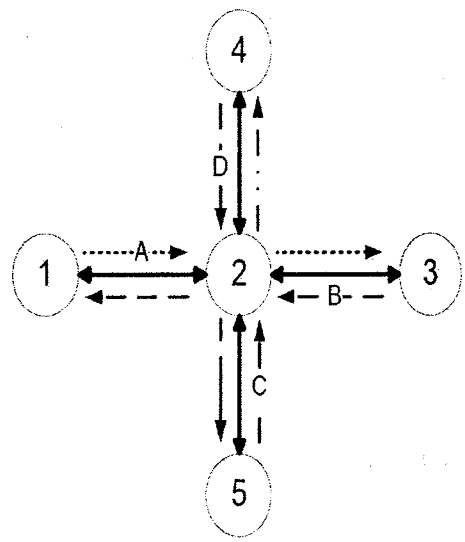


Figure 5.2: Opportunistic listening structure.

The advantage of opportunistic listening are illustrated using the following example in Figure 5.2, where 4 intended packet transfers are required in the network: from node 1 to node 3, from node 3 to node 1, from node 4 to node 5, and from node 5 to node 4. Due to the nodes covering range limitations all transfers need to transit via node 2. We assume that nodes 1, 3, 4, and 5 transmit their packets sequentially to node 2. When node 1 (node 3) transmits its packet A (B) to node 2, nodes 4 and 5, in promiscuous mode, snoop on the packet A (B). Similarly when node 4 (node 5) transmits its packet D (C) to 2, nodes 1 and 3 snoop on this packet. Therefore, at the end of these four packet transmissions, if node 2 were to transmit a single coded packet that XORs all of the four packets (A, B, C, D), then each node (1, 3, 4, and 5) would be able to correctly decode their intended packets. Thus the packet transfers are completed by using just 5 packet transmissions. Note that in absence of coding, 8 packet transmissions would have been necessary and when using opportunistic coding 6 packet transmissions would have been necessary [87].

### 5.3.3 Poison-Antidote "X" topology

Another basic topology that favors network coding in multiple unicast applications, is the poison-antidote topology illustrated in Figure 5.3 and which was firstly introduced by [95] and [69]. Such coding approach is similar to the opportunistic listening proposed by [87] where a node broadcasts the coded data to neighbors (poisoned transmissions), and after the data has been received, the corresponding neighbors will request the antidote (or the key data) to correctly decode the poisoned data.

For instance, consider the network example in Figure 5.3 and two connections (1,5) and (2,4) with data packets $b_1$ and $b_2$ respectively, where node 1 (node 5) is the source (destination) node of connection (1,5) and node 2 (node 4) is the source (destination) node of connection (S2,D2). Given the network structure (see Figure 5.3), these two connections must transit via node 3 (which is referred to by bottleneck node). Therefore 1 transmits packet $b_1$ and 2 transmits packet $b_2$ at different point of times. Once $b_1$ and $b_2$ are received at node 3, the data packet is coded as $b_1 \oplus b_2$

and broadcasted by node 3 towards 5 and 4. The broadcast transmission of $b_1 \oplus b_2$ is interpreted, by both nodes 5 and 4, as "poisoned information" of the two connections (1,5) and (2,4), since neither 5 nor 4 can decode the coded packet. To be able to decode $b_1 \oplus b_2$, node 5 requests the "antidote information" from node 2 which in this case is $b_2$, similarly node 4 requests the "antidote information" from node 1 which in this case is $b_1$. The essence of the poison-antidote strategy is that the bottleneck node (node 3 in the example) can code two streams together, which enables this node to drain its data twice as fast, yielding a Coding+MAC gain of 2. In case that there are K streams intersecting at a bottleneck node and this bottleneck node can code K streams together, then the Coding+MAC gain is K, which grows without bound with K [69].

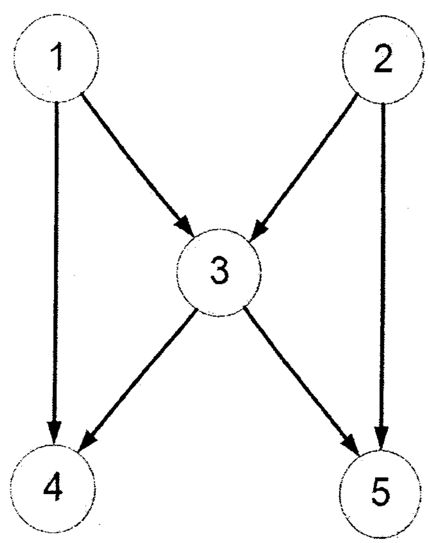


Figure 5.3: Poison-Antidote structure.

## 5.4 Benefits of Network Coding in WiMAX

Since the poison-antidote and the opportunistic listening basic topologies are not possible in the WiMAX routing tree, we adopt opportunistic coding in our cross-layer approach and study its benefits in the context of WiMAX multi-hop networks. Figure 5.4 shows a sample network to illustrate the benefit of coding-aware routing and scheduling in WiMAX multi-hop networks. Two uplink sessions (A-BS,B-BS) and two downlink sessions (BS-C, BS-D) are considered, each of one unit demand. Two possible routing WiMAX trees (among many others) may be used: (A-G-BS, B-E-BS) for uplink and (BS-G-A-C, BS-E-D) for downlink. We assume a single carrier channel where time is divided into time slots of equal size and we need to determine an appropriate link activation schedule to route these sessions using the minimum number of slots (minimum schedule length). We note that due to interference in the network, only some links can be activated concurrently. One possible straight forward schedule is to activate each link (of the tree) in a separate time slot. This results in a schedule of 9 slots length. If network coding is considered, then some improvement may be achieved by exploiting the opportunistic coding at node G and it can be easily verified that 8 slots are sufficient for routing the uplink and downlink demands.

Now, in the absence of network coding, one may look for links in the trees that may be active concurrently. Such set of links can be activated in the same time slot without corrupting each other's transmission and we refer to this set as a transmission configuration. We note that any link in a particular configuration meets the SINR requirement at the intended receiver. For convenience of illustration, we use the simple protocol model for interference. Two nodes not connected by a link are assumed to be outside the interference range of each other; for example, since A and E are not connected as well as B and G, then links (A, G) and (B, E) can be active in the same transmission configuration.

We can verify that only 5 time slots or transmission configurations $(g_1, g_2, g_3, g_4, g_5)$ are needed to perform link scheduling: $g_1 = \{$(A, C), (E, BS)$\}$, $g_2 = \{$(A, G), (B, E)$\}$, $g_3 = \{$(BS, G), (E, D)$\}$,

$g_4 = \{$(G, A), (BS, E)$\}$ and $g_5 = \{$(G, BS$\}$.

When enabling network coding at node G, it can also be verified that 4 time slots or transmission configurations ($g'_1$, $g'_2$, $g'_3$, $g'_4$) are needed for link scheduling: $g'_1 = \{$(G, BS), (G, A), (B, E)$\}$, $g'_2 = \{$(A, C), (BS, E)$\}$, $g'_3 = \{$(A, G), (E, BS)$\}$ and $g'_4 = \{$(BS, G), (E, D)$\}$. This example shows the substantial benefits achieved by both appropriate scheduling with opportunistic network coding.

To illustrate the benefits of joint coding-aware routing and scheduling, we assume now that uplink session (A-BS) is routed through path A-F-BS. It can be verified that coding is not possible and 5 time slots are needed to schedule all links in both uplink/downlink trees ($g''_1$, $g''_2$, $g''_3$, $g''_4$, $g''_5$): $g''_1 = \{$(A, C), (BS, E)$\}$, $g''_2 = \{$(E, D), (G, A)$\}$, $g''_3 = \{$(B, E), (G, BS)$\}$, $g''_4 = \{$(A, F), (E, BS)$\}$ and $g''_5 = \{$(F, BS$\}$. Therefore, incorporating network coding into the routing method (which identifies those broadcast transmissions) results in a better performance (4 time slots).

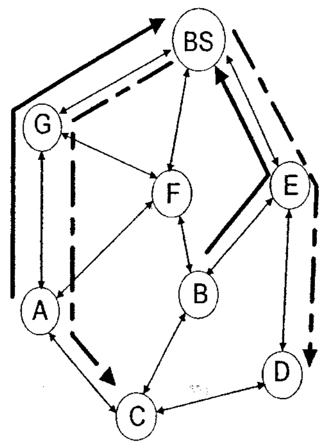


Figure 5.4: WiMAX Mesh network scenario: An example.

## 5.5 Transmission Configuration Generation Problem

We consider a directed graph $G(V, L)$ which represents the WiMAX/802.16 mesh network. $V$ denotes the set of nodes (BS and SS) and $L$ represents the set of RF-links that are available between nodes. Note that a RF-link exists if its receiving node is within the coverage range of its transmitting node. We assume that all nodes have the same maximum covering range $D$ and therefore if a link exists in a particular direction, its corresponding link in the opposite direction exists too.

As discussed in Section 5.4, the key issue is to select the appropriate set of transmission configurations that minimizes the number of time slots in the scheduling period. In this section, the constraints associated with a transmission configuration generation are formulated. We assume in Subsection 5.5.1 a fixed transmission power with maximum power $P_{max}$ per transmission and in Subsection 5.5.2 we extend the transmission configuration generation to include power aware unicast/broadcast transmissions.

Let $t_{ij}^{s}$ be a variable that is equal 1 if RF-link $(i, j) \in L$ is active, 0 otherwise for a transmission configuration $s$ that we generate at a particular point of time. We further enable sub-carrier allocation within a time slot, therefore we extend $t_{ij}^{s}$ and replace it by variable $t_{ij}^{s,c}$ that is equal 1 if RF-Link $(i, j) \in L$ is active in transmission configuration $s$ and a subcarrier $c \in C$ is allocated to it, and 0 otherwise. $C$ denotes the set of available orthogonal subchannels.

Identifying a transmission configuration requires satisfying a set of constraints that enable a group of RF-links to transmit simultaneously without corrupting each other's transmissions. Denote by $V_i^+$ the set of neighbors of $i$ such that $j \in V_i^+$ if and only if $(i, j) \in L$. Similarly, $V_i^-$ represents the set of neighbors of $i$ such that $j \in V_i^-$ if and only if $(j, i) \in L$. In addition we define $V_i = V_i^- \cup V_i^+$ the set of all neighbors of $i$.

Finally, we define variables $b_i^{s,c}$ and $u_i^{s,c}$ to identify whether $i \in V$ is either in broadcasting (i.e., can perform network coding) mode, or unicast mode respectively using subcarrier $c \in C$ for a transmission configuration $s$. More precisely, for a transmission configuration $s$, $b_i^{s,c} = 1$ if $i$ is a broadcasting node using subcarrier $c$, 0 otherwise; $u_i^{s,c} = 1$ if $i$ is in unicast mode using subcarrier $c$ (i.e., $b_i^{s,c} = 0$ and $\exists j \in V_i^+, t_{ij}^{s,c} = 1$), 0 otherwise.

### 5.5.1 Maximum Power Transmissions (MTP)

The following constraint is used to ensure the half duplex property where a node $i \in V$ cannot transmit and receive in the same time slot $s$ (or same transmission configuration).

$$\sum_{c \in C} t_{ji}^{s,c} + \sum_{c \in C} t_{ij}^{s,c} \leq 1; \quad i \in V \, , \, j \in V_i \tag{5.1}$$

Constraint (5.2) ensures that two or more nodes (whether in unicast or broadcast) do not transmit to a common receiving node, while using the same sub-carrier $c \in C$, during the same time slot $s$ (or transmission configuration).

$$\sum_{j \in V_i^-} t_{ji}^{s,c} \leq 1 \quad i \in V \, , \, c \in C; \tag{5.2}$$

Constraint (5.3) allows a node $i$ to receive multiple data streams at the same time slot on different subcarriers; thus, a node cannot receive from more than $|C|$ neighboring nodes at the same time slot.

$$\sum_{j:(j,i) \in L} \sum_{c \in C} t_{ji}^{s,c} \leq |C| \quad i \in V. \tag{5.3}$$

In addition, constraint (5.4) allows a node $i$ (in unicast mode $u_i^{s,c} = 1$) to transmit on only one subcarrier $c \in C$ (and to a particular neighbor $j$) in one transmission configuration $s$.

$$\sum_{j:(i,j)\in L} \sum_{c\in C} t_{ij}^{s,c} \leq 1 + (1 - \sum_{c\in C} u_i^{s,c}) \quad i \in V. \tag{5.4}$$

We point out that, in a transmission configuration (or time slot) $s$, a node $i \in V$ (whether in unicast mode or in broadcast mode) can select only one subcarrier $c \in C$ to transmit in, therefore we add the following constraints:

$$\sum_{c\in C} u_i^{s,c} \leq 1 \quad i \in V \tag{5.5}$$

$$\sum_{c\in C} b_i^{s,c} \leq 1 \quad i \in V \tag{5.6}$$

In addition, (5.7) ensures that a transmitting node (either in unicast or in broadcast mode) $i \in V$ meets the Signal to Interference plus Noise Ratio (SINR) requirement at a receiving node $j \in V$, while using a subcarrier $c \in C$.

$$P_{max}G_{ij} + M_{ij}^{s,c}(1 - t_{ij}^{s,c}) \geq \Gamma(\eta + \sum_{h\in V/\{i\}} P_{max}G_{hj}u_h^{s,c} + \sum_{h\in V/\{i\}} P_{max}G_{hj}b_h^{s,c}) \tag{5.7}$$

where $M_{ij}^{s,c} \geq (\eta + \sum_{h\in V/\{i\}} P_{max}G_{hj}u_h^{s,c} + \sum_{h\in V/\{i\}} P_{max}G_{hj}b_h^{s,c})\ \forall (i,j) \in L$, and is a constant. $\Gamma$ is the SINR threshold, $\eta$ is the background thermal noise and $P_{max}$ is the maximum transmission power. The first summation in expression (5.7) corresponds to the generated interference by unicast transmissions on receiving node $j$, while the second summation corresponds to generated interference from broadcasting nodes on receiving node $j$.

We point out that (5.7) captures the generated interference by both unicast nodes and broadcast nodes.

Constraints (5.8) to (5.12) ensure the correctness of $b_i^{s,c}$ and $u_i^{s,c}$ definitions, and provide the relationship between them.

Constraint (5.8) forces $b_i^{s,c}$ to 1, when more than one outgoing link (at node $i$) is active, using subcarrier $c \in C$.

$$b_i^{s,c} \geq \sum_{j \in V_i^+} t_{ij}^{s,c} - 1 \quad i \in V \,,\, c \in C \tag{5.8}$$

Constraint (5.9) forces $u_i^{s,c}$ to be equal 1, when $t_{ij}^{s,c} = 1$ and $b_i^{s,c} = 0$; i.e., only outgoing link $(i, j)$, in subcarrier $c$, is active, since $b_i^{s,c} = 0$.

$$u_i^{s,c} \geq t_{ij}^{s,c} - b_i^{s,c} \quad c \in C \,,\, j \in V_i^+ \,,\, i \in V \tag{5.9}$$

Constraint (5.10) states that a node $i$ is either in broadcasting mode, or in unicast mode at one time slot (or transmission configuration $s$).

$$u_i^{s,c} + b_i^{s,c} \leq 1 \quad c \in C \,,\, i \in V \tag{5.10}$$

Constraint (5.11) forces $b_i^{s,c}$ to be equal 0, when $u_i^{s,c} = 1$ and $\sum_{j \in V_i^+} t_{ij}^{s,c} = 1$. It also forces $b_i^{s,c}$ to equal 0, when $\sum_{j \in V_i^+} t_{ij}^{s,c} = 0$.

$$b_i^{s,c} \leq \sum_{j \in V_i^+} t_{ij}^{s,c} - u_i^{s,c} \quad c \in C \,,\, i \in V \tag{5.11}$$

Constraint (5.12) forces $u_i^{s,c}$ to be 0 when $\sum_{j \in V_i^+} t_{ij}^{s,c} = 0$.

$$u_i^{s,c} \leq \sum_{j \in V_i^+} t_{ij}^{s,c} \quad c \in C \quad i \in V \tag{5.12}$$

To ensure the broadcast nature of a node, constraints (5.13) (5.14) must be satisfied. Constraint (5.13) allows a node to broadcast ($b_i^{s,c} = 1$) on two of its outgoing RF-links at most (opportunistic coding property) while using a particular subcarrier $c \in C$. Constraint (5.14) ensures that, if a node is being selected for a broadcast transmission ($b_i^{s,c} = 1$), in a transmission configuration $s$, it will broadcast its transmission on two of its outgoing link always, while using subcarrier $c \in C$, hence preventing it from performing unicast transmissions (transmitting on only one outgoing link).

$$\sum_{j \in V_i^+} t_{ij}^{s,c} \leq 1 + b_i^{s,c} \quad c \in C \, , \, i \in V \tag{5.13}$$

$$1 + \sum_{j' \in V_i^+ / \{j\}} t_{ij'}^{s,c} \geq t_{ij}^{s,c} + b_i^{s,c} \quad c \in C \, , \, j \in V_i^+ \, , \, i \in V \tag{5.14}$$

### 5.5.2 Variable Power Transmissions (PA)

In this scheme, all the previous constraints remain the same except for the SINR constraint (4.5) which need to be separated into two constraints, respectively constraint (5.15) when a node is in broadcast mode and constraint (5.18) when a node is in unicast mode. We define variables $p_{i,\text{broad}}^{s,c}$ and $p_{ij}^{s,c}$ to denote the power at node $i$ when it is broadcasting, and the power at node $i$ when it is transmitting to node $j$ in unicast mode respectively, while using subcarrier $c$, in transmission configuration $s$.

$$p^{s,c}_{i,\text{broad}} G_{ij} + M^{s,c}_{ij}(1 - t^{s,c}_{ij}) + M_{ij}(1 - b^{s,c}_{i}) \geq \Gamma(\eta + \sum_{h \neq i,\, (h,m) \in L} p^{s,c}_{hm} G_{hj} + \sum_{h \neq i} p_{h,\text{broad}^{s,c}} G_{hj}) \tag{5.15}$$

$c \in C$ , $j \in V_i^+$, , $i \in V$, where $i$ is a broadcasting node ($b^{s,c}_i = 1$).

The correctness of $p^{s,c}_{i,\text{broad}}$ is ensured by expression (5.16). (5.16) ensures that when $b^{s,c}_i = 1$, $p^{s,c}_{i,\text{broad}}$ must have a strictly positive value given that $\varepsilon << 1$.

$$p^{s,c}_{i,\text{broad}} \geq \varepsilon b^{s,c}_i \quad c \in C \,,\, i \in V \tag{5.16}$$

where $\varepsilon$ is a very small number ($\varepsilon << 1$).

Moreover constraint (5.17) ensures that $p^{s,c}_{i,\text{broad}} = 0$ when $b^{s,c}_i = 0$ and $p^{s,c}_{i,\text{broad}} \leq P_{max}$ when $b^{s,c}_i = 1$.

$$p^{s,c}_{i,\text{broad}} \leq b^{s,c}_i \times P_{max} \quad c \in C \,,\, i \in V \tag{5.17}$$

For unicast transmissions (node $i$ transmitting to a receiving node $j$), while using subcarrier $c$ ,the SINR can be modeled as follows:

$$p^{s,c}_{ij} G_{ij} + M^{s,c}_{ij}(1 - t^{s,c}_{ij}) + M^{s,c}_{ij}(1 - u^{s,c}_{i}) \geq \Gamma(\eta + \sum_{(h,m) \in L : h \neq i} p^{s,c}_{hm} G_{hj} + \sum_{h \neq i} p_{h,\text{broad}^{s,c}} G_{hj}) \tag{5.18}$$

$c \in C$ , $j \in V_i^+$, , $i \in V$, where $i$ is a unicast node ($u^{s,c}_i = 1$).

The correctness of $p^{s,c}_{ij}$ $\forall j \in i$ is ensured by (5.19) such that $p^{s,c}_{ij} \neq 0$, if $i$ is active for unicast ($u^{s,c}_i = 1$) and $t^{s,c}_{ij} = 1$, within subcarrier $c$.

| | Type | | Scheme | | Definition |
|---|---|---|---|---|---|
| Term | Par | Var | MTP | PA | |
| $t_{ij}^{s,c}$ | | X | X | X | $(i,j)$ active or not, using subcarrier $c$ |
| $u_i^{s,c}$ | | X | X | X | node $i$ is in unicast mode or not, using subcarrier $c$ |
| $b_i^{s,c}$ | | X | X | X | node $i$ is in broadcast or not, using subcarrier $c$ |
| $M_{ij}^{s,c}$ | X | | X | X | value for constraint relaxation |
| $G_{ij}$ | X | | X | X | environment gain between nodes $i$ and $j$ |
| $\Gamma$ | X | | X | X | SINR threshold |
| $\eta$ | X | | X | X | thermal noise |
| $P_{max}$ | X | | X | X | maximum transmit power |
| $\varepsilon$ | X | | | X | small value ($<< 1$) |
| $p_{i,\text{broad}}^{s,c}$ | | X | | X | broadcast power at node $i$ |
| $p_{ij}^{s,c}$ | | X | | X | unicast power at node $i$ when transmitting to $j$ |

Table 5.1: Parameters and variables of the transmission configuration generation.

$$p_{ij}^{s,c} \geq \varepsilon t_{ij}^{s,c} - (1 - u_i^{s,c}) \quad c \in C \; , \; (i,j) \in L \tag{5.19}$$

where $\varepsilon$ is a very small number ($\varepsilon << 1$).

In addition, constraint (5.20) ensures that $p_{ij}^{s,c} = 0$, $j \in V_i^+$ when $u_i^{s,c} = 0$ and $p_{ij}^{s,c} \leq P_{max}$ when $u_i^{s,c} = 1$.

$$p_{ij}^{s,c} \leq u_i^{s,c} \times P_{max} \quad c \in C \; , \; i \in V, \; , \; j \in V_i^+ \tag{5.20}$$

We point out that in a transmission configuration $s$, only one subchannel $c$ can have $p_{ij}^{s,c} > 0$, and thus the transmission power on link $(i,j)$ becomes $p_{ij}^{s,c}$. Similar observation is done for $p_{i,\text{broad}}^{s,c}$, when node $i$ is in broadcast mode.

We summarize the parameters (Par) and variables (Var) for both MTP and PA schemes in Table 5.1.

## 5.6 Problem Formulation

In this section, a coding-aware joint routing-scheduling formulation is introduced. We first define some parameters and variables that are commonly used in this formulation. Let $S$ be the set of possible transmission configurations. In addition, an integer variable $\lambda_s$ is associated with each transmission configuration $s \in S$, which is equal to the number of times a transmission configuration $s$ is used throughout a TDMA scheduling period (i.e., number of times a transmission configuration is assigned to time slots part of the scheduling period). In addition the following variables $y_{ij}^{\text{UL}}$ ($y_{ij}^{\text{DL}}$) are introduced to identify whether or not RF-link $(i, j)$ is active for uplink (or downlink) transmission in a scheduling period (at least one time slot). These variables will come in handy when constructing the routing tree associated with the centralized scheduling.

$$y_{ij}^{\text{UL}} = \begin{cases} 1 & \text{if } (i,j) \text{ is active for uplink transmission,} \\ 0 & \text{otherwise.} \end{cases}$$

Similarly,

$$y_{ij}^{\text{DL}} = \begin{cases} 1 & \text{if } (i,j) \text{ is active for downlink transmission,} \\ 0 & \text{otherwise.} \end{cases}$$

Moreover, we define $t_{ij}^{s,c}$ as a parameter in the joint routing-scheduling problem such that:

$$t_{ij}^{s,c} = \begin{cases} 1 & \text{if } (i,j) \text{ is active in } s \in S \text{ using subcarrier } c \in C. \\ 0 & \text{otherwise.} \end{cases}$$

Similarly, we define $b_i^s$ and $u_i^s$ as parameters in the joint routing-scheduling problem such that:

$$b_i^{s,c} = \begin{cases} 1 & \text{if node } i \in V \text{ is broadcasting in } s \in S \text{ using subcarrier } c \in C. \\ 0 & \text{otherwise.} \end{cases}$$

$$u_i^{s,c} = \begin{cases} 1 & \text{if node } i \in V \text{ is unicast in } s \in S \text{ using subcarrier } c \in C. \\ \\ 0 & \text{otherwise.} \end{cases}$$

Note that parameters $t_{ij}^{s,c}$, $b_i^{s,c}$ and $u_i^{s,c}$ are completely determined by the generation of transmission configuration $s$.

Let $P_{\text{SS}^+}$ denotes the set of predetermined routing paths (for uplink demands) between a SS node and the BS and $P_{\text{SS}^-}$ the set of predetermined routing paths (for downlink demands) between the BS and a SS node. This formulation is referred to as a path-based formulation. Alternatively, a link-based formulation may be used where routes are determined dynamically by the model. In this work, we only use the path-based formulation due to its better scalability over the link-based formulation [39].

The following set of variables and parameters are used:

$w_p^{\text{SS}^+}$ represents the amount of uplink data which is being routed on path $p \in P_{\text{SS}^+}$.

$$x_p^{\text{SS}^+} = \begin{cases} 1, \text{ if } w_p^{\text{SS}^+} > 0; \\ \\ 0, \text{ otherwise.} \end{cases}$$

$w_p^{\text{SS}^-}$ represents the amount of downlink data which is being routed on path $p \in P_{\text{SS}^-}$.

$$x_p^{\text{SS}^-} = \begin{cases} 1, \text{ if } w_p^{\text{SS}^-} > 0; \\ \\ 0, \text{ otherwise.} \end{cases}$$

$W_i^{\{(i,j),(i,j')\}}$ is a real variable that defines the amount of data broadcasted using network coding by node $i$ over its outgoing links $(i, j)$ and $(i, j')$.

$W_i^{\{(i,j)\}}$ is a real variable that defines the amount of unicast data that is transmitted by node $i$ over link $(i, j)$.

We also define the parameter $\delta_p^{ij}$ such that:

$$\delta_p^{ij} = \begin{cases} 1, \text{ if link } (i,j) \text{ belongs to path } p; \\ \\ 0, \text{ otherwise.} \end{cases}$$

Moreover we define the parameter $\delta_p^{\{(j,i),(i,j')\}}$ that is 1 if link $(j,i)$ and $(i,j')$ belong to path $p$ (link $(j,i)$ and $(i,j')$ follow each other in a consecutive order in path $p$), 0 otherwise.

Note that, in this work we consider a path-based formulation where multiple ($k$)-shortest routing paths are precomputed between each SS and the BS. The selection of a routing path is determined by the ILP program. This methodology has shown to achieve the same performance as a link-based formulation where $k \geq 3$ [39] with substantially less computational CPU time for both moderate and large size networks.

In Table 5.2, we summarize the parameters and variables that are present in the coding-aware joint routing-scheduling formulation.

Our objective is to minimize the overall number of time slots (or minimize the scheduling length) to satisfy a certain traffic demand.

**Objective:**

$$\min \sum_{s \in S} \lambda_s \tag{5.21}$$

**Subject to:**

A direct relationship exists between $x_p^{\mathrm{SS}^+}$ ($x_p^{\mathrm{SS}^-}$) and $w_p^{\mathrm{SS}^+}$ ($w_p^{\mathrm{SS}^-}$), which requires the following additional constraints:

$$x_p^{\mathrm{SS}^+} \geq \frac{w_p^{\mathrm{SS}^+}}{W} \quad \forall p \in P_{\mathrm{SS}^+},\ \mathrm{SS} \in V \tag{5.22}$$

$$x_p^{\mathrm{SS}^-} \geq \frac{w_p^{\mathrm{SS}^-}}{W} \quad \forall p \in P_{\mathrm{SS}^-},\ \mathrm{SS} \in V \tag{5.23}$$

| | Type | | Definition |
|---|---|---|---|
| Term | Par | Var | |
| $\lambda_s$ | | X | number of times configuration $s$ is used |
| $t_{ij}^{s,c}$ | X | | $(i,j)$ is active or not in $s$ using subcarrier $c$ |
| $b_i^{s,c}$ | X | | $i$ is in broadcast or not in $s$ using subcarrier $c$ |
| $u_i^{s,c}$ | X | | $i$ is in unicast or not in $s$ using subcarrier $c$ |
| $W_{ij}^{s,c}$ | X | | time slot $s$ capacity, using subcarrier $c$, @ link $(i,j)$ |
| $W$ | X | | big value |
| $R_{\text{SS}}^{\text{UL}}$ | X | | uplink demand at SS node |
| $R_{\text{SS}}^{\text{DL}}$ | X | | downlink demand at SS node |
| $y_{ij}^{\text{UL}}$ | | X | $(i,j)$ is used or not for routing uplink demands |
| $y_{ij}^{\text{DL}}$ | | X | $(i,j)$ is used or not for routing downlink demands |
| $W_i^{\{(i,j),(i,j')\}}$ | | X | broadcast coded data by node $i$ on $(i,j)$ and $(i,j')$ |
| $W_i^{\{(i,j)\}}$ | | X | unicast data at link $(i,j)$ |
| $w_p^{\text{SS}^+}$ | | X | amount of uplink data routed on path $p$ for SS node |
| $w_p^{\text{SS}^-}$ | | X | amount of downlink data routed on path $p$ for SS node |
| $x_p^{\text{SS}^+}$ | | X | whether path $p$ is used to route uplink data for SS node |
| $x_p^{\text{SS}^-}$ | | X | whether path $p$ is used to route downlink data for SS node |
| $\delta_p^{ij}$ | X | | $(i,j)$ belongs to path $p$ or not |
| $\delta_p^{\{(j,i),(i,j')\}}$ | X | | $(i,j)$ and $(i,j')$ belong to path $p$ or not |

Table 5.2: Parameters and variables of the joint model.

where $W$ is a large value greater than the maximum throughput achievable in the network.

Constraints (5.24) and (5.25) ensure that one path among the potential paths is selected to route respectively the data from a particular SS to the BS (uplink) and the data from the BS to the corresponding SS (downlink).

$$\sum_{p \in P_{\text{SS}+}} x_p^{\text{SS}+} \leq 1 \qquad \text{SS} \in V/\{\text{BS}\} \tag{5.24}$$

$$\sum_{p \in P_{\text{SS}-}} x_p^{\text{SS}^-} \leq 1 \qquad \text{SS} \in V/\{\text{BS}\} \tag{5.25}$$

(5.26) and (5.27) state the flow conservation constraints for both uplink and downlink demands respectively:

$$\sum_{j \in V_i^-} \sum_{p \in P_{\text{SS}+}} \delta_p^{ji} w_p^{\text{SS}+} - \sum_{j \in V_i^+} \sum_{p \in P_{\text{SS}+}} \delta_p^{ij} w_p^{\text{SS}+} = \begin{cases} 0 & \text{if } i \in V \setminus \{\text{SS}, \text{BS}\}, \\ -R_{\text{SS}}^{\text{UL}} & \text{if } i = \text{SS}, \\ R_{\text{SS}}^{\text{UL}} & \text{if } i = \text{BS}. \end{cases} \qquad i \in V,\ \text{SS} \in V/\{\text{BS}\}. \tag{5.26}$$

$R^{\text{UL}}_{\text{SS}}$ is the uplink demand to be satisfied for a Subscriber Station SS.

$$\sum_{j\in V_i^-}\sum_{p\in P_{\text{SS}^-}} \delta_p^{ji} w_p^{\text{SS}^-} - \sum_{j\in V_i^+}\sum_{p\in P_{\text{SS}^-}} \delta_p^{ij} w_p^{\text{SS}^-} = \begin{cases} 0 & \text{if } i \in V\setminus\{\text{SS},\text{BS}\}, \\ R^{\text{DL}}_{\text{SS}} & \text{if } i = \text{SS}, \\ -R^{\text{DL}}_{\text{SS}} & \text{if } i = \text{BS}. \end{cases} \quad i\in V,\ \text{SS}\in V/\{\text{BS}\}. \quad (5.27)$$

$R^{\text{DL}}_{\text{SS}}$ is the downlink demand to be satisfied for a Subscriber Station SS.

In order to satisfy the definitions of $y^{\text{UL}}_{ij}$ and $y^{\text{DL}}_{ij}$, we formulate the following constraints :

$$\sum_{p\in P_{\text{SS}+}} x_p^{\text{SS}^+}\delta_p^{ij} \le y^{\text{UL}}_{ij} \quad \text{SS}\in V/\{\text{BS}\},\ (i,j)\in L \quad (5.28)$$

$$\sum_{p\in P_{\text{SS}-}} x_p^{\text{SS}^-}\delta_p^{ij} \le y^{\text{DL}}_{ij} \quad \text{SS}\in V/\{\text{BS}\},\ (i,j)\in L \quad (5.29)$$

In addition, constraints (5.30) and (5.31) are introduced to preserve the rooted tree property:

$$\sum_{j\in V_i^+} y^{\text{UL}}_{ij} \le 1 \quad i\in V \quad (5.30)$$

$$\sum_{j\in V_i^-} y^{\text{DL}}_{ji} \le 1 \quad i\in V \quad (5.31)$$

Constraints (5.32) and (5.33) determine the maximum amount of coded traffic that can be broadcast on outgoing links $(i,j)$ and $(i,j')$ at broadcasting node $i$. Constraint (5.32) identifies the total traffic traversing node $i$ along the link sequence $\{(j,i),(i,j')\}$. Whereas Constraint (5.33) identifies the total traffic traversing node $i$ along the link sequence $\{(j',i),(i,j)\}$. Thus $W_i^{\{(i,j),(i,j')\}}$ is at most the smallest of these amounts.

$$W_i^{\{(i,j),(i,j')\}} \leq \sum_{\text{SS}\in V/\text{BS}} \sum_{p\in P_{\text{SS}+}\cup P_{\text{SS}-}} \delta_p^{\{(j,i),(i,j')\}}(w_p^{\text{SS}^+} + w_p^{\text{SS}^-}) \tag{5.32}$$

$\forall j \in V_i^+,\ \forall j' \in V_i^+, \quad \forall i \in V.$

$$W_i^{\{(i,j),(i,j')\}} \leq \sum_{\text{SS}\in V/\text{BS}} \sum_{p\in P_{\text{SS}+}\cup P_{\text{SS}-}} \delta_p^{\{(j',i),(i,j)\}}(w_p^{\text{SS}^+} + w_p^{\text{SS}^-}) \tag{5.33}$$

$\forall j \in V_i^+,\ \forall j' \in V_i^+, \quad \forall i \in V.$

Constraint (5.34) gives the total amount of traffic $W_i^{(i,j)}$ that is unicast on link $(i,j)$. Namely it is made of (i) traffic where node $i$ is a source node (note that $i$ must be the BS in order to be a source node for downlink connections or sessions), and (ii) traffic that transits through $i$ but could not be coded with other transiting flows.

$$\begin{aligned} W_i^{\{(i,j)\}} = & \sum_{\text{SS}\in V/\text{BS}; i=\text{SS}} \sum_{p\in P_{\text{SS}+}} \delta_p^{ij} w_p^{\text{SS}^+} + \sum_{\text{SS}\in V/\text{BS}: i=\text{BS}} \sum_{p\in P_{\text{SS}-}} \delta_p^{ij} w_p^{\text{SS}^-} \\ & + \sum_{j'\in V_i^-} [ \sum_{\text{SS}\in V/\text{BS}} \sum_{p\in P_{\text{SS}+}\cup P_{\text{SS}-}} \delta_p^{\{(j',i),(i,j)\}}(w_p^{\text{SS}^+} + w_p^{\text{SS}^-}) - W_i^{\{(i,j),(i,j')\}}] \end{aligned} \tag{5.34}$$

$\forall j \in V_i^+, \quad \forall i \in V$

Finally, (5.35) guarantees that the amount of transmission configurations, where $(i,j)$ is active in unicast mode, must satisfy the unicast traffic demands routed on $(i,j)$. This is done by $\sum_{s\in S}\sum_{c\in C} u_i^{s,c} t_{ij}^{s,c} W_{s,c}\lambda_s \geq \sum_{c\in C} u_i^{s,c} W_i^{\{(i,j)\}}$ where $\sum_{c\in C} u_i^{s,c} = 1$ and $\sum_{c\in C} b_i^{s,c} = 0$. Similarly, (5.35) ensures that the broadcast coded demands routed along $(i,j)$ (i.e., $(i,j)$ belongs to a broadcast at node $i$) are satisfied as well. Note that in the latter case $\sum_{c\in C} b_i^{s,c} = 1$ and $\sum_{c\in C} u_i^{s,c} = 0$.

$$\sum_{s\in S}\sum_{c\in C} u_i^{s,c} t_{ij}^{s,c} W_{ij}^{s,c} \lambda_s + \sum_{s\in S}\sum_{c\in C} b_i^{s,c} t_{ij}^{s,c} W_{ij}^{s,c} \lambda_s \geq \sum_{c\in C} u_i^{s,c} W_i^{\{(i,j)\}} + \sum_{c\in C} b_i^{s,c} \sum_{j'\in V_i^+/j} W_i^{\{(i,j),(i,j')\}} \tag{5.35}$$

where $W_{ij}^{s,c}$ is the transport capacity of a time slot (associated with any transmission configuration $s$ and with subcarrier $c$), when $(i,j) \in L$ is active.

## 5.7 A Column Generation Approach

In the previous joint routing-scheduling problem all the transmission configurations $s \in S$ required to satisfy the nodes demands have to be made available so that the problem can be solved (please see the objective in (5.21) and constraint (5.35)).

Clearly, the number of feasible transmission configurations grows exponentially with the size of the network. To handle such complexity, we use the column generation approach. Such approach permits us to separate the joint routing-scheduling problem formulated in Section 5.6 (which we refer to as the master problem) from the admissible transmission configuration generation, formulated in Section 5.5 (which we refer to as the pricing problem). The master model is initialized with a subset of columns $S_0$ of the LP. The pricing model, which is a separate model for the dual LP, is solved to identify whether the master model should be enlarged with additional columns (transmission configurations) or not.

### 5.7.1 Master Problem

The objective of the joint coding-aware routing and scheduling is rewritten as follows:

$$\min \sum_{s \in S_0} \lambda_s \tag{5.36}$$

where $S_0$ is a subset of feasible configurations in $S$.

**Subject to:**

Constraints (5.22) - (5.34) and

$$\sum_{s \in S_0} \sum_{c \in C} u_i^{s,c} t_{ij}^{s,c} W_{ij}^{s,c} \lambda_s + \sum_{s \in S_0} \sum_{c \in C} b_i^{s,c} t_{ij}^{s,c} W^{s,c} \lambda_s \geq \sum_{c \in C} u_i^{s,c} W_i^{\{(i,j)\}} + \sum_{c \in C} b_i^{s,c} \sum_{j' \in V_i^+ / j} W_i^{\{(i,j),(i,j')\}} \tag{5.37}$$

We point out, that the column generation is solved with the LP-Relaxation of variables $\lambda_s$, i.e., $\lambda_s$ is a real value (instead of being an integer value as defined previously).

When the column generation finds the optimal solution of the LP-Relaxation, the associated found columns (transmission configurations) are then solved using integer variables $\lambda_s$ (Integer Linear Programing ILP) to find the ILP solution, [28].

### 5.7.2 Pricing Problem

The pricing problem formulation is the same as the formulation proposed in Section 6.5 but with an objective which is discussed and formulated in the following. Let $\sigma_{ij}$ be the dual variable associated with constraint (6.25). In order to add a new column (i.e., a transmission configuration $s$) to the master (to improve the master problem objective), we need to check if the reduced cost $(1 - \sum_{(i,j) \in L} \sum_{c \in C} t_{ij}^{s,c} \sigma_{ij})$ associated with transmission configuration $s$ is negative, after solving the pricing problem.

In other words, if the $\min\{1-\sum_{(i,j)\in L}\sum_{c\in C} t_{ij}^{s,c}\sigma_{ij}\}$ is negative then we can add its associated transmission configuration $s$ (or add a column) to the set of transmission configurations $S_0$ already present in the master problem. This is done by adding parameters $t_{ij}^{s,c}$, $b_i^{s,c}$ and $u_i^{s,c}$ in the master problem with their values obtained after solving the pricing problem. Thus, the pricing problem objective is to :

$$\min\{1-\sum_{(i,j)\in L}\sum_{c\in C} t_{ij}^{s,c}\sigma_{ij}\} = 1-\max\{\sum_{(i,j)\in L}\sum_{c\in C} t_{ij}^{s,c}\sigma_{ij}\}.$$

To solve the pricing problem, we must look for a transmission configuration $s$ (associated with variables $t_{ij}^{s,c}$), where $\sum_{(i,j)\in L}\sum_{c\in C}\sigma_{ij}t_{ij}^{s,c}$ is maximum. If $\max\{\sum_{(i,j)\in L}\sum_{c\in C}\sigma_{ij}t_{ij}^{s,c}\}\geq 1$, the column associated with $s$ is added to the master problem (to $S_0$). Otherwise no improvement to the master problem objective is possible and therefore optimality is reached.

The pricing problem objective and constraints are:

**Pricing Objective:**

$$\max\sum_{(i,j)\in L}\sum_{c\in C}\sigma_{ij}t_{ij}^{s,c} \tag{5.38}$$

**Subject to:** Constraints (5.1)- (5.14) for MTP.

**Subject to:** Constraints (5.1), (5.6), (5.8)-(5.20) for PA.

## 5.8 Numerical Results

We implemented the column generation formulation for the path-based joint routing and scheduling problem with maximum and variable transmission power. We study the benefits of network coding on improving the network performance using these methods. The resulting methods used in our comparison are: MTP-NC, PA-NC, MTP-WC and PA-WC. MTP-NC and PA-NC refer to the design methods without network coding and the transmissions are unicast transmissions both with maximum and variable power respectively. MTP-WC and PA-WC refer to the design methods with network coding. We used CPLEX Concert Technology adapted for C++ (version 9.1.3) to solve the programs on a 64-bit Linux powered machine at 3GHz and 4GB of RAM (based in CIRRELT [99] research labs).

The BS aggregate capacity is set to 100 Mbps. We assume a TDMA scheduling period [25] of 100ms duration and consisting of 10 frames each with 240 data time slots. Therefore a TDMA scheduling period has 2400 data time slots. We assume one single subcarrier $c \in C$ in the spectrum, where $|C| = 1$.

Note that a time slot (in our column generation model) is assigned to one transmission configuration and has a size of $W_{ij}^{s,c} = \frac{10^7}{2400} = 4,166.6$ bits ($W_{ij}^{s,c}$ is defined in Section 6.6) since our scheduling period has a 100ms duration and the BS aggregated capacity is 100Mbps.

In addition, we set the thermal noise $\eta = 10^{-6}$ mW, the path loss factor $\alpha = 2$ and the SINR threshold $\Gamma = 2.5$ [27]. The maximum transmission power is set to $P_{max} = 0.6$ Watt.

### 5.8.1 Small Network Case:

First, we consider the network shown in Figure 6.2 to study the MTP-WC design method shown above. Here, node D has one uplink demand of 0.5 Mbits (per second) and node C has a downlink demand of 0.5 Mbits (per second).

When using $k = 1$-shortest path between each node of Figure 6.2 and the BS, our optimal routing trees are (D,E,BS) for uplink and (BS,G,A,C) for downlink transmissions. The minimum length schedule is $\sum_{s\in S_0} \lambda_s = 48$ time slots. More precisely we have four transmission configurations $s_1$, $s_2$, $s_3$ and $s_4$ with respectively $\lambda_{s_1} = 12$, $\lambda_{s_2} = 12$, $\lambda_{s_3} = 12$ and $\lambda_{s_4} = 12$. Recall that $\lambda_s$ is the number of times a transmission configuration $s$ is repeatedly assigned to time slots during a scheduling period. The transmission configurations are: $s_1 = \{$(A, C), (E, BS)$\}$, $s_2 = \{$(G, A)$\}$, $s_3 = \{$ (D, E) $\}$ and $s_4 = \{$(BS, G)$\}$. Given that 1-shortest path has been precomputed between each node and the BS, our optimal routing tree was unable to find appropriate routing structures to perform network coding.

Now, when using $k = 2$-shortest paths between each node of Figure 6.2 and the BS, our optimal routing trees are (D,E,BS) for uplink and (BS,E,D,C) for downlink. The minimum length schedule is $\sum_{s\in S_0} \lambda_s = 36$ time slots. More precisely the optimal solution contains transmission configurations $s'_1$, $s'_2$, $s'_3$ with respectively $\lambda_{s'_1} = 12$, $\lambda_{s'_2} = 12$ and $\lambda_{s'_3} = 12$ (time slots), where $s'_1 = \{$(D, C), (BS, E)$\}$, $s'_2 = \{$(D, E)$\}$ and $s'_3 = \{$ (E, BS), (E, D) $\}$. Notice that, our coding-aware joint routing-scheduling (MTP-WC) selects routing trees (uplink/downlink) that favor overlap between the routes of uplink and downlink demands to exploit the broadcast nature of the medium and hence perform coding operations to reduce the total number of required transmissions.

### 5.8.2 Medium Scale Network

We designed a random real-like WiMAX/802.16 mesh network, with a single base station (BS) and 22 SS nodes. We assumed 58 bidirectional radio links (116 unidirectional RF-links) between some pairs of nodes within transmission range of each other. The 23-node mesh network and its corresponding bidirectional radio links is depicted in Figure 5.5. In this figure, the BS is represented by the biggest node and the remaining nodes are the SSs, whereas the bidirectional links are represented by non-oriented lines (a line corresponds to a pair of unidirectional RF-links in opposite directions). Recall that in Section 6.3, we assumed that $(i, j)$ exists $\Leftrightarrow$ $(j, i)$ exists.

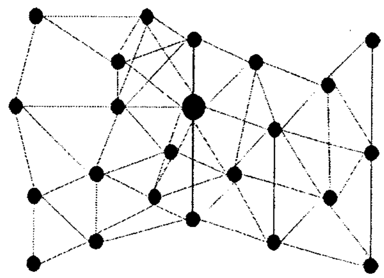

Figure 5.5: 23-Node WiMAX/802.16 Centralized Mesh Network

We consider random uplink/downlink traffic demands for SSs such that 50% of SSs have uplink demands and 50% of SSs have downlink demands. The uplink/downlink traffic demand per each SS node varies between $[1, 1.5]$ Mbits. In Table 5.3 we show the number of slots (schedule length) required to satisfy the demands for the four different schemes (MTP-NC, PA-NC, MTP-WC and PA-WC) with different values of $k$-shortest paths per SS node.

We also considered two other traffic patterns; one with 25% of SSs having uplink demands (50% of SSs have downlink demands) and the other with none (0%) of SSs have uplink demands (50% of SSs have downlink demands). The results associated with these traffic patterns are depicted respectively in Tables 5.4 and 5.5. For both traffic patterns the uplink/downlink demand per each SS node varies between $[1, 1.5]$ Mbits.

We observe from Table 5.3 that generally power-aware methods outperform the fixed transmit power methods (both with and without network coding). This is due to the fact that with power-aware methods, the spectrum spatial reuse can substantially be improved where the transmitters adjust their transmission power to enable the wireless medium to be reused concurrently by spatially separated nodes. For example, when $k = 1$, PA-NC achieves a reduction (in the schedule length or number of slots required to satisfy the network demand) of 15.59% over MTP-NC; this shows that by appropriately configuring the transmit power, more transmission links can be concurrently active in the same time slot, effectively yielding better spectrum reuse. We observe too that varying $k$ does not yield any benefit for MTP-NC model; however, PA-NC benefits from varying $k$ as shown in Table 5.3 since different routes can be selected to further improve the spatial reuse.

When network coding is enabled, both MTP-WC and PA-WC show significant performance gains, with reduction of 20.34% and 24.41% in the schedule length over MTP-NC respectively (see Table 5.3 for $k = 1$) and 5.6% and 10.4% over PA-NC respectively. These gains are attributed to the benefits obtained from the coding opportunities on the selected routing trees for both upstream and downstream demands as well as the efficient spectrum reuse resulting from having fewer number of transmissions by virtue of broadcast transmissions. We note that by varying $k$, better improvement is obtained when network coding is enabled. For example, for PA-NC, a reduction in the schedule length of 4.82% is obtained by varying $k$ from 1 to 3. However, a reduction of 11.66% is obtained for PA-WC. This shows that (with PA-WC) a more efficient construction of routing trees which exploit the coding opportunity is possible and can help in achieving better network performance. With maximum transmission power, while varying $k$ does not yield any benefit for MTP-NC, MTP-WC results in a reduction of 5.96% as $k$ changes from 1 to 3. As mentioned earlier, a better selection of routing trees with coding opportunities improves the system performance.

It is to be noted that any reduction in the schedule length for satisfying the demands means more demands can be admitted to the network and may be scheduled within the TDMA scheduling period (consisting of 2400 slots maximum) defined earlier. Hence a better system utilization can be obtained.

Table 5.4 shows the same comparative study derived earlier, but using different traffic profile:

| Number Of Slots | | | |
|---|---|---|---|
| Scheme | $k$-shortest paths | | |
| | k=1 | k =2 | k =3 |
| (a) | 1770 | 1770 | 1770 |
| (b) | 1494 | 1458 | 1422 |
| (c) | 1410 | 1410 | 1326 |
| (d) | 1338 | 1242 | 1182 |

(a) : MTP-NC
(b) : PA-NC
(c) : MTP-WC
(d) : PA-WC

Table 5.3: 50% uplink, 50% downlink traffic demands: Number of time slots.

25% of SSs have uplink demands and 50% of SSs have downlink demands. We observe from this table that as the opportunity for network coding reduces (as a result of the reduction in upstream traffic which means less chances of overlap among routes for uplink/downlink demands), the performance gain obtained from network coding decreases. For example, when $k = 3$ (in Table 5.4), the gain of PA-WC over PA-NC reaches 10.07% (in contrast to 16.8% from Table 5.3) and the gain of MTP-WC over MTP-NC reaches 14.16% (in contrast to 25.08% observed Table 5.3). Observe, however, that network coding with adaptive transmission power still shows significant performance gains. This, as explained earlier, is due to the improved spectrum spatial reuse (achieved by varying the transmit power) and the benefits that network coding brings by reducing the total number of transmissions that need to be scheduled through appropriate selection of routing trees.

Table 5.5 shows the results obtained by considering another traffic profile, which contains no uplink demands. Clearly, we see that network coding does not yield any gain. We next compare the computational time (CPU time) for the various methods and the results are shown in Table 5.6. MTP-NC exhibits the smallest CPU time, followed, followed by MTP-WC, PA-NC and PA-WC. The MTP-NC model works with a much smaller number of variables and constraints; for example,

| Number Of Slots | | | |
|---|---|---|---|
| Scheme | $k$-shortest paths | | |
| | k=1 | k =2 | k =3 |
| (a) | 1440 | 1440 | 1440 |
| (b) | 1155 | 1139 | 1131 |
| (c) | 1236 | 1236 | 1236 |
| (d) | 1043 | 1025 | 1017 |

(a) : MTP-NC
(b) : PA-NC
(c) : MTP-WC
(d) : PA-WC

Table 5.4: 25% uplink, 50% downlink traffic demands: Number of time slots.

| Number Of Slots | | | |
|---|---|---|---|
| Scheme | $k$-shortest paths | | |
| | k=1 | k =2 | k =3 |
| (a) | 1200 | 1200 | 1200 |
| (b) | 972 | 948 | 936 |
| (c) | 1200 | 1200 | 1200 |
| (d) | 972 | 948 | 936 |

(a) : MTP-NC
(b) : PA-NC
(c) : MTP-WC
(d) : PA-WC

Table 5.5: 0% uplink, 50% downlink traffic demands: Number of time slots.

| Average CPU time in seconds | | | |
|---|---|---|---|
| Scheme | $k$-shortest paths | | |
| | k=1 | k =2 | k =3 |
| (a) | 2 | 3 | 4 |
| (b) | 27 | 30 | 32.4 |
| (c) | 6 | 8.4 | 10.8 |
| (d) | 58 | 117 | 211 |

(a) : MTP-NC
(b) : PA-NC
(c) : MTP-WC
(d) : PA-WC

Table 5.6: Average (of the different traffic instances) CPU time (seconds) to obtain the solution.

the transmission power is a constant parameter (whereas it becomes a variable in PA-NC, PA-WC) and since only unicast transmissions occur under MTP-NC and PA-NC, then variables $u_i$, $b_i$ will no longer be needed. We now measure the throughput obtained in the system for the four design methods and the results are shown in Figures 5.6 and 5.7. The throughput is defined as the total number of demands (in bits) delivered within a scheduling period: $\frac{\sum \text{demands (bits)}}{\sum\limits_{s \in S_0} \lambda_s \text{ (seconds)}}$. We consider $k$ = 3-shortest paths and (50% uplink, 50% downlink) traffic profile in Figure 5.6. Clearly, PA-WC and MTP-WC both outperform PA-NC and MTP-NC respectively in terms of throughput. That is, the same total number of bits can be delivered in a shorter period of time using the PA-WC and MTP-WC design methods. Similar observations can also be seen in Figure 5.7 when we use a different traffic profile.

### 5.8.3 A 35-node Mesh Network

We consider a larger size network with 35 nodes and 316 RF-links. Traffic is randomly generated at SSs, with 50% uplink and 50% downlink demands. Traffic per each demand is randomly selected in $[1, 1.5]$ Mbits. Table 5.7 shows the numerical results of the various design methods and for

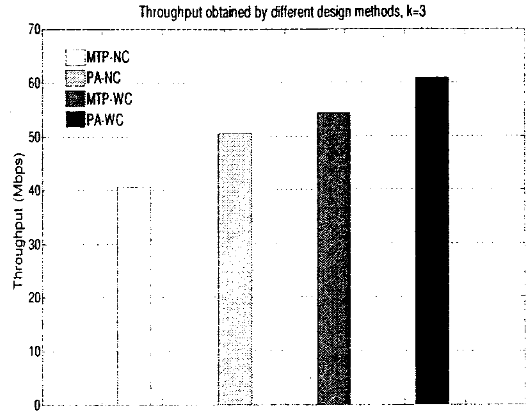


Figure 5.6: 50 % uplink & 50 % downlink Traffic: Throughput of different schemes.

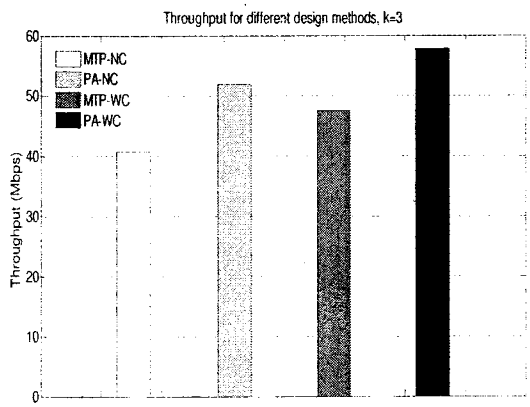


Figure 5.7: 25 % uplink & 50 % downlink Traffic: Throughput of different schemes.

$k = 1, .., 6$.

We first observe that increasing $k$ from 1 to 6 yields good benefits on the system performance for PA-NC, MTP-WC and PA-WC and the gains achieved are 8.58%, 12.7% and 8.1% respectively. For PA-NC, increasing $k$ gives better opportunities for demands to be diversely routed so that the spectrum can be better spatially reused. For both MTP-WC and PA-WC, higher values for $k$ results in more opportunities for selecting uplink/downlink routing trees with more overlap to perform network coding. Performance gains can be observed when comparing MTP-WC, PA-WC to MTP-NC and PA-NC for different values of $k$. For example, MTP-WC acieves a reduction gain in the

| Number Of Slots | | | | | | |
|---|---|---|---|---|---|---|
| Scheme | $k$-shortest paths | | | | | |
| | k=1 | k =2 | k =3 | k = 4 | k =5 | k =6 |
| (a) | 2580 | 2580 | 2580 | 2580 | 2580 | 2580 |
| (b) | 2296 | 2178 | 2160 | 2160 | 2099 | 2099 |
| (c) | 2172 | 2040 | 1992 | 1950 | 1950 | 1896 |
| (d) | 1952 | 1824 | 1813 | 1805 | 1793 | 1793 |

(a) : MTP-NC
(b) : PA-NC
(c) : MTP-WC
(d) : PA-WC

Table 5.7: 50% uplink, 50% downlink traffic demands: Number of time slots.

| CPU time in seconds | | | | | | |
|---|---|---|---|---|---|---|
| Scheme | $k$-shortest paths | | | | | |
| | k=1 | k =2 | k =3 | k = 4 | k =5 | k =6 |
| (a) | 17 | 29 | 34 | 39 | 43 | 48 |
| (b) | 251 | 310 | 430 | 492 | 517 | 580 |
| (c) | 28 | 40 | 52 | 59 | 69 | 77 |
| (d) | 2430 | 4667 | 5784 | 7044 | 7637 | 9576 |

(a) : MTP-NC
(b) : PA-NC
(c) : MTP-WC
(d) : PA-WC

Table 5.8: 50% uplink, 50% downlink traffic demands: CPU time (seconds).

schedule length of 26.5% over MTP-NC and PA-WC achieves a gain of 14.58% over PA-NC. The CPU time is shown in Table 5.8; similar observation to the results presented in Table 5.6 can be seen with PA-WC exhibiting the worst CPU time. Finally, the throughput results for this network scenario, with $k$ = 6-shortest paths are presented in Figure 5.8 with both MTP-WC and PA-WC showing better performance in terms of delivering the same number of bits in shorter scheduling period.

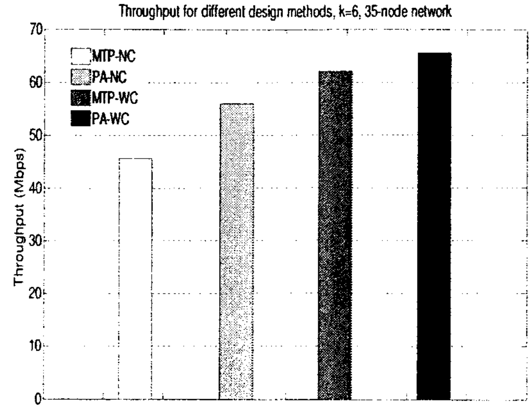


Figure 5.8: 50 % uplink & 50 % downlink Traffic: Throughput of different schemes.

## 5.9 Conclusion

We presented in this chapter a cross layer design framework for joint coding-aware routing and scheduling in a WiMAX-based wireless mesh network. Our formulation exploits opportunistic coding to construct uplink/downlink trees for routing traffic demands. We presented a path-based formulation wherein the set of routes between every source-destination pair is predetermined but a path is not preselected. Scheduling is used to determine which links on the constructed trees can be active concurrently while meeting the SINR requirement at intended receivers. Two formulations for the problem are presented; the maximum transmission power (MTP) and the variable transmission power (PA). Various experiments are performed and numerical results are presented. Our comparisons focused on the benefits one can achieve from network coding as well as the interplay between coding and spectrum spatial reuse. Our results indicate that while power-aware (PA) design method with network coding yield best results, however the method suffers from scalability issues, as shown from the increased computation time needed to solve optimally the model.

# Chapter 6

# Joint Routing-Scheduling in Mobile WiMAX: Maximum Network Stability

In this Chapter, we adopt a cross-layer approach to design a mobility aware joint routing-scheduling for Mobile WiMAX networks. For that matter, we assume that nodes are not necessarily stationary, but rather mobile with a mobility that may yield to frequent topology changes (e.g., failure of existing links and creation of new transmission links). We model the joint routing and scheduling as an optimization problem (based on a column generation approach) whose objective is either to determine a minimum length schedule by maximizing spectrum spatial reuse or maximizing the network lifetime by routing around the less stable RF-links, while satisfying a set of (uplink/downlink) end-to-end demands.

## 6.1 Introduction

It is evident that the focus of next generation mobile wireless technology development has been to enable the efficient delivery of broadband mobile multimedia and Internet services to users [48]. While WiMAX/802.16 [3] [4] has emerged as a serious competitor to other last-mile access technologies, it has become the most popular and cost-effective technology due to its capability of providing high throughput over long distances. WiMAX has been evolving to provide optimizations for Voice over IP (VoIP) and multimedia IP services with high mobility and a target of a much larger mobile Internet market in coming years [48]. With many commercial deployments and more than 100 large-scale trials globally, WiMAX is gaining more and more attention as a viable candidate to realize the convergence of broadband wireless and Internet services. Currently, several active amendments have been specified to the original 802.16 standard, to, for example, provide Mobile Internet services such as the 802.16e, or provide higher transmission data rates (close to 1Gbps for fixed and 100Mbps for mobile users) such as the 802.16m, among others. With this, mobility-related issues, such as handover, routing (and thus scheduling), and security are becoming increasingly important. In this current work, we consider mobile WiMAX technology and we perform joint routing and resource scheduling while considering both interference from concurrent transmissions and mobility of nodes.

We consider routing and scheduling in a WiMAX-based mesh network with Time Division Multiple Access (TDMA) scheme, and allow TDMA time slots to be shared/reused by simultaneous transmissions on neighboring links that are sufficiently apart; this scheme is appropriately termed as spatial-TDMA scheme or network with spatial reuse [78]. We also consider a network where nodes (SSs) are not necessarily stationary, but rather mobile and their mobility may yield to frequent topology changes (e.g., failure of existing links and creation of new transmission links), which indeed introduces additional challenges. We model the joint routing (tree construction) and scheduling as an optimization problem whose objective is either to determine a minimum length schedule by maximizing spectrum spatial reuse or maximize the network lifetime by routing around the less stable RF-links, while satisfying a set of (uplink/downlink) end-to-end demands. We use the term *transmission configuration* to denote the set of transmission links that can be concurrently activated in the same time slot without causing enough interference that can corrupt each other's transmission. Through time sharing of these transmission configurations, routing (tree construction) is formulated as a multi-commodity network flow problem. Indeed, since enumeration of all transmission configurations is only possible for relatively small networks, our solution is based on a column generation approach (a decomposition method of the original optimization problem into subproblems which are then solved iteratively) where we do not require to enumerate all transmission configurations but rather generate, as needed, only a very small subset of them that contribute towards determining an optimal solution.

Unlike, our previous work [43] where we considered the energy consumption in a static environment (where nodes are powered by batteries), we study here the tradeoffs, in a mobile environment, in solving our model for achieving either of the two objectives; indeed, minimizing the schedule length forces the joint routing and scheduling problem to generate a routing tree and feasible transmission configurations which favor higher spectrum spatial reuse (and hence higher system throughput), irrespective of the robustness (e.g., their life time) of the transmission links selected for constructing the routing tree to satisfy the demands. Alternatively, maximizing the network life time (time until the first link fails) yields to the selection of different routing tree and slot assignment which does not necessarily result in shorter schedule length.

The remainder of the chapter is organized as follows. Related work on routing and scheduling is reviewed in Section 6.2 with the most recent work on mobile WiMAX technology. Section 6.3 presents the network communication model preliminaries and assumptions. Section 6.4 defines the problem through an illustrative example and present modifications. In Section 6.5, the transmission configuration generation problem is formulated, then in Section 6.6 the joint routing-scheduling problem is presented and formulated as an optimization problem with the associated objectives. Section 6.7 decomposes the optimization problem, using column generation, into a master problem and a pricing problem that are efficiently solved iteratively. In Section 6.8, the numerical results are discussed and finally we conclude our work in Section 6.9.

## 6.2 Related Work

Joint scheduling and power control has been considered in prior work [45][20][71] where a set of parallel transmissions is considered feasible if it is possible to find a power assignment that satisfies power limitations and provides the required SINR. A further improvement can be achieved considering also transmission rate control within a cross-layer approach [36], [66], where according to the SINR value, the best transmission rate that provides an error rate sufficiently low can be selected. All of the above mentioned models have been proposed for fixed networks, making their performance not optimized for networks with mobile nodes.

Recently, the IEEE 802.16 standard for WiMAX technology has addressed mobility through the 802.16e amendment [6], which includes component to support P2MP, mesh modes and seamless handover operations [105] [104]. This technological uprising is now becoming a fast growing popular access technology which enables low-cost mobile Internet applications and realizes the convergence of mobile and fixed broadband access in a single air interface and network architecture [47]. Accordingly, SS nodes need no longer be stationary, with some of them subject to mobility (up to a vehicular speed), referred to as mobile subscriber stations MSSs. However, Mobile WiMAX will face new challenges and dealing with them is inevitable. Few work on Mobile WiMAX have appeared in the literature lately [47, 96, 49, 82, 31, 92, 84]; however, given its novelty, its recent introduction to the Telecom industry, and its close to be finalized amendments (802.16m and WiMAX network release 2.0), most of the work focused on presenting an overview of Mobile WiMAX, its performance and evolution in order to stimulate and attract researchers from both academia and industries to invest in this technology.

In this chapter our efforts are complementary to the above work, in that, we propose a joint routing-scheduling modeling framework for Mobile WiMAX multihop relaying (mesh) networks, which overcomes some of the challenges faced in such networks, such as frequent RF-link failures and topology change owed to mobility of nodes (MSSs), which could lead to service outage and erroneous network operation. Precisely, the BS keeps track of the mobility of the nodes and seeks the most stable RF-links (with the highest time of operation or availability) when performing joint routing-scheduling for delivering the network (uplink and downlink) traffic. In doing so, the BS will enable higher network lifetime (time elapsed until the first RF-link failure) and thus higher network delivery (amount of data delivered to end-subscribers). It is also to be noted that, when an RF-link failure occurs or the network's topology changes, the BS needs to recompute the routing tree (and thus reschedule the uplink and downlink demands), otherwise erroneous network operation and service outage due to unexpected interference is inevitable. Hence the mobility awareness is indispensable to reduce the frequency of recomputing and rescheduling efforts while seeking the most stable end-to-end paths.

## 6.3 Network Communication model preliminaries and assumptions

### 6.3.1 Interference Model

We consider a directed graph $G(V, L)$ which represents the WiMAX/802.16 mesh network. $V$ denotes the set of nodes ($BS$ and SS) and $L$ represents the set of RF-links that are available between nodes. Note that a RF-link $(i, j)$ exists if its receiving node $j$ is within the maximum coverage range $D_i$ of its transmitting node $i$, i.e., the distance between node $i$ and node $j$, $d_{ij} \leq D_i$. We assume that all nodes have the same maximum covering range $D$ and therefore if a RF-link exists in a particular direction, its corresponding RF-link in the opposite direction exists too, i.e., $(i, j)$ exists $\Leftrightarrow$ $(j, i)$ exists.

There are two possible interference models that can be considered for multi-hop wireless networks; namely, the interference-graph based model (or protocol model) and the physical model [56]. In the protocol model, interference constraints can be modeled through the use of an interference graph where each node corresponds to a transmission link in the original (network) graph and links exist between nodes in the interference graph if the corresponding links in the network graph interfere with each other [60]. In this model, the mutual interference among concurrent transmissions in the neighborhood is the main concern in link scheduling (slot allocation). In this chapter, we use the protocol model where two links $(i, j)$ and $(u, v)$ can transmit simultaneously if and only if receivers $j$ and $v$ are located out of the mutual interference range of the transmitters $i$ and $u$, i.e., $d_{iv} > (1 + \gamma) \times D_i = (1 + \gamma) \times D$ and $d_{uj} > (1 + \gamma) \times D_u = (1 + \gamma) \times D$, where $\gamma \geq 0$ is a positive constant. If the above condition is satisfied, we say that the two links $(i, j)$ and $(u, v)$ are independent [101] and may be scheduled for transmission at the same time. Accordingly, we use the following function $I((i, j), (u, v))$ $\forall((i, j), (u, v)) \in L \times L$, to identify whether or not $(i, j)$ and $(u, v)$ are independent [101]. This function is applied to all pairs of links, where

$$I((i,j),(u,v)) = \begin{cases} 1, \text{if } (i,j) \text{ and } (u,v) \text{ are independent} \\ 0, \text{otherwise.} \end{cases} \tag{6.1}$$

where $((i, j), (u, v)) \in L \times L$.

The IEEE WiMAX/802.16 mesh mode of operation uses Time Division Multiple Access (TDMA) technology [25] [37] where a scheduling period is divided into time slots. We further assume sub-channelization (sub-carrier allocation) within a time slot; sub-channelization divides the spectrum into multiple orthogonal sub-channels (e.g., OFDM technology). This sub-channelization allows multiple data streams to be successfully received concurrently either at the same node or at neighboring nodes.

### 6.3.2 RF-Link availability

We will use the mobility prediction mechanisms suggested in [90] to predict the Link Expiration Time (LET) of the adjacent nodes. We assume that all nodes in the network have their clock synchronized; therefore, if the motion parameters of two neighbors (mobile subscriber stations MSSs) are known, we can determine the duration of the time that these two nodes (MSSs) will remain connected. Let $(X_i, Y_i)$ and $(X_j, Y_j)$ be the coordinates of nodes $i$ and $j$ which are moving in directions $\theta_i$ and $\theta_j$ ($0 \leq \theta_i$ , $\theta_j < 2\pi$) with the speed $V_i$ and $V_j$ respectively, and let $D$ be the transmission range. We can estimate the amount of time they will stay connected as

$$LET_{ij} = \frac{-(ab+cd) + \sqrt{(a^2+c^2)D^2 - (ad-bc)^2}}{a^2+c^2} \tag{6.2}$$

where $a = V_i cos\theta_i - V_j cos\theta_j$, $b = X_i - X_j$,

$c = V_i sin\theta_i - V_j sin\theta_j$ and $d = Y_i - Y_j$.

If both nodes ($i$ and $j$) have the same speed and speed angles ($V_i = V_j$ and $\theta_i = \theta_j$), then $LET_{ij}$ is set to $\infty$. Alternatively, if both nodes ($i$ and $j$) are stationary, then their corresponding $LET_{ij}$ is also set to $\infty$. For example, nodes can use the north axis as a reference for the directional angle and a predefined two-dimensional coordinate for positions. $LET_{ij}$ is hence the Link Expiration Time of the link between nodes $i$ and $j$. Note that since the BS is stationary, it does not move and therefore its speed is 0.

## 6.4 Problem Statement and Motivations

The objective of this work is to compare the minimum scheduling length which satisfies all the demands (uplinks, downlinks) of all MSSs with the schedule length obtained when we select the most available (stable) RF-links to route the demands. We assume multi-hop routing (tree) for delivery of uplink (downlink) sessions from MSSs (BS) to BS (MSSs). However, due to the interference-limited nature of a wireless environment, appropriate link scheduling to also improve spatial reuse becomes essential. To achieve our objective, we need to jointly optimize routing (tree construction) and scheduling for traffic delivery. We note that to maximize spatial reuse (under interference constraints), many RF-links (with enough spatial separation) should be activated simultaneously (we refer to such group of links as a transmission configuration).

Consider the network shown in Figure 6.1 for illustration where bidirectional edges represent the feasible transmission links. Two uplink sessions of one unit demand each are to be established between N0, N2 and the BS. We assume a single carrier channel where time is divided into slots (of one unit demand capacity each) and we need to determine a link activation schedule to satisfy the traffic demand. In addition, suppose that N4 is a mobile node such that RF links (N2-N4), (N4-N3) and (N4-BS) have a small link expiration time (LET), i.e., less stable. To deliver traffic from N0 and

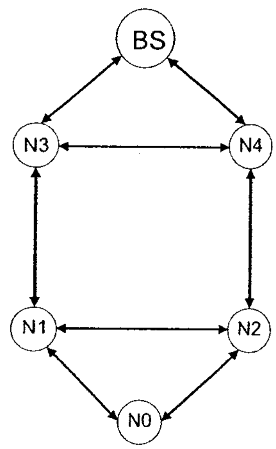


Figure 6.1: WiMAX Mesh network example.

N2 to the BS, we consider 2 possible trees that might be chosen: $T_1$ =(N0-N1-N3-BS, N2-N4-BS) and $T_2$ =(N0-N1-N3-BS, N2-N1-N3-BS). Indeed, if $T_1$ is selected, traffic from N0 to BS must be routed through nodes N1 and N3. Due to self-interference (or intra-path interference) and single radio constraint at nodes N1 and N3, links (N0-N1) and (N1-N3) cannot be active during the same time slot; similarly (N1-N3) and (N3-BS) cannot be active in the same time slot. A similar argument is made for (N2-N4-BS) at node N4. One feasible non-optimal solution for the problem is to use 5 time slots, each for activating one link. However, by exploiting the spectrum spatial reuse, we can activate both links (N0-N1) and (N4-BS) at the same time, assuming that (N0-N1) and (N4-BS) are independent. Similarly, (N2-N4) and (N1-N3) (assuming their independence of one another) can be active simultaneously in one time slot, an finally, a time slot is used to activate link (N3-BS) alone. This results respectively, in scheduling three transmission configurations $(g_1, g_2, g_3)$, each group consists of a set of links that can be active in the same time slot (except for $g_3$), and thereby forming a routing tree $(T_1)$ for delivering uplink demands.

It can be easily verified that the other tree $T_2$ will require more time slots (and hence transmission configurations), for delivering the two uplink demands (and hence longer scheduling period). Note that while $T_1$ resulted in a shorter schedule length, the uplink demand of N2 has been routed through unstable links using intermediate mobile node N4. Accordingly the route lifetime for this flow is short, which clearly may result in poor network delivery. On the other hand, while $T_2$ requires more time slots to deliver both upstream demands (and hence longer scheduling length), both demands are routed through more stable routes, which yield a better network delivery. It is to be noted finally that, transmission configurations could be repeatedly assigned to more time slots in a scheduling period to meet the bandwidth requirements of the demands.

In a mobile environment, RF-links may exist only temporarily and therefore the network topology is prone to frequent changes. We assume that all nodes maintain synchronization with the base station and the BS is aware of the movement of these nodes. A subtle problem which may arise, in addition to the removal of some RF-links from the topology, is that a schedule may become erroneous upon a topology change. In particular, new links may be created that may break the independency assumption among other links that have been scheduled concurrently. We illustrate this using an example shown in Figure 6.2. Consider the same traffic demands as before. In Figure 6.2

a), node N4 moves to a new position at close proximity from node N1. As a result, N1 now falls inside the transmission range (or N4 falls within the interference range of N1) of N4. Using the schedule developed earlier for tree $T_1$, both (N0-N1) and (N4-BS) cannot be active concurrently, otherwise strong interference from N4 will corrupt the packet reception at node N1. Accordingly, a new schedule (as well as a routing tree) need to be generated by the BS.

Alternatively, if node N4 moves in the opposite direction as shown in Figure 6.2 b), the topology changes as a result of the failure of some existing RF-links. Again, adopting $T_1$ for routing the two demands will result in a service outage for the demand between N2 and the BS. Accordingly, the BS must keep track of the movement of nodes and recompute a new schedule upon topology changes. More specifically, we assume that the BS has complete information of the network through appropriate signaling methods developed for mobile WiMAX. The information of each node is maintained and upgraded by the BS (system) through appropriate control messages before performing the joint routing-scheduling. If link failures occur frequently, the BS will have, at each link failure, to fetch again for the changing nodes information and perform another joint routing-scheduling.

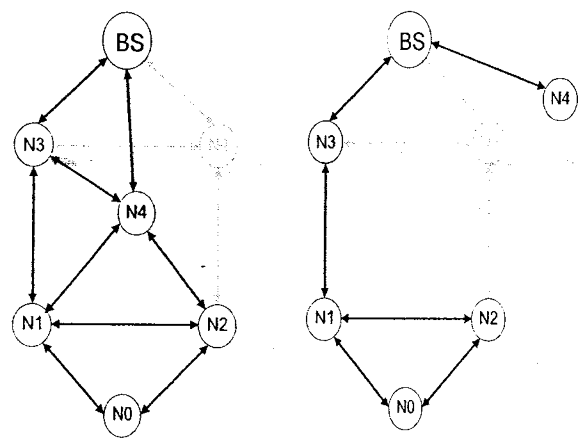


Figure 6.2: WiMAX mesh Mobile Awareness: a) left Figure, b) right Figure

## 6.5 Transmission Configuration Generation Problem

As discussed in Section 6.4, the key issue is to select an appropriate set of transmission configurations that minimizes the number of time slots in the scheduling period. In this section, we formulate the constraints that govern the definition of a transmission configuration which is defined as a group of RF-links that can transmit concurrently without causing enough interference on each other so that the communication is corrupted. Let $S$ be the set of possible transmission configurations.

Let $t^s_{ij}$ be a decision variable that is equal 1 if RF-link $(i,j) \in L$ is active, 0 otherwise for a given transmission configuration $s$. We further enable sub-carrier allocation within a time slot, therefore we extend $t^s_{ij}$ and replace it by variable $t^{s,c}_{ij}$ that is equal 1 if RF-Link $(i,j) \in L$ is active in transmission configuration $s$ and a subcarrier $c \in C$ is allocated to it, and 0 otherwise. $C$ denotes the set of available orthogonal subchannels.

The following set of constraints is used to ensure the half duplex property (self-interference) where a node $i \in V$ cannot transmit and receive at the same time slot (or same transmission configuration):

$$\sum_{c \in C} t^{s,c}_{ji} + \sum_{c \in C} t^{s,c}_{ij} \leq 1; \quad i \in V\ ,\ (j,i) \in L\ ,\ (i,j) \in L \tag{6.3}$$

Constraints (6.4) ensure that two or more nodes do not transmit to a common receiving node, while using the same sub-carrier $c \in C$, during the same time slot $s$ (or transmission configuration).:

$$\sum_{j:(j,i) \in L} t^{s,c}_{ji} \leq 1 \quad i \in V\ ,\ c \in C; \tag{6.4}$$

Constraints (6.5) allow a node $i$ to receive multiple data streams at the same time slot on different subcarriers; thus, a node cannot receive from more than $|C|$ neighboring nodes at the same time slot.

$$\sum_{j:(j,i)\in L} \sum_{c\in C} t_{ji}^{s,c} \leq |C| \quad i \in V. \tag{6.5}$$

In addition, constraints (6.6) allow a node $i$ to transmit on only one subcarrier $c \in C$ (and to a particular neighbor $j$) in one transmission configuration $s$.

$$\sum_{j:(i,j)\in L} \sum_{c\in C} t_{ij}^{s,c} \leq 1 \quad i \in V. \tag{6.6}$$

Finally, if two links are simultaneously active (in a transmission configuration $s$), while using the same subcarrier $c \in C$, they must be independent to one another. This is formulated by the following set of constraints:

$$t_{ij}^{s,c} + t_{uv}^{s,c} \leq 1 + I((i,j),(u,v)) \qquad c \in C \ , \ ((i,j),(u,v)) \in L^2. \tag{6.7}$$

Recall that $I((i,j),(u,v))$ is a function defined in (6.1), which determines whether a pair of links are independent from one another.

## 6.6 Joint Routing-Scheduling Problem

In this section, the joint routing-scheduling formulation is introduced.

### 6.6.1 Parameters and Variables

We introduce the integer vector $\lambda = (\lambda_s)$ where $\lambda_s$ is an integer variable associated with each transmission configuration $s \in S$ such that it is equal to the number of times a transmission configuration $s$ is used throughout a TDMA scheduling period. We also introduce the vectors $y^{\text{UL}} = (y_{uv}^{\text{UL}})$ and $y^{\text{DL}} = (y_{uv}^{\text{DL}})$ such that $y_{uv}^{\text{UL}}$ and $y_{uv}^{\text{DL}}$ are variables that identify whether or not RF-link $(u, v)$ is active for uplink and downlink transmission respectively in a scheduling period (at least one time slot). These variables will come in handy when constructing the routing tree associated with the centralized scheduling.

$$y_{uv}^{\text{UL}} = \begin{cases} 1 \text{ if } (u, v) \text{ is active for uplink transmission,} \\ 0 \text{ otherwise.} \end{cases}$$

Similarly,

$$y_{uv}^{\text{DL}} = \begin{cases} 1 \text{ if } (u, v) \text{ is active for downlink transmission,} \\ 0 \text{ otherwise.} \end{cases}$$

Moreover, we define the parameter $t_{ij}^{s}$ such that:

$$t_{ij}^{s,c} = \begin{cases} 1 \text{ if } (i, j) \text{ is active in transmission configuration } s \in S \text{ while using subcarrier } c \in C \\ 0 \text{ otherwise.} \end{cases}$$

Finally, denote by $V_i^+$ the set of neighbors of $i$ such that $j \in V_i^+$ if and only if $(i, j) \in L$. Similarly, $V_i^-$ represents the set of neighbors of $i$ such that $j \in V_i^-$ if and only if $(j, i) \in L$.

### 6.6.2 Mathematical model

We propose a path-based formulation approach where we associate each SS with some potential routing paths towards the BS (for uplink connections) denoted by $P_{\mathrm{SS}^+}$ and some potential paths from the BS towards the SS (for downlink connections) denoted by $P_{\mathrm{SS}^-}$. The following set of variables and parameters are used:

$w_p^{\mathrm{SS}^+}$ represents the amount of uplink data which is being routed on path $p \in P_{\mathrm{SS}^+}$

$$x_p^{\mathrm{SS}^+} = \begin{cases} 1, \text{ if } w_p^{\mathrm{SS}^+} > 0, \\ 0, \text{ otherwise.} \end{cases}$$

$w_p^{\mathrm{SS}^-}$ represents the amount of downlink data which is being routed on path $p \in P_{\mathrm{SS}^-}$

$$x_p^{\mathrm{SS}^-} = \begin{cases} 1, \text{ if } w_p^{\mathrm{SS}^-} > 0, \\ 0, \text{ otherwise.} \end{cases}$$

We also define the parameter $\delta_p^{ij}$ such that:

$$\delta_p^{ij} = \begin{cases} 1, \text{ if link } (i, j) \text{ belongs to path } p, \\ 0, \text{ otherwise.} \end{cases}$$

Note that, if a RF-link is part of the routing paths of the granted demands, then its corresponding link expiration time LET will affect the network stability otherwise its LET will have no impact on the network stability. Accordingly, for every RF-link $(u, v) \in L$, we define $\xi_{uv}^+$ to be $LET_{uv}$ if link $(u, v)$ is traversed by at least one uplink demand, otherwise $\xi_{uv}^+ = M$, where $M$ is a very large integer. We define $\xi_{uv}^-$ for downlink traffic in a similar manner.

Hence,

$$\xi_{uv}^+ = (1 - x_p^{\mathrm{SS}^+} \delta_p^{uv})M + x_p^{\mathrm{SS}^+} \delta_p^{uv} LET_{uv} \qquad \mathrm{SS} \in V \;,\; p \in P_{\mathrm{SS}^+} \tag{6.8}$$

$$\xi_{uv}^{-} = (1 - x_p^{\mathrm{SS}^-} \delta_p^{uv})M + x_p^{\mathrm{SS}^-} \delta_p^{uv} LET_{uv} \qquad \mathrm{SS} \in V \ , \ p \in P_{\mathrm{SS}^-} \tag{6.9}$$

Note that, our objective is to either minimize the overall number of transmitting groups (minimize the schedule length) or to maximize the network stability (time elapsed until the failure of the *first* RF-link in the routing tree due to the mobility of its end nodes) in a mobile environment. We therefore introduce a hierarchical objective which minimizes the overall number of transmitting groups first, referred to as MinSchedLength. We also define the opposite objective where we maximize the network stability first, referred to as MaxNetStab.

**Objective:**

$$\min\{\alpha_1 \times \sum_{s \in S} \lambda_s - \alpha_2 \times z\} \tag{6.10}$$

where $z$ is a real variable that represents network stability, $\alpha_1$ and $\alpha_2$ are weight parameters. Note that $\alpha_1 >> \alpha_2$ corresponds to MinSchedLength, whereas $\alpha_2 >> \alpha_1$ corresponds to MaxNetStab.

**Subject to:**

The network stability constraint for both uplink and downlink demands are as follows:

$$z \leq \xi_{uv}^{+} \quad (u, v) \in L \tag{6.11}$$

$$z \leq \xi_{uv}^{-} \quad (u, v) \in L \tag{6.12}$$

A direct relationship exists between $x_p^{\mathrm{SS}^+}$ ($x_p^{\mathrm{SS}^-}$) and $w_p^{\mathrm{SS}^+}$ ($w_p^{\mathrm{SS}^-}$), which requires the following additional constraints:

$$x_p^{\mathrm{SS}^+} \geq \frac{w_p^{\mathrm{SS}^+}}{W} \quad p \in P_{\mathrm{SS}^+}, \ \mathrm{SS} \in V/\{\mathrm{BS}\} \tag{6.13}$$

$$x_p^{\mathrm{SS}^-} \geq \frac{w_p^{\mathrm{SS}^-}}{W} \quad p \in P_{\mathrm{SS}^-},\ \mathrm{SS} \in V/\{\mathrm{BS}\} \tag{6.14}$$

where $W$ is a large value greater than the maximum throughput achievable in the network.

Constraints (6.15) and (6.16) ensure that one path among the potential paths is selected to route respectively the data from a particular SS to the BS (uplink) and the data from the BS to the corresponding SS (downlink).

$$\sum_{p \in P_{\mathrm{SS}+}} x_p^{\mathrm{SS}^+} \leq 1\ ,\ \mathrm{SS} \in V/\{\mathrm{BS}\} \tag{6.15}$$

$$\sum_{p \in P_{\mathrm{SS}-}} x_p^{\mathrm{SS}^-} \leq 1\ ,\ \mathrm{SS} \in V/\{\mathrm{BS}\} \tag{6.16}$$

(6.17) and (6.18) state the flow conservation constraints for both uplink and downlink demands respectively:

$$\sum_{j \in V_i^-} \sum_{p \in P_{\mathrm{SS}+}} \delta_p^{ji} w_p^{\mathrm{SS}^+} - \sum_{j \in V_i^+} \sum_{p \in P_{\mathrm{SS}+}} \delta_p^{ij} w_p^{\mathrm{SS}^+} = \begin{cases} 0 & \text{if } i \in V \setminus \{\mathrm{SS}, \mathrm{BS}\}, \\ -R_{\mathrm{SS}}^{\mathrm{UL}} & \text{if } i = \mathrm{SS}, \\ R_{\mathrm{SS}}^{\mathrm{UL}} & \text{if } i = \mathrm{BS}. \end{cases} \tag{6.17}$$

where $i \in V$, $\mathrm{SS} \in V/\{\mathrm{BS}\}$ and $R_{\mathrm{SS}}^{\mathrm{UL}}$ is the uplink demand to be satisfied for one SS.

$$\sum_{j \in V_i^-} \sum_{p \in P_{\mathrm{SS}-}} \delta_p^{ji} w_p^{\mathrm{SS}^-} - \sum_{j \in V_i^+} \sum_{p \in P_{\mathrm{SS}-}} \delta_p^{ij} w_p^{\mathrm{SS}^-} = \begin{cases} 0 & \text{if } i \in V \setminus \{\mathrm{SS}, \mathrm{BS}\}, \\ R_{\mathrm{SS}}^{\mathrm{DL}} & \text{if } i = \mathrm{SS}, \\ -R_{\mathrm{SS}}^{\mathrm{DL}} & \text{if } i = \mathrm{BS}. \end{cases} \tag{6.18}$$

where $i \in V$, $\text{SS} \in V/\{\text{BS}\}$ and $R^{\text{DL}}_{\text{SS}}$ is the downlink demand to be satisfied for one SS.

In order to satisfy the definitions of $y^{\text{UL}}_{uv}$ and $y^{\text{DL}}_{uv}$, we formulate the following constraints :

$$\sum_{p \in P_{\text{SS}+}} x_p^{\text{SS}^+} \delta_p^{uv} \leq y^{\text{UL}}_{uv} \quad \text{SS} \in V/\{\text{BS}\},\ (u,v) \in L \tag{6.19}$$

$$\sum_{p \in P_{\text{SS}-}} x_p^{\text{SS}^-} \delta_p^{uv} \leq y^{\text{DL}}_{uv} \quad \text{SS} \in V/\{\text{BS}\},\ (u,v) \in L \tag{6.20}$$

In addition, constraints (6.21) and (6.22) are introduced to preserve the rooted tree property.

$$\sum_{v' \in N(u)} y^{\text{UL}}_{uv'} \leq 1 \quad u \in V \tag{6.21}$$

$$\sum_{v' \in N(u)} y^{\text{DL}}_{v'u} \leq 1 \quad u \in V \tag{6.22}$$

Finally, the following constraint is to guarantee the minimum number of active slots (transmission configurations) to satisfy the demand/bandwidth of all connections routed on a particular link $(i,j) \in L$ (bandwidth constraint).

$$\sum_{s \in S} \sum_{c \in C} t_{ij}^{s,c} W_{ij}^{s,c} \lambda_s \geq \sum_{\text{SS} \in V/\{\text{BS}\}} \Big( \sum_{p \in P_{\text{SS}+}} w_p^{\text{SS}^+} \delta_p^{ij} + \sum_{p \in P_{\text{SS}-}} w_p^{\text{SS}^-} \delta_p^{ij} \Big) \tag{6.23}$$

where $W_{ij}^{s,c}$ is the transport capacity of a time slot (associated with transmission configuration $s$ while using subcarrier $c$) at RF-link $(i,j)$.

## 6.7 A Column Generation Approach

All the transmission configurations ( $s \in S$) required to satisfy the nodes demand feed the joint routing-scheduling problem described in Section 6.6.2. All possible transmission configurations could be generated either all off line and added all together to the joint routing-scheduling problem or one at a time generated and added, to the joint routing-scheduling problem. The second generation scheme, that is associated with a column generation scheme, adds wisely, in an on-line fashion, the most suitable transmission configuration and therefore the optimal solution Linear Programming (LP) can be obtained without the need to enumerate all possible transmission configurations. We use the latter scheme in this work.

Recall that column generation decomposes a Linear Program (LP) into a master problem (which here corresponds to the joint routing-scheduling problem) and a pricing problem (which here corresponds to the transmission configuration generation problem). The master problem starts with a subset of columns, or equivalently of variables $\lambda_s, s \in S_0$ where $S_0$ can be derived from a set of feasible transmission configurations. The pricing problem is a column (transmission configuration) generator that keeps generating and adding columns as long as there exists one that can improve the LP solution of the master problem. Given the augmenting property of the pricing problem, where a transmission configuration is generated only to improve the master problem solution, a tiny fraction of such groups is usually enough to reach optimality.

Finally, such optimization techniques (column generation) are indeed vital in Mobile WiMAX, where frequent RF-link failures occur (owed to the mobility of their end nodes) and topology changes are ubiquitous. Given its drastically reduced CPU time to identify the optimal solution, column generation allows quick recovery (rerouting and rescheduling of traffic demands) from RF-link failures and network topology changes.

### 6.7.1 Master Problem

The objective of the master problem can be written as follows:

$$\min\{\alpha_1 \sum_{s \in S_0} \lambda_s - \alpha_2 \times z\} \tag{6.24}$$

where $S_0$ is a subset of $S$.

**Subject to:**

Constraints (6.11)-(6.22), and

$$\sum_{s \in S_0} \sum_{c \in C} t_{ij}^{s,c} W_{ij}^{s,c} \lambda_s \geq \sum_{\text{SS} \in V/\text{BS}} \Big( \sum_{p \in P_{\text{SS}+}} w_p^{\text{SS}^+} \delta_p^{ij} + \sum_{p \in P_{\text{SS}-}} w_p^{\text{SS}^-} \delta_p^{ij} \Big) \tag{6.25}$$

### 6.7.2 Pricing Problem: On-line Transmission Configuration Generation

The pricing problem corresponds to the on-line generation of a transmission configuration, one at a time, with the guarantee that each added transmission configuration improves the current solution of the linear program. Its formulation is the same as the formulation proposed in Section 6.5. The pricing objective is defined by the reduced cost of the $\lambda_s$ variables, a classical optimality metric in linear programming theory [32]. Using that theory, we can claim that any transmission configuration with a negative reduced cost is an augmented one, i.e., a group whose addition, improves the LP value of the objective of the master problem. The expression of the reduced cost can be written as follows:

$$(1 - \sum_{(i,j) \in L} \sum_{c \in C} t_{ij}^{s,c} \sigma_{ij})$$

, where $\sigma_{ij}$ is the dual variable associated with constraint (6.25).

To solve the pricing problem, we must look for a transmission configuration $s$ (associated with variables $t_{ij}^{s,c}$), where $\sum\limits_{(i,j) \in L} \sum\limits_{c \in C} \sigma_{ij} t_{ij}^{s,c}$ is maximum. If $\max\{\sum\limits_{(i,j) \in L} \sum\limits_{c \in C} \sigma_{ij} t_{ij}^{s,c}\} \geq 1$ (negative reduced cost), the column associated with $s$ is added to the master problem (to $S_0$). Otherwise, no improvement to the master problem objective is possible and therefore optimality is reached.

The pricing problem objective and constraints can be written as follows:

**Pricing Objective:**

$$\max \sum_{(i,j) \in L} \sum_{c \in C} \sigma_{ij} t_{ij}^{s,c} \tag{6.26}$$

**Subject to:**

Constraints (6.3)-(6.7).

### 6.7.3 Solution Scheme

In order to solve the joint routing-scheduling ILP problem, we first solve the LP relaxation of the master problem using the column generation technique, where $\lambda_s$ take real values. Once the optimal LP solution has been solved, we solve the ILP problem, called ILP0, defined by the set of explicitly generated columns, where $\lambda_s$ are now integer variables. The optimal solution of the LP relaxation defines a lower bound on the optimal ILP solution, while the the optimal solution of the ILP0 problem defines an upper bound. Difference between the two bounds provides the so-called optimality gap, i.e., the precision of the ILP0 optimal solution with respect to the optimal solution of the joint routing-scheduling ILP problem.

## 6.8 Numerical Results

We implemented the Column Generation based models MinSchedLength and MaxNetStab using CPLEX Concert Technology adapted for C++ (version 9.1.3) [35]. The machine used to run the Column Generation models is a 64-bit Linux powered machine at 3GHz and 4GB of RAM (based in CIRRELT [99] research labs).

### 6.8.1 Network and Parameters

We designed a random real-like WiMAX/802.16 mesh network, with a single base station (BS) and 22 SS nodes. We assumed 58 bidirectional radio links (116 unidirectional RF-links) between some pairs of nodes within transmission range of each other. The 23-node mesh network and its corresponding bidirectional radio links is depicted in Figure 6.3. In this figure, the BS is represented by the biggest node and the remaining nodes are the SSs, whereas the bidirectional links are represented by non-oriented lines (a line corresponds to a pair of unidirectional RF-links in opposite directions). Recall that in Section 6.3, we assumed that $(i, j)$ exists $\Leftrightarrow$ $(j, i)$ exists.

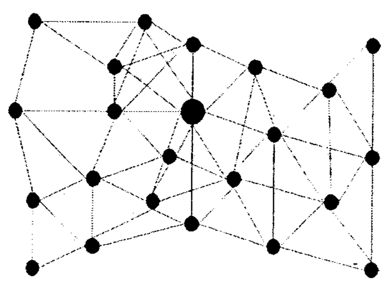

Figure 6.3: 23-Node WiMAX/802.16 Centralized Mesh Network

The aggregate capacity of the BS is set to 100 Mbps. We assume a TDMA scheduling period [25] of 100ms duration and consisting of 20 frames (of 5ms duration) each of 240 data time slots. Therefore a TDMA scheduling period has 4800 data time slots. Note that we only assume a single subcarrier $c \in C$ in the channel, where $|C| = 1$.

In addition a time slot (which in our column generation models is assigned to one transmission configuration only) has a size of $W_{ij}^{s,c} = \frac{10^7}{4800} = 2,083.3$ bps ($W_{ij}^{s,c}$ is defined in Section 6.6.2), since our scheduling period has a 100ms duration and is associated with a 100 Mbps BS.

Moreover, we considered 3 potential paths ($k$ = 3-shortest paths [46]) between each SS (MSS) node and the BS. We assume each SS has both uplink and downlink demands.

### 6.8.2 Impact of $\gamma$

#### 6.8.2.1 Static Environment

We first consider a static environment where all nodes are fixed (fixed subscriber stations) and run our MinSchedLength model for different values of $\gamma$ (0, 0.2, 0.5), and for different load per SS: $R_{\text{SS}}^{\text{DL}} = R_{\text{SS}}^{\text{UL}} = \{0.25, 0.5, 0.75, 1\}$ Mbps. Note that $\gamma$ is a parameter that is used to determine the interference range of a receiver and hence the set of transmission links that could interfere with the current transmission, as defined in Section 6.3. We do not present the results of MaxNetStab model since all nodes are considered stationary. Our results after solving the MinSchedLength model are presented in Figure 6.4 where we show the minimum schedule length needed to satisfy all the demands for different traffic loads per each SS.

First, we observe that as the load increases, the length of the schedule increases linearly for different values of $\gamma$, and this is justified by the need for more slots to satisfy the demands. We note however that a smaller value for $\gamma$ requires less number of slots to satisfy the demands. For example, at 1 Mbps, when $\gamma = 0$, the schedule length is 2112 slots, where as when $\gamma = 0.5$, the schedule length becomes 2400 slots. Indeed, a larger value of $\gamma$ results in larger interference range which in turns affects the spatial reuse since fewer transmission links could be activated concurrently in a transmission configuration. In other words, to satisfy the demands, more transmission configurations are needed and hence the longer schedule length.

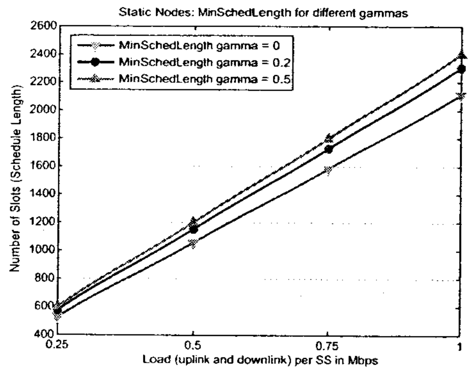


Figure 6.4: Scheduling Length: MinSchedLength for different $\gamma$s

#### 6.8.2.2 Mobile Environment

We consider now a network where 20% of the nodes (except the BS) are mobile and moving at a speed of 20 km/h. The SSs are moving in a 10 degrees modulus random directions. For instance one SS can have a direction of 10 degrees from the horizontal axis, while another can have a direction of 20 degrees from the horizontal axis. We investigate the performance of both MaxNetStab and MinSchedLength models for different loads per each SS and for different values of $\gamma$. The schedule length and the network stability (lifetime) are used as metrics for our comparisions. Figure 6.5 shows the obtained schedule length for the two models. First, we observe that the schedule length obtained in MaxNetStab model is larger than that of MinSchedLength for any value of $\gamma$, which is intuitive. However, when looking at MaxNetStab, we notice that higher value of $\gamma$ results in a schedule length that is clearly much higher than for a smaller value of $\gamma$. For example, at a load of 1 Mbps, 2264 slots are needed to satisfy all the demands when $\gamma = 0$ and 2784 slots are required for

$\gamma = 0.5$ (note that this difference is much larger than the difference for MinSchedLength model). This is justified by the fact that in a mobile environment, the topology is first more prone to frequent changes due to failures of existing links and creation of new links; second, when $\gamma$ is higher, the interference range is larger and hence any node mobility would either change the topology or move transmission links from outside the interference range of a certain receiver to inside that range. Consequently, such links cannot be anymore concurrently active and our model (MaxNetStab) would try not to include them in the same transmission configuration. The impact of mobility is also clear when $\gamma = 0$, since the schedule length of MaxNetStab is larger than that of MinSchedLength. Overall, MinSchedLength favors spatial reuse over network lifetime and that is evident from the obtained values for the length of the schedule period.

Figure 6.6 shows the network lifetime obtained in each model; it is clear that MaxNetStab enjoys longer lifetime than MinSchedLength at the expense of lower spatial reuse. Note however that the network lifetime remains the same when varying the load; this is justified by the fact that at these loads the routing tree does not change, which makes the routing to be only affected by the mobility of nodes (recall that the link capacity is 100 Mbps). Similarly, it can be observed that different values of $\gamma$ do not affect the network lifetime as it is only affecting the length of the schedule; and our MaxNetStab model is always searching for those stable paths through which the demands are routed.

### 6.8.3 Varying the Speed and Percentage of MSSs

In this section, we set $\gamma = 0.2$ and we study the performance of the two models (MinSchedLength and MaxNetStab) when varying the speed (20 km/h, 50 km/h) and the percentage of mobile nodes in the network. We fix the load (uplink, downlink) per each SS to 1 Mbps. The metrics of comparison

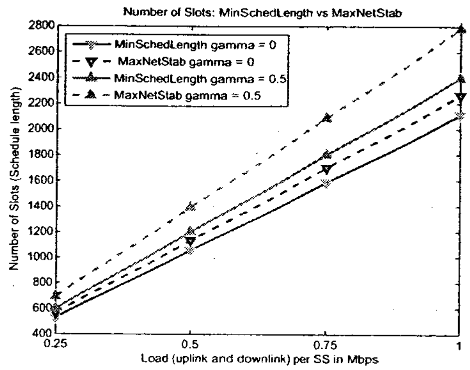


Figure 6.5: Scheduling Length: MinSchedLength Vs MaxNetStab for different $\gamma$s

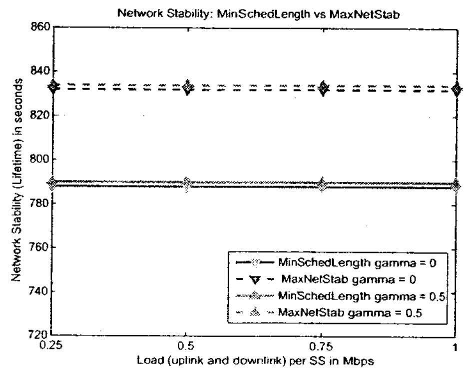


Figure 6.6: Network Stability: MinSchedLength Vs MaxNetStab for different $\gamma$s

are the schedule length and the network lifetime. Tables 6.1 and 6.2 depict the results for 20 km/h speed and for different percentages of mobile nodes (mobile SSs $\equiv$ MSSs). First, we note that the schedule length of MinSchedLength model remains constant regardless of the percentage of mobile nodes and their speed. This is intuitive since this model is oblivious to node's mobility and therefore the route selection and transmission configuration generation remain the same. MaxNetStab model, on the other hand, results in higher schedule length (Table 6.1) than MinSchedLength (for the same reasons as explained before); however, as the percentage of mobile nodes increases, the schedule length increases since the MaxNetStab model attempts to route the demands away from vulnerable links, which indeed affects the spatial reuse through changing both the routing tree construction

| Schedule Length (Number of Slots) | | | | |
|---|---|---|---|---|
| Scheme | Percentage of MSSs | | | |
| | 20 % | 30 % | 40 % | 50 % |
| MinSchedLength | 2304 | 2304 | 2304 | 2304 |
| MaxNetStab | 2402 | 2422 | 2448 | 2502 |

Table 6.1: Schedule Length : MinSchedLength vs MaxNetStab; 20 Km/h MSSs speed

| Network Stability (lifetime) in seconds | | | | |
|---|---|---|---|---|
| Scheme | Percentage of MSSs | | | |
| | 20 % | 30 % | 40 % | 50 % |
| MinSchedLength | 788 | 435 | 372 | 305 |
| MaxNetStab | 832 | 789 | 737 | 636 |

Table 6.2: Network Stability : MinSchedLength vs MaxNetStab; 20 Km/h MSSs speed

as well as the generation of transmission configurations. The same observation is made for higher speed as shown in Table 6.3. Alternatively, as discussed earlier, the MaxNetStab always results in longer network lifetime than MinSchedLength model; in addition, it is interesting to observe that as the percentage of mobile nodes increases, the network stability (lifetime) of MinSchedLength is drastically affected (for example more than 50% reduction in lifetime can be observed when the percentage of mobile nodes increases from 20% to 50% as shown in Tables 6.2 and 6.4). MaxNetStab enjoys extended network lifetime and is not as much affected when the percentage of mobile nodes increases in the network.

Finally, we note that the CPU time required to solve the objective till optimality is reached (in both models) varies between 7 and 9 seconds. This shows that our column generation approach

| Schedule Length (Number of Slots) | | | | |
|---|---|---|---|---|
| Scheme | Percentage of MSSs | | | |
| | 20 % | 30 % | 40 % | 50 % |
| MinSchedLength | 2304 | 2304 | 2304 | 2304 |
| MaxNetStab | 2354 | 2426 | 2532 | 2604 |

Table 6.3: Schedule Length: MinSchedLength vs MaxNetStab; 50 Km/h MSSs

| Network Stability (lifetime) in seconds | | | | |
|---|---|---|---|---|
| Scheme | Percentage of MSSs | | | |
| | 20 % | 30 % | 40 % | 50 % |
| MinSchedLength | 374 | 282 | 213 | 177 |
| MaxNetStab | 553 | 496 | 467 | 445 |

Table 6.4: Network Stability: MinSchedLength vs MaxNetStab; 50 Km/h MSSs

| Schedule Length (Number of Slots) | | | |
|---|---|---|---|
| Scheme | Percentage of MSSs | | |
| | 20 % | 30 % | 50 % |
| MinSchedLength | 2832 | 2832 | 2832 |
| MaxNetStab | 2894 | 2916 | 3062 |

Table 6.5: 56 Nodes: Schedule Length: MinSchedLength vs MaxNetStab; 50 Km/h MSSs

is efficient in terms of being able to reconfigure quickly (reschedule and reroute the demands) the network as soon as any RF-link failure happens.

#### 6.8.3.1 56-Nodes Network

In this section, we extend our experiments to a 56-node network (540 RF-links) to show the scalability of our models (MinSchedLength and MaxNetStab). We consider the same BS characteristics described at the beginning of Section 6.8, and set the demand (uplink and downlink) to satisfy per each SS (MSS) to : $R_{\text{SS}}^{\text{DL}} = R_{\text{SS}}^{\text{UL}} = 0.5$ Mbps. We use different percentages (20 %, 30%, and 50 %) of mobile nodes (MSSs) of the overall set of nodes except the BS.

Tables 6.5 and 6.6 depict respectively the schedule length (number of time slots required to satisfy the network demand) and the network stability associated with MSSs at 50 km/h velocity. Similar conclusions are observed as before; MaxNetStab achieves higher network lifetime when compared with MinSchedLength (Table 6.6), whereas MinSchedLength provides a smaller scheduling length as shown Table 6.5. Note however that in this large network, the CPU time to obtain the optimal solution is much longer (varies between 1072 and 7709 seconds).

| Network Stability (lifetime) in seconds | | | |
|---|---|---|---|
| Scheme | Percentage of MSSs | | |
| | 20 % | 30 % | 50 % |
| MinSchedLength | 187 | 146 | 91 |
| MaxNetStab | 308 | 223 | 169 |

Table 6.6: 56-Nodes: Network Stability: MinSchedLength vs MaxNetStab; 50 Km/h MSSs

## 6.9 Conclusion

The uprising of Mobile WiMAX (802.16e) has introduced more unprecedent difficulties and challenges for the joint routing and scheduling problem due to the frequent changes in the network topology caused by transmission link failures resulting from node mobility. In this chapter, we investigated this problem and we proposed a column generation method for joint routing and scheduling in Mobile WiMAX-based mesh network. Two objectives have been defined for our model; namely, maximum network stability (MaxNetStab) and minimum scheduling length (MinSchedLength). We studied the tradeoffs between the two objectives. We showed that minimizing the schedule length forced the joint routing and scheduling problem to generate a routing tree and feasible transmission configurations which favored higher spectrum spatial reuse (and hence higher system throughput), irrespective of the robustness of the transmission links selected. On the other hand, we showed that maximizing the network stability or lifetime (time until the first link fails) yielded to the selection of different routing tree and slot assignment which did not necessarily resulted in shorter schedule length.

# Chapter 7

# Conclusions and Future Work

In this chapter, we summarize our PhD thesis work by reviewing our major contributions and we provide some insights for future work and directions that we will eventually follow.

## 7.1 Conclusions

Multi-hop "mesh" wireless backhaul networks have emerged as a cost-effective and rapid deployment solution to enable ubiquitous and broadband multimedia applications while supporting Quality of Service. One popular technology that is being considered for multi-hop broadband wireless networks (wireless metropolitan area networks) is the IEEE 802.16 WiMAX, given its high speed Internet capacity and its high coverage range. However, as mentioned earlier, achieving good multi-hop throughput is challenging due to several factors, such as lossy wireless links caused by interference from concurrent transmissions, and intra-path interference caused by transmissions on successive hops along a single path. Thus, demand routing and link scheduling problems become tightly coupled and therefore, joint cross layer design emerged as a problem of extreme importance, in a multi-hop wireless mesh.

In Chapter 4, we presented a joint routing and scheduling for WiMAX-based wireless "mesh" multi-hop network. We assumed centralized scheduling at the base station (BS) and attempt to maximize the system throughput through appropriate routing tree selection and achieving efficient spectrum reuse through opportunistic link scheduling. We presented an integer linear programming ILP optimization model for the joint problem, which relies on the enumeration of all possible link schedules (transmission configurations). Given its complexity, we decomposed the problem using a column generation (CG) approach which iteratively finds a subset of the transmission configurations for MAC scheduling through exploring implicitly all possible feasible link schedules. We presented two formulations for modeling our joint problem, namely the link-based and the path-based formulation. These two formulations differed mainly in the number of routing decision variables. Our numerical results indicated that the path-based formulation needed much less computational (CPU) time than the link-based formulation in order to determine the (same) optimal or near optimal solution with the same spatial reuse gain.

Instead of using simple forwarding, a technique known as network coding, has shown to substantially improve the network performance. This technique exploits the broadcast nature of the wireless medium where intermediate nodes may perform opportunistic coding to better utilize the wireless spectrum. Opportunistic coding refers to the situation where two connections are transiting through an intermediate node but in opposite directions, and instead of using simple forwarding at different point of times to transit the data packets of the two different connections, the intermediate node can code the packets of the two connections into one packet, and broadcast it to the intended receivers (which can decode the code packet once received) at the same time. From its definition, enabling network coding (identifying those routing structures where opportunistic coding is possible, coding the data packets and broadcasting them to the intended receivers) requires a tight coupling between the MAC layer (where the coded transmissions are being scheduled) and the network layer where the connections routing algorithm is taking place.

In Chapter 5, we proposed a cross-layer design framework for the joint problem of coding-aware routing and scheduling in WiMAX-based mesh networks with unicast sessions. Our coding-aware model attempts to maximize the system throughput by exploiting opportunistic coding opportunities through appropriate routing and achieving efficient spectrum reuse through appropriate link scheduling. We again assumed centralized scheduling at the base station (BS), and focused on minimizing the total schedule length to satisfy a certain traffic demand. We presented a column generation optimization model for the joint problem, which relies on the implicit enumeration of all possible schedules. Our numerical results showed that significant gains may be achieved when network coding is incorporated into the design. We compared the performance to that of a joint coding-oblivious model with and without power control.

Finally, we consider the case where SS stations are no longer stationary, with some of them subject to mobility (up to a vehicular speed), referred to as mobile subscriber stations MSSs. Hence new challenges must be addressed in the design of wireless mesh networks, otherwise the network operation would become erroneous. Indeed, the first problem that faces a mobile WiMAX mesh network is its frequent RF-link breaks that makes some of its routing paths no longer available (rerouting becomes inevitable). Another issue that faces mobile WiMAX is that some mobile nodes that were transmitting concurrently in a time slot (given that they were outside the interference range of each other), could move towards each other and start interfering on one another when transmitting simultaneously. In such a case the schedule is no longer valid and re-computation is required. Given the frequent RF-link failures (leading to routing path brakes) along with the topology changes where new links are created and some transmitting nodes become close enough to interfere on each other's transmissions, the MAC layer scheduling and the network layer routing must be interconnected and designed jointly for a correct network operation.

Chapter 6 discussed the design of a joint routing and scheduling in a WiMAX-based mobile multi-hop network (based on a column generation approach) whose objective is either to determine a minimum length schedule by maximizing spectrum spatial reuse or maximizing the network lifetime by routing around the less stable RF-links, while satisfying a set of (uplink/downlink) end-to-end demands. We studied the trade-offs between these two objectives and showed that minimizing the schedule length forces the joint routing and scheduling problem to generate a routing tree and feasible transmission configurations which favor higher spectrum spatial reuse (and hence higher system throughput), irrespective of the robustness of the selected transmission links. In addition, we showed that maximizing the network stability or lifetime yields the selection of different routing trees and slot assignments which do not necessarily resulted in shorter schedule length. We performed numerical experiments where we compared the performances of our proposed models with respect to the network stability and resource spatial reuse.

## 7.2 Future Work

In this thesis, we assumed the IEEE 802.16 (2004) WiMAX [3] [4] mesh with centralized scheduling where the BS is the only node responsible for allocating the network resources. As mentioned earlier, our models are however still readily applicable with the IEEE 802.16 2009 standard [12] with some minor changes. A first extension of our work would be then to consider distributed scheduling in a WiMAX multi-hop network, with cooperative relay stations, where each node part of the network, decides when to transmit (receive) data to (from) its neighboring nodes, in collaboration with its neighboring nodes, so to achieve a common objective. For that matter, each node's decision must be based on its neighboring (e.g., 1-hops) nodes status information (whether these nodes are idle or active) so that the performance (e.g., throughput) of the network is optimized and no erroneous transmissions occur due to interference.

Another direction for our future work would be to extend our model to try to minimize the end-to-end connection's delay and the buffer size at each relay node. For that matter, our joint routing-scheduling design must possibly give priorities to nodes to transmit before others. This is possible with additional constraints deciding on the time slot allocation order. It should be done with the preoccupation of identifying which user's resources are more/less stringent to time and need to be delivered faster to guarantee delay and QoS requirements.

Note that, throughout our PhD thesis, we limited our studies to the IEEE 802.16 WIMAX broadband multi-hop "mesh" last mile Internet access networks. Given the existence of several technologies such as optical and cable technologies for last mile Internet access, one possible future direction is to consider a hybrid wireless-optical access network through incorporating wireless and optical constraints in a same model. Such study favors the interaction and the coexistence of these technologies in a same metropolitan area.

Finally, given the fact that WiMAX SS nodes can serve as Internet access points for WiFi local area users, another possible future work, is to have a global modeling which considers both WiMAX and WiFi constraints and incorporate for instance Quality of Service where our objective is to serve

WiFi users with higher priorities so that to reduce their end-to-end delay.

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