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Channel Assignment, Routing and Cross Layer issues for Multi-radio Multi-channel Wireless Mesh Networks

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To my parents who have always supported me

To my two brothers

To my friends

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Publications

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Abstract

Next generation wireless mobile communications will be driven by *converged networks* that integrate disparate technologies and services. The Wireless Mesh Network (WMN) is envisaged to be one of the key components in the converged networks of the future, providing flexible, high-bandwidth wireless backhaul over large geographical areas. While single radio mesh nodes, operating on a single channel suffer from capacity constraints, equipping mesh routers with multiple radios using multiple non-overlapping channels can significantly alleviate the capacity problem and increase the aggregate bandwidth available to the network. However, the assignment of channels to the radio interfaces poses significant challenges. The goal of channel assignment algorithms in multi-radio mesh networks is to minimize interference while improving the aggregate network capacity and maintaining the connectivity of the network. In this thesis, we examine the unique constraints of channel assignment in wireless mesh networks and identify the key factors governing assignment schemes, with particular reference to interference, traffic patterns, and multi-path connectivity. After presenting a taxonomy of existing channel assignment algorithms for WMNs, we describe a new channel assignment scheme, called *MesTiC,* which incorporates the mesh traffic pattern together with connectivity issues in order to minimize interference in multi-radio mesh networks.

In a second part of this thesis, we consider that a paradigm shift from the classic routing schemes is needed. Usual approaches are not always satisfactory since they often use shortest-path heuristic and tend to concentrate transmissions to certain nodes. To efficiently exploit the presence of multiple channels instead, a proper routing algorithm should avoid congested links and possibly make use of an estimation of the actual network traffic. Therefore, cross-layer information exchange can be useful for an efficient functioning of the routing protocols. We analyze all these issues and propose and identify possible solutions.

Chapter 1
Introduction

1.1 Motivation

A major goal toward the 4G Wireless evolution is to provide pervasive computing environments that can ubiquitously and seamlessly support users in accessing information, accomplishing their tasks, or communicating with each other anytime, anywhere. Mobile ad hoc networks (MANET) are expected to become an important part of the 4G architecture.
MANETs are complex distributed systems that consist of wireless mobile nodes that can dynamically and freely self-organize into temporary and arbitrary ad hoc network topologies. This allows people and devices to seamlessly interact via wireless links in areas with no pre-existing communication infrastructure or centralized administration (e.g., disaster recovery environments). The introduction of low cost wireless technologies like the IEEE 802.11, HyperLAN, and Bluetooth are helping enable eventual commercial MANET deployments outside the military field **[1]**.

But despite important efforts in researching and developing MANETs in the last decade, this type of network has not yet achieved mass commercial deployment. This low market penetration of products based on ad hoc networking technology can only be justified by the fact that the ongoing research is mainly focused on implementing military or specialized civilian applications. Whereas, users are mostly interested in general-purpose applications where high bandwidth and open access to the Internet are effective and cheap commodities.

To turn mobile ad hoc networks into a commodity, we should adopt a more practical concept of ad hoc networking in which multi-hop ad hoc nodes are not self-configured and isolated, but rather emerge as a flexible and low-cost extension of wired infrastructure

networks and coexisting with them. In fact, a new class of networks emerging from this view is wireless mesh networks (WMNs) **[3]**.
The goal of this thesis is to contribute to the research for the development and the commercialization of wireless mesh networks. In spite of recent advances in wireless mesh networking, many research challenges remain in all protocol layers. In order to increase the capacity, improve the quality of service, reliability and robustness in these networks, research in the network layer is very important and active. We would like to focus on the design and performance analysis of the main research ideas of channel assignment algorithms, routing protocols, and their cross layer interaction.

1.2 Content of the thesis

The thesis is organized as follows, chapter 2 gives an overview of the Wireless Mesh Network technology, the architecture, benefits and application. Chapter 3 presents in details the channel assignment problems for the multi-radio wireless mesh networks and focuses on their specific constraints and challenges. Chapter 4 basically lists different channel assignment strategies, categorized into fixed, dynamic and hybrid strategies. A comparison of these channel assignment schemes is presented as well. Our novel channel assignment scheme, called MesTiC is presented in Chapter 5 with all its features and properties. Finally in chapter 6 we give conclusions and future work.

Chapter 2

Wireless Mesh Networks: An Overview

2.1 Introduction

WMNs consist of two types of nodes: mesh routers and mesh clients. A wireless mesh router contains additional routing functions to support mesh networking other than the conventional routing capability for gateway/repeater functions as in conventional wireless routers. For further improvement of the flexibility of mesh networking, mesh routers can be equipped with multiple wireless interfaces (NIC cards) built on either the same or different wireless access technologies. If we compare a conventional wireless router, a wireless mesh router can achieve the same coverage with much lower transmission power through multi-hop transmissions. As opposed to mesh routers, mesh clients usually have only one wireless interface and so the hardware platform and the software for mesh clients can be much simpler **[3]**.
Wireless routers communicate among each other in order to provide wireless transport services to data traveling from users to either other users or to the wired Internet backbone through access points. The network of wireless routers forms a wireless backbone which provides multi-hop connectivity between mesh users and wired gateways. The meshing among wireless routers and access points creates a *wireless backhaul* communication system, which provides each mobile user with a high-bandwidth, low-cost, and seamless multi-hop interconnection with the wired backbone and with other mobile users. The *backhaul* concept is used to indicate the service of forwarding traffic from the originator node to an access point through which it is distributed over the Internet **[2]**.

2.2 WMN Architecture

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

2.2.1 Infrastructure/Backbone WMNs

Infrastructure/Backbone (**Figure 1**) includes mesh routers forming an infrastructure for clients connecting to them. This type of WMNs can be built using various types of radio technologies, the most common are IEEE 802.11 technologies. The mesh routers form a mesh of self-healing, self-configuring links among themselves. With gateway functionality, mesh routers can be connected to the Internet. Infrastructure/Backbone WMNs are the most commonly used type.

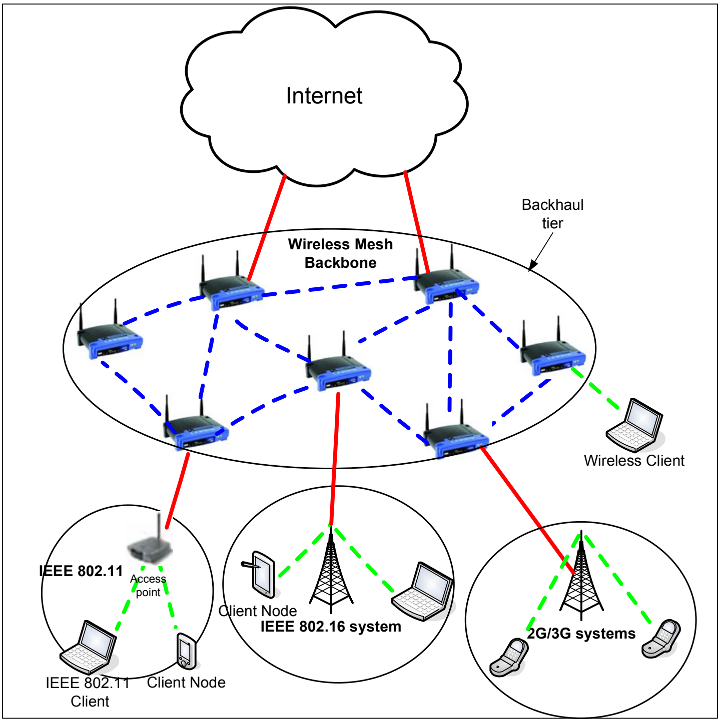

Figure 1 - Infrastructure/backbone WMNs

2.2.2 Client WMNs

Client meshing (**Figure 2**) provides peer-to-peer networks among client devices. In this type of WMN, client nodes form the actual network to perform routing and configuration functionalities as well as providing end-user applications to customers. Therefore, a mesh router is not needed for this type of networks.

In Client WMNs, a packet intended to a node hops through multiple nodes to reach the destination. Client WMNs usually use one type of radios on all devices. Also, the requirements on end-user devices is increased when compared to infrastructure meshing, since, Client WMNs end-users must perform additional functions such as routing and self-configuration.

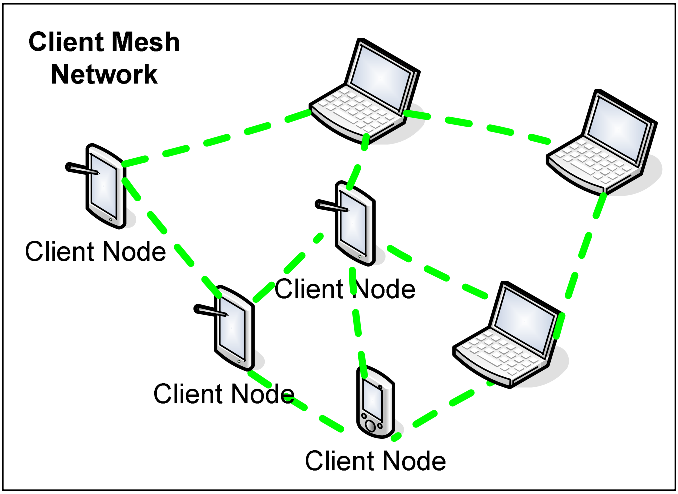

Figure 2 - Client WMNs

2.2.3 Hybrid WMNs

Hybrid WMNs (**Figure 3**) represent the combination of infrastructure and client meshing. Mesh clients can access the network through mesh routers as well as directly through other mesh clients. While the infrastructure provides connectivity to other networks such as the Internet, Wi-Fi, WiMAX, cellular, and sensor networks. The routing capabilities of clients add improved connectivity and coverage inside the WMN **[3]**.

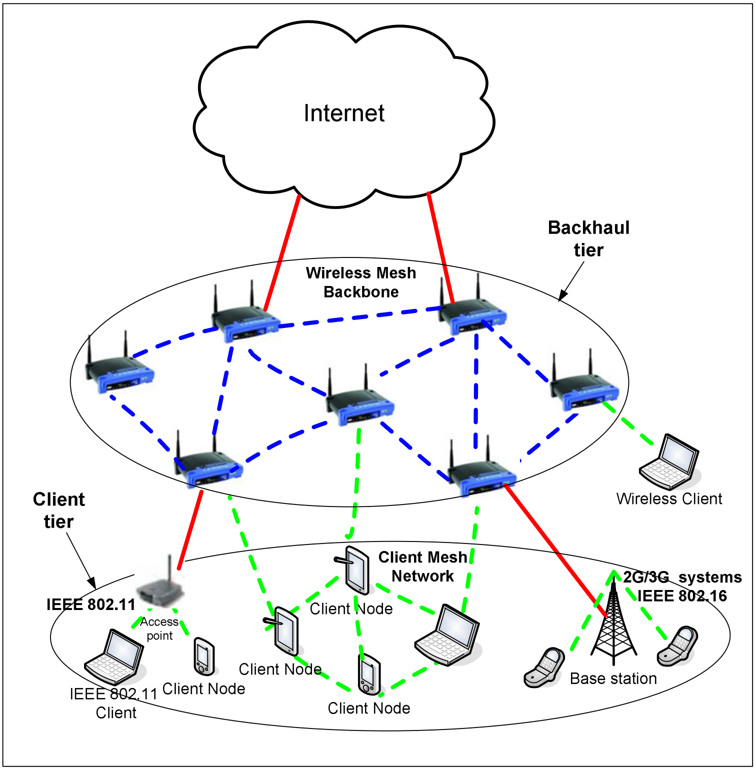

Figure 3 - Hybrid WMNs

2.3 Characteristics and benefits of WMNs

The mesh network architecture addresses a number of market requirements for building wireless networks highly scalable and cost effective, offering an appropriate solution for the easy deployment of high-speed wireless Internet **[2]**. The characteristics of WMNs are explained in the following:

2.3.1 Multi-hop wireless network

One of the objectives to develop WMNs is to provide non-line-of-sight (NLOS) connectivity among the users without any direct line-of-sight (LOS) links. Another objective is to extend the coverage range of wireless networks without sacrificing the channel capacity. In order to meet these requirements, there is a need for multi-hop communication along with the mesh connectivity. This achieves more efficient frequency re-use, less interference between the nodes, and higher throughput without sacrificing effective radio range via shorter link distances.

2.3.2 Capability of self-forming, self-healing, self-organization and support for ad hoc networking

Advantages of mesh connectivity are flexible network architecture, easy configuration and deployment, fault tolerance, and enhanced network performance. When adding new nodes to the mesh network, these nodes use their meshing functionalities to automatically discover all possible wireless routers and determine the optimal paths to the wired network. Moreover, the existing wireless routers reorganize, taking into account the new available routes. Therefore, the network can grow gradually as needed.

2.3.3 Multiple types of network access

In WMNs, both peer-to-peer (P2P) communications and backhaul access to the Internet are supported. In addition to this, the integration of WMNs with other wireless networks allows to provide services to end-users of these networks.

2.3.4 Compatibility and interoperability with existing wireless networks

As an example, WMNs built based on IEEE 802.11 technologies must be compatible with IEEE 802.11 standards in the sense of supporting both conventional Wi-Fi and mesh capable clients. These WMNs also need to be inter-operable with other wireless networks such as WiMAX, Zig-Bee and cellular networks **[3]**.

Based on their characteristics, WMNs are generally considered as a type of ad hoc networks due to the lack of wired infrastructure. WMNs provide the following benefits:

2.3.4.1 Reduction of installation costs

Nowadays, one of the most emerging technologies for providing wireless Internet beyond the boundaries of indoor WLANs is the Wi-Fi hot spot technology. Basically, a hot spot is an area in which an access point provides wireless broadband Internet access services to wireless mobile clients through an 802.11-based access technology. In order to ensure ubiquitous coverage in a metropolitan area, it is necessary to install a large number of access points because only a limited distance can be covered by the 802.11 signal. The drawback of this solution is an unacceptable increase in the infrastructure costs due to the fact that a cabled connection to the wired backbone is needed for every access point. Installing a cabling infrastructure does not only slow down hot spot implementation, but also significantly increases the installation costs. As a consequence, the hot spot architecture is non scalable, costly, and slow to deploy. Building a wireless mesh backbone enormously reduces the costs associated with building infrastructure since the mesh network needs only a few points of access to the wired backbone.

2.3.4.2 Large-scale deployment

With recent WLAN technologies, such as IEEE 802.11a and 802.11g, increased data rates have been achieved by using more spectrally efficient modulation schemes. But, for a specific transmit power, using more efficient modulation techniques reduces coverage (i.e., the data rate available is lower farer from the access point). Moreover, for a fixed total coverage area, more access points should be installed to cover small size cells.

On the other hand, multi-hop communications offer long distance communications via multi-hopping through intermediate nodes. Since there are multiple intermediate links, these links can be short and transmissions can be at high data rates, resulting in increased throughput compared to direct communications. Moreover, the wireless backbone can take advantage of fixed powered wireless routers to implement more sophisticated transmission techniques than those implemented in client devices. Consequently, the wireless backbone can realize a high degree of spatial reuse and wireless links covering longer distance at higher speed than conventional WLAN technologies.

2.3.4.3 Reliability

The wireless backbone provides redundant paths between pairs of endpoints which significantly increases communication reliability, eliminates single points of failure and potential bottleneck links within the mesh. Network resilience and robustness against potential problems (e.g., node failures) are also ensured by the existence of multiple possible destinations (i.e., anyone of the gateway nodes toward the wired Internet) and alternative routes to these destinations **[3]**.

2.4 Applications of WMNs

Research and development of WMNs is motivated by several emerging and commercially interesting applications which demonstrate a very promising market, at the same time these applications cannot be supported directly by other conventional wireless networks such as ad hoc networks, cellular networks, wireless sensor networks, or standard IEEE 802.11.

2.4.1 Broadband home networking

Currently broadband home networking is based on the IEEE 802.11 WLAN technology. An obvious problem is the location of the access points. Solutions based on site survey are expensive and not practical for home networking, while installation of multiple access points is expensive and not convenient because of wiring from access points to the backhaul network. Moreover, communications between end nodes under two different access points have to go all the way back to the access hub. Mesh networking can resolve all these issues in home networking by replacing the access points by wireless mesh routers with mesh connectivity established among them.

2.4.2 Community and neighborhood networking

The common architecture for network access in a community is based on DSL or cable connected to the Internet, then the last-hop is wireless by connecting a wireless router to a cable or DSL modem. This type of network access has several drawbacks: first, even though the information need to be shared within a community or neighborhood, all traffic must flow through Internet, which significantly reduces the network performance. Second, only a single path may be available for one home to access the Internet or communicate with neighbors. Third, an expensive but high bandwidth gateway between multiple homes or neighborhoods may not be shared and so wireless services must be set up individually. And this can increase the service costs.

The WMN technology's goal is to mitigate the above disadvantages with its flexible mesh connectivity.

2.4.3 Enterprise networking

This type can be a small network in one single office or a medium-size network for all offices in an entire building, or alternatively a large scale network for offices in multiple buildings. Currently, standard IEEE 802.11 wireless networks are widely used in offices. However, communications among these wireless networks have to be achieved through wired Ethernet connections, that is the reason for the high cost of enterprise wireless networks. If the access points are replaced by mesh routers, Ethernet wires can be eliminated. Multiple backhaul access modems can be shared by all nodes in the entire network, and therefore improve the resource utilization and robustness.
WMNs for enterprise networking are much more complicated than home networking because of complicated network topologies and higher number of nodes.

2.4.4 Metropolitan area networks

WMNs in metropolitan area have several advantages. The physical layer transmission rate of a node in WMNs is much higher than that of any cellular network. For example, an IEEE 802.11g node can transmit at a rate of 54 Mbps. In addition, the communication between nodes in WMNs does not rely on a wired backbone as in wired networks. A Wireless mesh MAN is an economic alternative to broadband networking because it can cover a potentially large area. Thus, the requirement on the network scalability by a wireless mesh MAN is much higher than that required by other applications.

2.4.5 Transportation systems

Instead of limiting IEEE 802.11 or 802.16 access to stations and stops, mesh networking technology can extend access into buses and trains. This can provide convenient passenger information services, remote monitoring of in-vehicle security video, and driver communications. To enable such mesh networking for a transportation system, two key techniques are needed: the high-speed mobile backhaul from a vehicle (car, bus, or train) to the Internet and mobile mesh networks within the vehicle as shown in **Figure 4 [3]**.

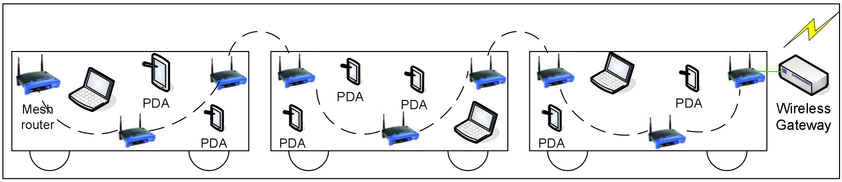

Figure 4 - WMNs for transportation systems

An example of this application scenario is the Portsmouth Real-Time Travel Information System (PORTAL), a system that aims at providing real-time travel information to passengers. This system is realized by equipping more than 300 buses with mesh technology provided by MeshNetworks Inc. The wireless mesh network allows anybody to display, at more than 40 locations throughout the city, real-time information on transportation services. The same system is also expected to be used to address and alleviate transportation congestion problems, control pollution, and improve transportation safety and security **[2]**.

2.4.6 Security surveillance systems

As security is turning out to be a very high concern, security surveillance systems become a necessity for shopping malls, enterprise buildings, etc. In order to deploy such systems at locations as needed, WMNs are a much more viable solution than wired networks to connect all devices. Since still images and videos are the major traffic flowing in the network, this application demands much higher network capacity than other applications **[3]**.

For example, the San Matteo Police Department in the San Francisco Bay Area has equipped all its patrol cars with laptops, and motorcycle and bicycle patrols with PDAs, using standard 802.11b/g wireless cards for communications. The outdoor wireless network is built using mesh networking technology provided by Tropos Networks **[2]**.

2.4.7 Testbeds and implementations

Numerous testbeds have been established to carry out research and development for WMNs. In the following we briefly mention some of the most important among them.

2.4.7.1 Academic research testbeds

One of the earliest mesh network testbeds was implemented at Carnegie-Mellon University. This mobile ad hoc network testbed **[19]** consists of seven nodes: two stationary nodes, five car mounted nodes that drive around the testbed site, and one car mounted roving node that enters and leaves the site. Packets are routed between the nodes using Dynamic Source Routing (DSR) which also integrates the ad hoc network into the Internet via a gateway.

MIT's Roofnet is an experimental multi-hop 802.11b mesh network **[13]**. It consists of about 50 wireless nodes to interconnect the Ethernet networks with Internet gateways in apartments in Cambridge, MA. A primary feature of Roofnet is that it requires no configuration or planning.

The Broadband and Wireless Network (BWN) Lab at Georgia Institute of Technology has recently built a testbed of WMNs, called BWN-Mesh, consists of 15 IEEE 802.11b/g based mesh routers. Currently, the research is focused on adaptive protocols for transport layer, routing and MAC layers and their cross-layer design.

2.4.7.2 Industrial practice

Microsoft Research Lab implements ad hoc routing and link quality measurement in a software module called the mesh connectivity layer (MCL) **[20]**. Architecturally, MCL is a loadable Windows driver. It implements a virtual network adapter, so that the ad hoc network appears as an additional (virtual) network link to the rest of the system. MCL routes by using a modified version of DSR called Link Quality Source Routing) LQSR. Later in this report, we will describe the Microsoft testbed at Redmond, WA, on which they conducted very important research that we will describe in details in **Error! Reference source not found.**.
A variety of research and development at Intel are geared toward understanding and addressing the technical challenges of multi-hop mesh networks. Nortel's commercial roll out of the WMN products **[21]** includes wireless access point (WAP) which is a dual radio system supporting a 2.4 GHz access link and a 5 GHz transit link, equipped with smart antennas. Many other companies are commercializing the WMN solution, among them are: MeshNetworks **[22]**, Tropos Networks **[23]**, PacketHop **[24]**, and Kiyon **[25]**.

2.4.7.3 Open standard activities

Open standard radio technologies are very important for industry because they enable economies of scale, which decreases the cost of equipments and ensures interoperability. For this, several IEEE standard groups are actively working to define specifications for wireless mesh networking techniques. In particular, special task groups have been established to define the requirements for mesh networking in wireless personal area networks (WPANs), WLANs, and WMANs. Although at different degrees of evolution, the following emerging standards may be identified: IEEE 802.11s, IEEE 802.15.5, IEEE 802.16a **[2]**.

IEEE 802.11s

Currently, IEEE 802.11 wireless networks can achieve a peak rate of 11 Mbps (802.11b) and 54 Mbps (802.11a/g). Also under development is a high-bandwidth extension to the current Wi-Fi standard. Researchers expect 802.11n to increase the speed of Wi-Fi connections by 10–20 times.

A working group within IEEE 802.11, called 802.11s, has been formed recently to standardize the Extended Service Set (ESS). 802.11s aims to define PHY and MAC layers for mesh networks that extend coverage with no single point of failure. More specifically, the goal is to create a distribution system that supports both broadcast/multicast and unicast delivery at the MAC layer using radio-aware metrics over self-configuring multi-hop topologies **[2][3][4]**.

IEEE 802.16a

While IEEE 802.11 networks fulfill the need for data services in a local area, IEEE 802.16 aims at serving the broadband wireless access in metropolitan area networks, supporting point-to-multipoint connection oriented QoS communications. The original 802.16 standard operates in the 10–66 GHz frequency band and requires line-of-sight (LOS) transmission. The 802.16a extension, ratified in January 2003, uses a lower frequency of 2–11 GHz, enabling non-line-of-sight (NLOS) connections. With 802.16a, carriers will be able to connect more customers to a single tower and substantially reduce service costs.

The 802.16 mesh in the current standard has several limitations, the most important of them is that the 802.16 mesh has limited scalability. The mesh can only support around 100 subscribers due to centralized scheduling message structures. A group within 802.16, the Mesh Ad Hoc committee, is investigating ways to improve the performance of mesh networking **[3][5]**.

IEEE 802.15.5

IEEE 802.15.3a standard is based on Multi-Band OFDM Alliance (MBOA)'s physical layer that uses ultra wide band (UWB) to reach up to 480 Mbps. A competing proposal of a Direct Sequence-UWB (DS-UWB) claims support for up to 1.3 Gbps. It is intended for high throughput personal area networking (PAN) that has communication distances of up to 10 meters. UWB networks have many advantages such as low power, cost requirement, and extra high bandwidth. However, the communication range is rather short. Mesh networks have been predicted to be the killer application for UWB radio systems. Recently a new working group IEEE 802.15.5, is established to determine the necessary mechanisms in the physical and MAC layers to enable mesh networking in wireless PANs **[3][6]**.

2.5 Open research issues

The mesh network architecture, as conceived earlier, is an economically viable solution for the wide deployment of high-speed, scalable, and ubiquitous wireless Internet services. However, the major technical challenges of building a large-scale high-performance multi-hop wireless backhaul system are not solved yet. One of the major problems to address while building a multi-hop wireless backhaul network is the *scalability* of both the network architecture and protocols. In the following we discuss the most relevant and promising research activities, focusing on the design and development of a scalable and high-performance wireless backbone for WMNs **[2]**. More specifically, many research challenges remain in all protocol layers, in the following the focus will be more on the first three layers: physical, MAC and network layers because they are more related to the proposed work.

2.5.1 Physical layer

Physical layer techniques advance fast as circuit design and RF for wireless communications evolve. Most of the existing wireless radios are able to support multiple transmission rates by a combination of different modulation and coding rates. In order to increase the capacity of wireless networks, various high-speed physical techniques have been invented. For example, Orthogonal Frequency multiple access (OFDM) has significantly increased the speed of IEEE 802.11 from 11 Mbps to 54 Mbps. In order to further increase capacity and mitigate the impairments such as fading, delay-spread, and co-channel interference, multiple-antenna systems have been used for wireless communication. When strong interference is present, diversity processing alone is not sufficient to receive signals with high quality. To resolve this issue, directional antennas are used to shape the antenna beamform so as to enhance the desired signals while nullifying the interfering signals. Antenna diversity and smart antenna techniques are applicable to WMNs. However, MIMO systems are extremely complex and directional antennas bring many challenges to the MAC protocol design. In addition to the previously mentioned techniques, the system capacity of a WMN can also be improved by using multiple radios or multi-channel radios.

2.5.2 MAC layer

The scalability of WMNs can be addressed by the MAC layer in two ways. The first way is to enhance existing MAC protocols or propose new MAC protocols to increase end-to-end throughput when only a single channel is available in a network node. The second way is to allow transmission on multiple channels in each network node.

2.5.2.1 Single channel MAC

The first technique is to improve the existing 802.11 MAC protocols by enhancing the Carrier Sense Multiple Access with Collision Avoidance (CSMA/CA) protocol. It consists of adjusting the parameters of CSMA/CA such as the contention window size and the backoff procedures. However, for a multi-hop situation which is the case of WMNs, these solutions still reach a low end-to-end throughput and a very poor scalability. Therefore, the second technique is to design an innovative MAC protocol based on CDMA or TDMA. However the cost and the complexity of this option has to be taken into account. The third idea is cross layer design with advanced physical layer techniques. Two major schemes exist in this category: MAC based on directional antennas and MAC with power control. However we already mentioned that the directional antennas complicate the MAC protocol and increase cost. Power control on the other hand may worsen the hidden node problem because lower transmission power level reduces the possibility of detecting a potential interfering node.

2.5.2.2 *Multi-channel MAC*

Here again, there are three techniques depending on the underlying hardware. The first type is a multi-channel single-transceiver MAC, this option is the most desirable whenever cost and compatibility are a major concern. In order to improve system capacity, different nodes may operate on different channels simultaneously, therefore a new MAC is needed to coordinate communication. The second type is a multi-channel multi-transceiver MAC for radios that include multiple parallel RF front-end chips and baseband processing modules to support several simultaneous channels. So the MAC protocol has to coordinate the functions of these multiple channels. Finally, the third type is a multi-radio MAC in which case a network node has multiple radios each with its own MAC and physical layers. Communications in these radios are totally independent. Thus, a virtual MAC protocol is required on top of the MAC to coordinate communications of all channels.

2.5.3 Network layer

WMNs will be tightly integrated with the Internet, and IP has been accepted as a network layer protocol for many wireless networks including WMNs. However, routing protocols for WMNs are very different from those in wired and cellular networks.

Since WMNs share common features with ad hoc networks, the routing protocols developed for ad hoc networks can be applied to WMNs. As a matter of fact, Microsoft WMNs are built based on Dynamic Source Routing (DSR), a protocol designed for ad hoc networks [see Appendix A]. But despite the availability of several routing protocols for ad hoc networks, research in routing protocols for WMNs is very active for many reasons: First of all, new performance metrics need to be discovered and utilized to improve the performance of routing protocols. Moreover, existing routing protocols still have limited scalability. In addition, the existing routing protocols treat the underlying MAC protocol as a transparent layer. However, the cross-layer interaction must be considered to improve the performance of the routing protocols in WMNs. Finally and more importantly, the requirements on power efficiency and mobility are much different between WMNs and ad hoc networks. In a WMN, mesh routers which constitute the backhaul have minimal mobility and no constraint on power consumption, while mesh client nodes usually desire the support of mobility and a power efficient routing protocol.
Based on the performance of the existing routing protocols for ad hoc networks and the specific requirements of WMNs, an optimal routing protocol for WMNs must capture the following features:

2.5.3.1 Performance metrics

The minimum hop count is one of the most common performance metrics used in the existing routing protocols. However, performance evaluation studies for wireless networks **[11]** show that this metric is not a good choice to select a wireless path. Usually Round Trip Time (RTT) is used as an additional performance metric. Good performance can be achieved using multiple performance metrics.

2.5.3.2 Fault tolerance with link failures

One of the objectives to deploy WMNs is to ensure robustness in the case of link failures. If a link breaks, the routing protocol should be able to quickly select another path to avoid service disruption.

2.5.3.3 Scalability

Scalability is a very critical aspect of the routing protocol because setting up a routing path in a very large wireless network may take a long time, and the end-to-end delay can become large.

2.5.3.4 Load balancing

One of the objectives of WMNs is to share the network resources among many users.

2.5.3.5 Adaptive support of both mesh routers and clients

Taking into consideration the minimal mobility and no constraint of power consumption of mesh routers, a much simpler routing protocol than that for ad hoc networks can be developed for mesh routers. However, for mesh clients, the routing protocol must have the full functions of ad hoc routing protocols. Therefore, it is necessary to design an efficient routing protocol for WMNs that can adaptively support both mesh routers and mesh clients.

2.5.4 Transport layer

A large number of reliable transport protocols have been proposed for ad hoc networks. They can be classified into two types: TCP variants and entirely new transport protocols. The performance of classical TCP degrades significantly in ad hoc networks. One of the major reasons of this is that the classical TCP do not differentiate congestion and non-congestion losses. As a result, when non-congestion losses occur, the network throughput quickly drops. Link failure also degrades the TCP performance. In WMNs, link failure is not as critical as in mobile ad hoc networks, but due to wireless channels and mobility in mesh clients, link failure may still happen. How to enhance a TCP so that it is robust to large RTT variations has not been thoroughly studied for both WMNs and mobile ad hoc networks. On the other hand, despite its advantages, an entirely new transport protocol is not favored by WMNs due to the compatibility issue. WMNs will be integrated with the Internet and many other wireless networks and so their transport protocol must be compatible with other TCPs.

2.5.5 Application layer

Numerous applications can be supported by WMNs, for example, Internet access and distributed information storage and sharing within WMNs. It is a key step to find out what existing applications can be supported by WMNs and what new applications need to be developed **[3]**.

2.6 Conclusion

In this chapter, we described how WMNs emerged from MANETs, we presented their architecture, and main features and benefits. Then we listed most of their numerous applications and showed the importance of mesh networking within the open standard activities. Finally we provided a thorough discussion on the main open research issues in WMNs in all the protocol layers. Our aim is to show the growing importance of the newly emerging WMNs from the technological, economical and research point of view. Research is ongoing in this field and many challenges are still to be solved to make this type of networks robust and practical.

Chapter 3
Channel Assignment Problem in Multi-radio Wireless Mesh Networks

3.1 Introduction

A wireless mesh network (WMN), as illustrated in **Figure 5**, consists of mesh routers and mesh clients, where mesh routers are generally stationary nodes and form a multi-hop wireless backbone (referred to as the *backhaul tier*) between the mesh clients and the Internet gateways (a gateway is the node directly connected to the wired network). Each mesh router operates not only as a host but also as a router, forwarding packets on behalf of other nodes that may not be within direct wireless transmission range of their destinations. On the other hand, mesh clients form the *client tier*; they are either stationary or mobile, and can form a client mesh network among themselves and with mesh routers. The gateway and bridge functionalities in mesh routers enable the integration of WMNs with various existing wireless networks such as wireless sensor, cellular, wireless-fidelity (Wi-Fi), and worldwide inter-operability for microwave access (WiMAX).

Recently, WMNs have emerged as a highly flexible, reliable and cost efficient solution to wirelessly cover large areas and provide low-cost Internet access through multi-hop communications. They are anticipated to resolve the limitations yet significantly improve the performance of wireless ad hoc networks, local area networks (WLANs), personal area networks (WPANs), and metropolitan area networks (WMANs). Several emerging and commercially interesting applications for commodity networks based on the WMN architecture have also been deployed recently, see **[2]**. They include community and neighborhood networks, broadband home networking, enterprise networking, building automation, intelligent transportation systems, public safety networks, and the like. Perhaps among the earliest and the most important of these are community and neighborhood networks. The networking solution based on WMNs mitigates many of the disadvantages of the conventional WLAN architecture based on a digital subscriber line (DSL) and the last hop being wireless. For example, within the WLAN scenario, even if information must be shared within a community or neighborhood, all traffic must flow through the Internet. Moreover, only a single path may be available for one home to access the Internet. Additionally, wireless services must be set up individually at every home. As a result, network service costs may increase **[3]**. Deployment of a WMN is a robust and inexpensive alternative; the wireless backbone has the ability to support both internal (among the mesh routers) and external (to the Internet) traffic. It also guarantees the existence of multiple paths and makes it possible to cover larger areas with lower costs.

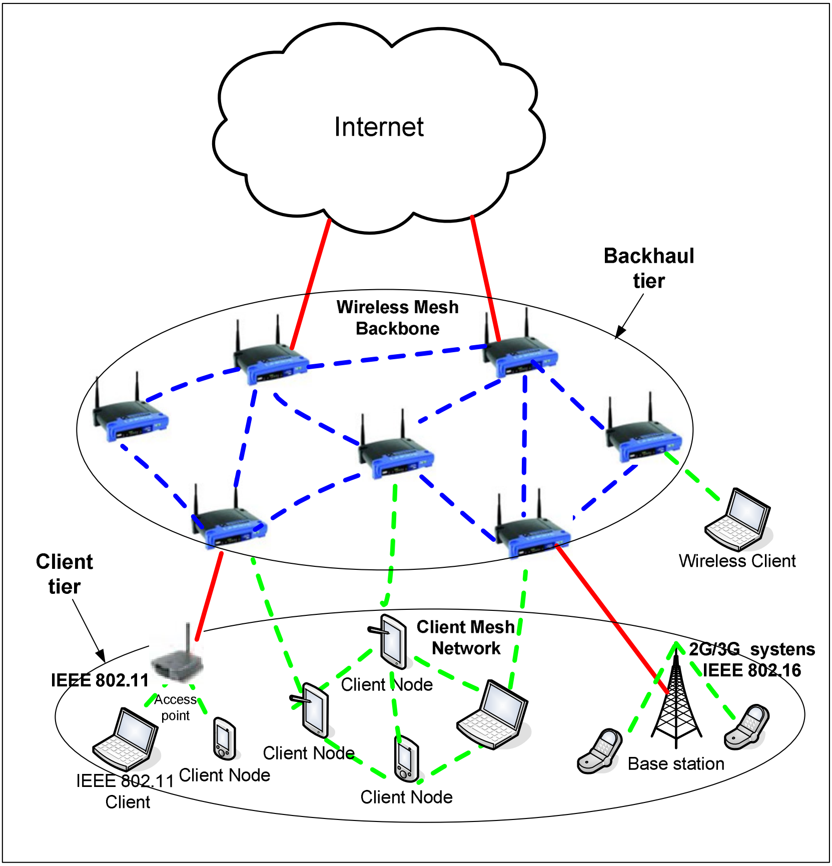

Figure 5 - Wireless Mesh Network architecture

3.2 Technical problems

The major technical challenges (i.e. capacity, scalability) of building a large-scale high-performance multi-hop wireless mesh networks are not solved yet. Wireless mesh networks **[33]**, which use off-the-shelf 802.11 based network cards[1], are typically configured to operate on a single channel (a part of the frequency spectrum with a specified

[1]Throughout this chapter, the terms interface and network interface card (NIC) will have equivalent meaning to 'radio'.

bandwidth) using a single radio. This configuration adversely affects the capacity of the mesh due to interference from adjacent nodes in the network (i.e. all neighboring nodes will compete on the same channel).

Currently, there exist several research efforts to improve the capacity of wireless mesh networks by exploiting such alternative approaches as multiple radio interfaces **[9]**, directional antennas **[34]**, multiple-input multiple-output (MIMO) techniques [3], and modified medium access control (MAC) protocols adapted to WMNs **[35]**. By using directional transmission, the interference between network nodes can be mitigated, and thus the network capacity can be improved [36]. Directional antennas can also improve energy efficiency **[37]**. However, they bring challenges to the MAC protocol design **[38][39]**. The MIMO technique consists of using multiple antennas in both the transmitter and the receiver. MIMO deploys simultaneous transmissions and transmit/receive diversity (receive diversity is when the same information is received by different antennas; transmit diversity is when the same information is sent from multiple transmit antennas). Thus, MIMO can potentially increase the system capacity **[40]**; however, in this case also an efficient MAC protocol exploiting MIMO characteristics is needed to achieve significant throughput improvement. As far as the MAC protocols are concerned, scalability remains a very important challenging issue for designing an efficient MAC protocol for WMNs. Most of the existing MAC protocols partially solve the problem, but raise other problems such as throughput, capacity or fairness **[2]**. Moreover, a MAC protocol for WMNs must consider both scalability and heterogeneity between different network nodes (i.e., mesh routers, mesh clients).

To this end, equipping each node with multiple radios is emerging as a promising approach to improving the capacity of WMNs. First, the IEEE 802.11b/g [41] and IEEE 802.11a **[42]** standards provide 3 and 12 non-overlapping channels, respectively, which can be used simultaneously by a mesh router for transmission and reception within a neighborhood by tuning non-overlapping channels to different radios. This then leads to efficient spectrum utilization and increases the actual bandwidth available to the network. Secondly, the availability of cheap, off-the-shelf commodity hardware makes multi-radio solutions also economically attractive. Finally, the spatiotemporal diversity of radios operating on different frequencies with different sensing-to-hearing ranges, bandwidth, and fading characteristics can be leveraged to improve the overall capacity of the network.

In a realistic WMN, the total number of radios is much higher than the number of available channels. Thus, many links between the mesh routers will be operating on the same set of channels. At the same time, the interference among transmissions on these channels can dramatically decrease their utilization (e.g., due to contention among the nodes, as in the IEEE 802.11 protocol). Therefore, similar to cellular networks, the key factor for minimizing the effect of interference is the efficient reuse of the scarce radio spectrum. Therefore, a key issue to be addressed in a multi-radio, multi-channel WMN architecture is the channel assignment problem that involves assigning (binding) each radio to a channel in such a way that efficient utilization of available channels can be achieved. Specifically, the channel assignment problem in multi-hop communication is targeted at minimizing interference on any given channel. In addition, another fundamental goal of WMN channel assignment is guaranteeing an adequate level of connectivity among the mesh nodes. In other words, the assignment of channels to radios should ensure that multiple paths are available among mesh routers. This is a major characteristics and requirement for the robustness and reliability of the WMN backhaul tier.

A WMN node needs to share a common channel with each of its neighbors in the communication range, requiring it to set up a *virtual link*[2]. Moreover, to reduce the network interference, a node should minimize the number of neighbors with which to share a common channel. Therefore, there exists a trade-off between maximizing connectivity and minimizing interference. This trade-off is illustrated by an example in **Figure 6**. **Figure 6(a)** shows the connectivity of the network when a single channel is operating on a single radio. In this scenario, a link is placed between two nodes if they are inside their respective transmission ranges.

[2] A *virtual link* between two nodes is defined as a possible direct communication link between them.

This is the maximum achievable network connectivity since a single common channel is shared between all the nodes. Now, let us focus our attention on the multi-channel multi-radio scenario represented in **Figure 6(b)** and **(c)**. Specifically, there are four non-overlapping channels available for communication, given every node is equipped with two radios. Let us illustrate a case where the network connectivity is maximized (same as single radio single channel connectivity), and another case where the interference is minimized (efficient use of the available channels). We also explain how one affects the other. In **Figure 6(b),** the assignment of channels to the radios results in maximum network connectivity, however, this goal cannot be achieved unless at most three of the four available channels are assigned and three of the links are assigned the same channel (i.e., channel 2). For instance, a direct communication link exists between every pair of neighbors. However, not all the links can be active simultaneously because of possible interference. On the other hand, **Figure 6(c)** shows how interference could be completely eliminated and all links can be simultaneously active. The compromise here is that there is no common channel between neighbors, b and d.

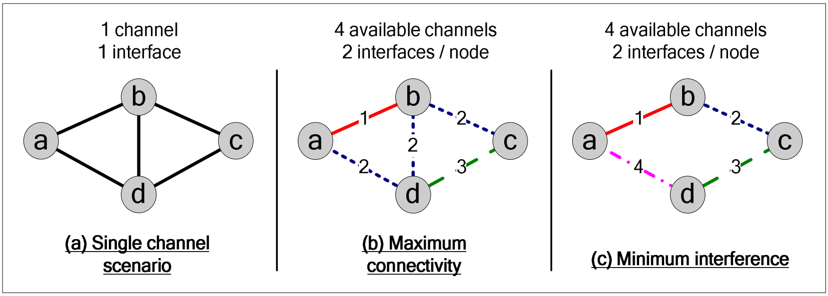

Figure 6 - Trade-off between connectivity and interference

The above example clearly illustrates that the goal of the channel assignment is to balance between (i) minimizing interference (on any given channel), and (ii) maximizing connectivity. In this sense, the channel assignment in a multi-hop wireless network can be viewed as a *topology control* problem **[43]** (similar to the transmission power control, for example). Unlike a wired network, links in a wireless network are flexible and can be tuned or configured. The tunable parameters in a wireless environment can be channel frequency, transmission power, bit rate, and directional transmission (using directional antennas) **[43]**. In general, topology control exploits these parameters in order to obtain a desired topology of the network. This can be one of the roles of the channel assignment in WMNs in addition to maximizing connectivity and minimizing interference.

3.3 Channel Assignment in Cellular Networks versus WMNs

The channel assignment (CA) problem has been extensively studied in the context of wireless cellular networks **[44]**. The basic concept used there is to divide the radio spectrum into a set of non-interfering disjoint radio channels. These channels can then be used simultaneously while maintaining an acceptable adjacent channel separation.

Different techniques are used to divide the radio spectrum, such as frequency division (FD), time division (TD) or code division (CD). In FD, the spectrum is divided into disjoint frequency bands. While in TD, the channel separation is achieved by dividing the channel usage into time slots. A combination of FD and TD can also be used to divide every frequency band into time slots. Let $S_i(k)$ be the set i of wireless terminals, that communicate with the base station using the same channel k. Because of the scarcity of the radio spectrum, there is a limited number of channels; thus the same channel k can be *reused* simultaneously by another set j if the members of set i and j are spaced enough. These sets using the same channel are called *co-channels*. The concept of channel *reuse* is illustrated in **Figure 7,** where there are seven orthogonal channels available (labeled A to G). Each channel is used for communication inside one cell and is *reused* simultaneously by another cell that is far enough.

The minimum distance at which co-channels can be reused with acceptable interference is called the co-channel reuse distance. This is possible because due to the path loss, the average power received from a transmitter at distance d is proportional to $P_T d^{-\alpha}$, where α is in the range 3-5 depending on the physical environment and P_T is the average

transmitter power. The co-channel interference caused by the frequency reuse is the most restraining factor on the system capacity.
Therefore, the role of a channel assignment scheme is to minimize this interference by adjusting (i) the distance between co-channels and/or (ii) the transmitter power level. These two methods (i and ii) present the underlying concept for channel assignment in cellular systems whose goal is to minimize the carrier-to-interference ratio (CIR) and hence increase the radio spectrum reuse efficiency.

In contrast, the channel assignment problem in WMNs is different in several aspects. First of all, the architectures of WMNs are different from those of cellular networks. In a WMN, the mesh routers form a multi-hop wireless backbone between the mesh clients and the wired network. While in a cellular network, the end-user terminals communicate directly through a single hop with the base-station, and the base-station to base station communication is carried over a separate network which is not the concern of channel assignment.

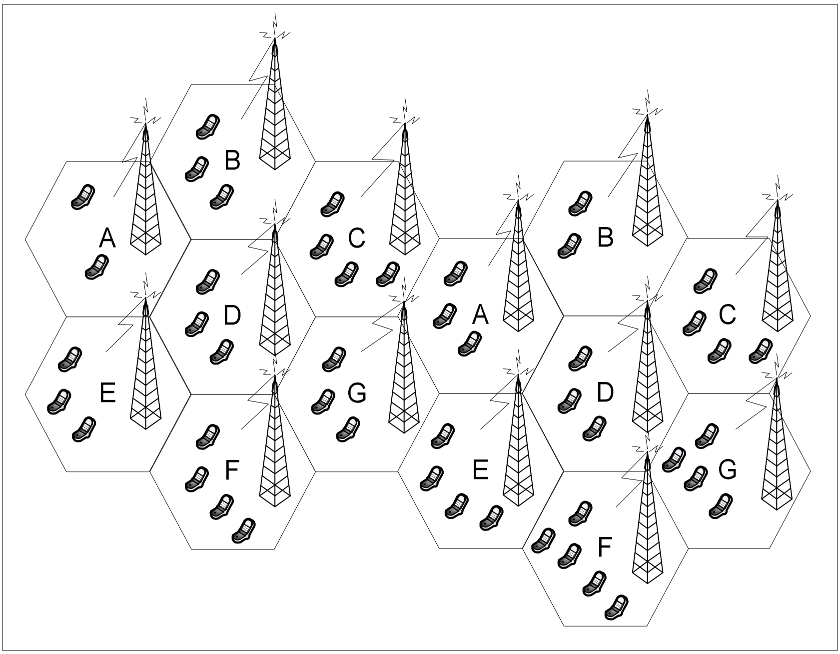

Figure 7 - The channel reuse concept in cellular networks

Secondly, the channel assignment in WMNs is mainly aimed at minimizing the interference in the wireless backbone. The backhaul is the main focus of research in capacity improvement in WMNs. On the other hand, channel assignment in cellular networks is only concerned with minimizing interference on the last hop wireless communication between the base station and the end-user mobile devices and vice versa.

Additionally, frequency hopping (FH) is a commonly used technique in cellular networks by rapidly switching frequencies during radio transmission by the base station. FH has many advantages, especially in reducing the effect of noise and interference. This technique can possibly be used in WMNs, however, with the current IEEE 802.11 hardware standard, the switching time latency is still extremely high **[10]** (e.g., in the order of milliseconds). Therefore, such possibility of channel switching is difficult to achieve, and this makes the channel assignment in WMNs more challenging.

3.4 Preliminaries

Before we present a taxonomy of the existing channel assignment strategies in WMNs, let us first provide some background concepts and definitions relevant to our context.

3.4.1 Connectivity Graph

For modeling purpose, we consider a WMN with mesh routers[3] distributed on a plane. Each mesh router is equipped with one or multiple radios with omni-directional antennas. We assume that all radios are characterized by an identical transmission range ($\boldsymbol{R}$) and also by the same interference range ($\boldsymbol{R'}$). The *transmission range* is defined as the distance at which a neighbor can receive packet transmission successfully. When a receiver is within the transmission range of two

[3] We use the terms mesh router and mesh node interchangeably to refer to the stationary mesh routers that constitute the WMN backbone.

transmitters that are transmitting simultaneously, the packets are assumed to interfere with each other leading to a collision at the receiver, and thus no packet is received successfully. The *interference range* is defined as the distance at which packet transmission cannot be decoded successfully at the receiver. However, any new transmission from a router within interference range from the receiver interferes with the packet reception. It is generally assumed that the transmission range is smaller than the interference range ($R < R'$) **[45]**.

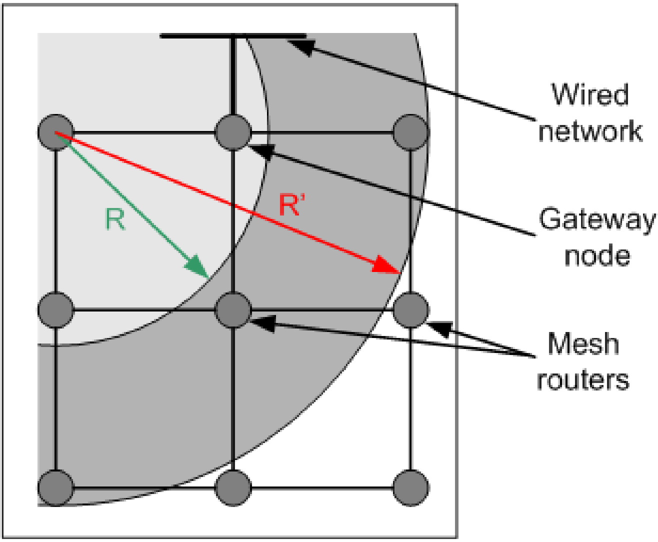

Figure 8 - An example of a Connectivity graph

Under the above assumptions, the connectivity between mesh routers can be modeled using an undirected graph referred to as *connectivity graph*, ***G***. As illustrated in **Figure 8,** two nodes in the connectivity graph have a link between them if they are located within transmission range of each other (see the protocol model, explained in the next section). In general, the network topology (also called logical topology) differs from the connectivity graph, since: a) a link in the connectivity graph may be absent in the *network topology graph* if the nodes at the end points of this link do not have any radios assigned to a common channel; and b) a link in the connectivity graph may have several corresponding links in the network topology graph if the nodes at the end points have more than one radio each with common channels. Note that the links present in the network topology are referred to as the *logical links*.

3.4.2 Conflict Graph

Because of the broadcast nature of the wireless medium, the success of a transmission is greatly influenced by the amount of multiple access interference. This interference can be modeled using a *conflict graph* derived on the basis of a connectivity graph. The concept of conflict graph is illustrated in **Figure 9**, in which a link between nodes **x** and **y** in the connectivity graph of **Figure 9(a)** is represented by a vertex $\mathbf{l}_{xy}$ in the conflict graph of **Figure 9(b)**. We use the terms "node" and "link" in reference to the connectivity graph and reserve the terms "vertex" and "edge" for the conflict graph, as in [46]. An edge is placed between two vertices in the conflict graph if the corresponding links in the connectivity graph interfere. The existence and extent of interference between a pair of links is determined by an *interference model*. There exist two well-known interference models: (i) the *protocol model,* and (ii) the *physical model*. The protocol model is the simplest and the most commonly used to represent the interference (see **Table 4**) while the physical model is more complex but offers a more realistic paradigm.

Assuming that all nodes in the network have the same interference range, the transmission from **x** to **y** is successful only if no other node located within distance $\boldsymbol{R'}$ from **y** transmits at the same time as **x**. Additionally, in the case of IEEE 802.11, if the RTS/CTS (Request to Send/Clear to Send) mode is used, then also no other node within distance $\boldsymbol{R'}$ from **x** should be transmitting at the same time. Therefore, the conflict graph for the protocol model contains an edge between two vertices (i.e., $\mathbf{l}_{xy}$, $\mathbf{l}_{xz}$) if either **x** or **y** are located within distance $\boldsymbol{R'}$ from **z**.

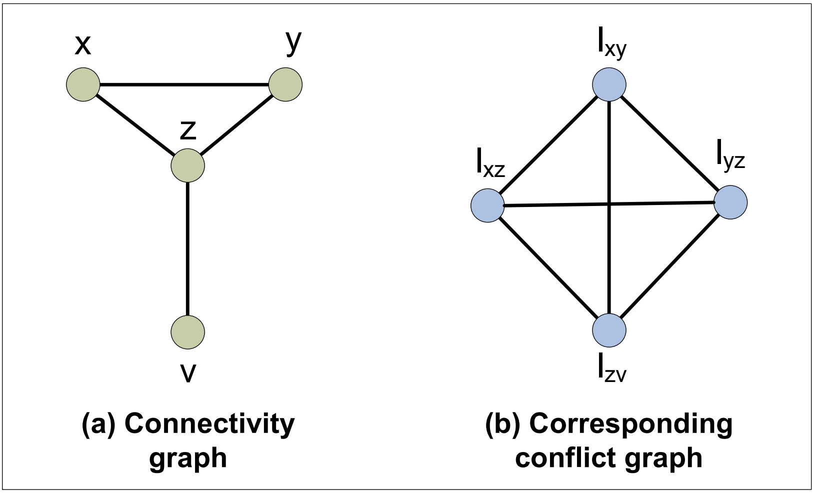

Figure 9 - Example illustrating the concept of the conflict graph

On the other hand, in the physical interference model, conflicts are not represented as binary. Suppose node **x** wants to transmit to node **y**. The signal strength $\mathbf{SS_{xy}}$ of **x**'s transmission is calculated as received at **y**. The transmission is successful if $\mathbf{SNR_{xy}} \geq \mathbf{SNR_{tresh}}$, where $\mathbf{SNR_{xy}}$ is the signal to noise ratio at **y** of the transmission received from **x**. The total noise $\mathbf{N_y}$ at **y** is the total of the ambient noise ($\mathbf{N_a}$) and the interference due to other ongoing transmissions in the network. Based on this model, a link $\mathbf{l_{xy}}$ exists between **x** and **y** in the connectivity graph if and only if $\mathbf{SS_{xy}} / \mathbf{N_a} \geq \mathbf{SNR_{tresh}}$ (that is the SNR exceeds the minimum threshold at least in the presence of just the ambient noise). Because conflicts are not binary, the interference in the physical model gradually increases as more neighboring nodes transmit and becomes unacceptable when the noise level reaches a threshold. This gradual increase implies that the conflict graph should be a weighed graph, where the weight of a directed edge between two vertices indicates the fraction of the permissible noise at the receiving node. For further details on the physical model, we refer the reader to **[46]**.

3.4.3 Multi-Radio Conflict Graph

The multi-radio conflict graph (MCG) **[47]** is an extension to the conflict graph described in the previous section. In the MCG, instead of representing the links between mesh routers, vertices represent the links between mesh radios. To create the MCG, each radio in the mesh is represented by a node in a new graph ***G′*** instead of representing routers by nodes as in ***G***.

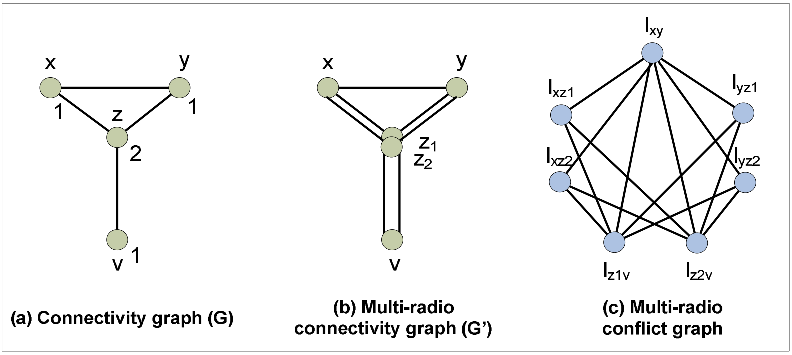

Figure 10 - An example illustrating the multi-radio conflict graph

In the above example, let us assume node **z** has two radios and the rest of the nodes have one radio as shown in **Figure 10(a)**. Therefore, node **z** will be represented by two nodes in ***G′*** as in **Figure 10(b)**, corresponding to its two radios instead of just one node as in ***G***. Then each link in ***G′*** is represented using a vertex in the MCG. The edges between the vertices in the MCG are created the same way as in the original conflict graph. Two vertices in the MCG have an edge between them if the links in ***G′*** represented by these two vertices interfere. **Figure 10(c)** shows the MCG of the wireless mesh network represented in **Figure 10(a)**. In this figure, each vertex is labeled using the radios that make up the vertex. For example, the vertex **xz**$_2$ represents the link between the radio on router **x** and the second radio on router **z**.

3.5 Constraints and Challenges in Channel Assignment (CA)

Given the connectivity graph and the interference model, the main challenges for channel assignment are: how to assign a (frequency) channel to each radio in such a way as to minimize the interference and maximize the connectivity among the nodes. The main constraints **[15]** that a channel assignment algorithm should satisfy are:

1. The total number of channels is fixed.
2. The number of distinct channels that can be assigned to a mesh router is limited by the number of its radios.
3. Two nodes, that share a virtual link expected to carry certain amount of traffic, should be bound to a common channel.
4. The sum of the expected traffic loads on the links that share the same channel and that interfere with each other should not exceed the channel's raw capacity.

At a first sight, the problem of channel assignment seems to be a straightforward problem of graph coloring **[15]**. However, standard graph coloring cannot capture the above constraints and specifications of the problem. A node-multi-coloring formulation **[48]** fails to capture the third constraint where the communicating nodes need a common color. On the other hand, an edge-coloring formulation fails to capture the second constraint where no more than the number of radios per node colors can be incident to a node. While a constrained edge-coloring might be able to roughly model the remaining constraints, it is incapable of satisfying the fourth constraint of limited channel capacity. Additionally, a key problem in the design of channel assignment for multi-radio WMNs is the *channel dependency* among the logical links that share a common channel. Consider the WMN shown in **Figure 11** where six non-overlapping channels are available. Notice that links (**a**,**e**), (**e**,**d**), (**d**,**i**) and (**i**,**h**) all share channel 3 and therefore, if anyone of the nodes **a**, **e**, **d**, **i**, and **h** decides to reassign the channel on these virtual links, then the rest of the links have to change their assignment which produces a *ripple effect*. This channel dependency among the nodes makes it difficult to predict the effect of node revisits or re-assignment.

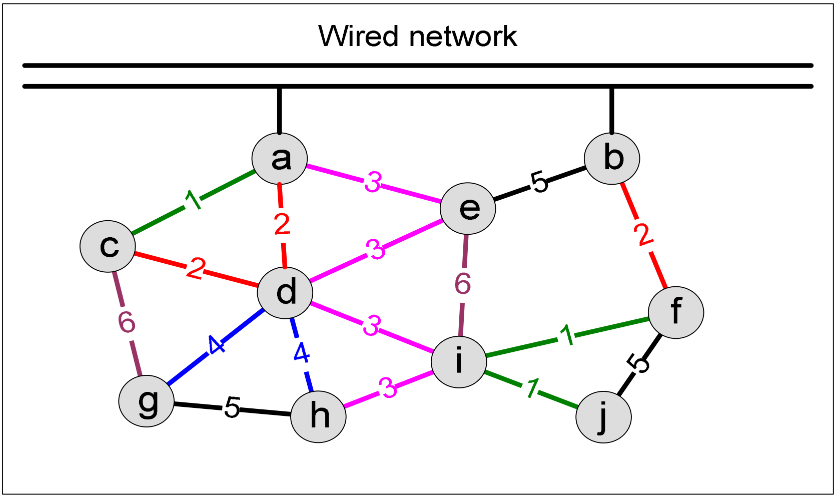

Figure 11 - An example illustrating channel dependency

Finally, a channel assignment algorithm should take into consideration the amount of traffic load on the virtual links. It may be assumed that each virtual link in the network has the same traffic load. However, this does not hold true in most cases as some links generally carry more traffic than others **[15]** (for example, links associated with the gateway node). Generally, more bandwidth should be given to nodes that support higher traffic. In other words, channels assigned to these links should be shared among a fewer number of nodes. Such traffic-aware channel assignment strategy would distribute the radio resources so as to match the distribution of traffic load in the mesh backbone.

Because channel assignment depends on the expected load on each virtual link, which in turn depends on routing, there exists a circular dependency between channel assignment and routing **[15]**. Routing depends on the capacity of virtual links, which is determined by channel assignment. This is because the capacity of a virtual link depends on the number of other links that are within its interference range and that are using the same channel. Similarly, channel assignment depends on the virtual links' expected load, which is affected by routing. There exist two different strategies to deal with this circularity between the routing and the channel assignment as depicted in **Figure 12**.

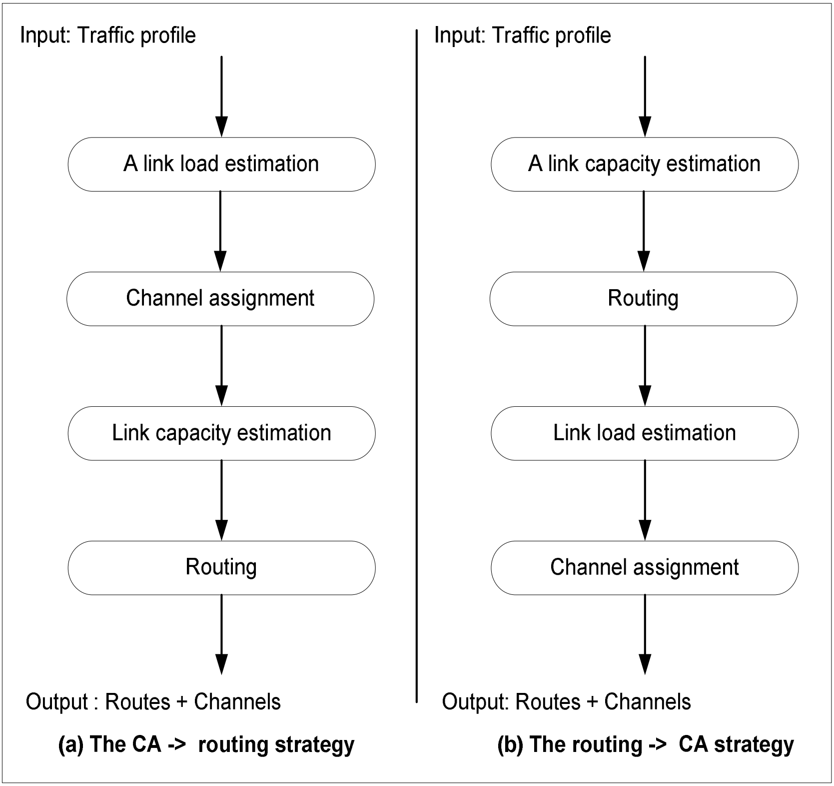

Figure 12 - Strategies for load aware channel assignment

Given a set of node pairs and the expected traffic load between each node pair, according to the first strategy shown in **Figure 12(a),** the routing algorithm devises the initial routes for the node pairs. Given these initial routes for the node pairs and hence the traffic load on each virtual link, the channel assignment algorithm assigns a channel to each radio taking into account the link traffic load. This assignment of

channels is finally fed back to the routing algorithm. The second strategy, shown in **Figure 12(b),** is different from the first one in the sense that the routing algorithm assumes some initial assignment of channels to the radios. Based on that, the link capacities are estimated and passed to the routing algorithm, which in turn passes the link load needed for channel assignment. Obviously, both strategies may end up with inaccurate link capacities/link loads fed to the routing algorithm/channel assignment, which may require iterations between routing and channel assignment as in **[15]**.
Examples of methods used for the estimation of link load and link capacity are presented in the next sections.

3.4.1 Link Load Estimation

There are different methods to derive a rough estimate of the expected link traffic load. These methods depend on the routing strategy used (e.g., load balanced routing, multi-path routing, shortest path routing, and so on).
One approach is based on the concept of load criticality **[49]**; this method assumes perfect load balancing across all acceptable paths between each communicating pair of nodes. Let **P(s,d)** denote the number of acceptable paths (or *virtual connections*) between a pair of nodes (**s,d**), and let $\mathbf{P_l(s,d)}$ be the number of acceptable paths between (**s,d**) that pass through a link ***l***. And finally, let **B(s,d)** be the estimated load between (**s,d**). Then the *expected traffic load* (Φ_l) on link ***l*** is calculated as:

$$\phi_l = \sum_{s,d} \frac{P_l(s,d)}{P(s,d)} * B(s,d) \qquad \textbf{Eqn. 1}$$

This equation implies that the initial expected traffic on a link is the sum of the loads from all acceptable paths, across all possible node pairs, which pass through the link. Because of the assumption of uniform multi-path routing, the load that an acceptable path between a

pair of nodes is expected to carry is equal to the pair of nodes' expected load divided by the total number of acceptable paths between them.
Let us consider the same logical topology as shown in **Figure 11**. Additionally, let us assume that we have the following three flows**:**

Table 1 - Traffic profile with 3 flows

Source (s)	Destination (d)	B(s,d) (Mbps)
a	g	0.9
i	a	1.2
b	j	0.5

Because we have three different sources and destinations, $\mathbf{\Phi}_l$ will be equal to:

$$\frac{P_l(a,g)}{P(a,g)} * B(a,g) + \frac{P_l(i,a)}{P(i,a)} * B(i,a) + \frac{P_l(b,j)}{P(b,j)} * B(b,j) \qquad \text{Eqn. 2}$$

Furthermore, for every flow, let us assume the following are all the possible paths from source to destination. Consequently, we can also calculate P(s,d) for each flow:

Table 2 – Possible flows between communicating nodes

(s,d)	(a,g)	(i,a)	(b,j)
Possible paths	a-c-g	i-e-a	b-f-j
	a-c-d-g	i-e-d-a	b-f-i-j
	a-d-g	i-d-a	b-e-i-j
	a-d-c-g	i-d-c-a	b-e-i-f-j
	a-d-h-g	i-d-e-a	b-e-d-i-j
	a-d-i-h-g	i-d-g-c-a	
	a-e-d-g	i-h-d-a	
	a-e-i-h-g	i-h-g-c-a	
P(s,d)	8	8	5

From the above information, we can now calculate how many paths pass a specific link in the network topology. These values and the corresponding link traffic load (**Φ_l**) calculated using Eqn. 2 are shown in the following table:

Table 3 – Link traffic load calculation

Link ID	l	$P_l(a,g)$	$P_l(i,a)$	$P_l(b,j)$	Φ_l (Mbps)
1	a-c	2	3	0	0.675
2	c-g	2	2	0	0.525
3	c-d	2	1	0	0.375
4	d-g	2	1	0	0.375
5	a-d	4	3	0	0.9
6	g-h	0	1	0	0.15
7	d-h	1	1	0	0.2625
8	a-e	2	2	0	0.525
9	d-e	1	2	1	0.5125
10	d-i	1	3	1	0.6625
11	h-i	2	2	0	0.525
12	e-i	1	2	2	0.6125
13	b-e	0	0	3	0.3
14	b-f	0	0	2	0.2
15	f-i	0	0	2	0.2
16	i-j	0	0	2	0.2
17	f-j	0	0	2	0.2

Based on these calculations, we can estimate the load between every neighboring node. The meaning of the measure **Φ_l**, we calculated throughout this example, is the link expected traffic load. That is the amount of traffic expected to be carried over a specific link. This representation of traffic between neighboring nodes is also referred to as the *traffic matrix*. The traffic matrix is indeed an important estimation that allows achieving a traffic aware channel assignment.

3.4.2 Link Capacity Estimation

The link capacity, or the portion of channel bandwidth available to a virtual link, is determined by the number of all virtual links in its interference range that are also assigned to the same channel. Obviously, the exact short-term instantaneous bandwidth available to each link is dynamic and continuously changing depending on such complex system dynamics as physical obstacles, distance, capture effect, coherence period, and stray radio frequency (RF) interferences **[15]**. The goal here is to derive an approximation of the long-term bandwidth share available to a virtual link. One approximation of a virtual link ***i***'s capacity bw_i can be obtained using the following equation:

$$bw_i = \frac{\phi_i}{\sum_{j \in Intf(i)} \phi_j} * C \qquad \text{Eqn. 3}$$

Where Φ_i is the expected load on link ***i***, ***Intf(i)*** is the set of all virtual links in the interference zone of link ***i***, and ***C*** is the sustained radio channel capacity. The rationale of this formula is that when a channel is not overloaded, the channel share available to a virtual link is proportional to its expected load. The higher the expected load on a link, the more channel share it would get. The accuracy of this formula decreases as $\sum_{j \in Intf(i)} \phi_j$ approaches *C*.

To summarize this section, the inputs to a channel assignment algorithm are: (1) the connectivity graph, (2) the number of non-overlapping channels, (3) the number of radios available on each mesh router, and (4) an estimated traffic load for each communicating pair of nodes. The output is the channel bound to each radio in the multi-radio WMN.

In the next chapter, we present various channel assignment schemes proposed in the literature.

Chapter 4

Channel Assignment strategies for Wireless Mesh Networks

4.1 Introduction

As mentioned in the previous chapter, Channel Assignment (CA) in a multi-radio WMN environment consists of assigning channels to the radios in order to achieve efficient channel utilization (i.e. minimize interference) and, at the same time, to guarantee an adequate level of connectivity. The problem of optimally assigning channels in an arbitrary mesh topology has been proven to be NP-hard based on its mapping to a *graph-coloring* problem **[15]**. Therefore, channel assignment schemes predominantly employ heuristic techniques to assign channels to radios belonging to WMN nodes. In this chapter, we present a taxonomical classification of various CA schemes for mesh networks. **Figure 13** presents the taxonomy on which the rest of the section is based. Specifically, the proposed CA schemes can be partitioned into three main categories – *fixed*, *dynamic* and *hybrid* – depending on the frequency the CA scheme is modified. In a fixed scheme the CA is almost constant, while in a dynamic scheme it is continuously updated to improve performance. A hybrid scheme applies a fixed scheme for some radios and a dynamic one for others. In the following, we analyze these three categories and give examples of CA schemes from each category.

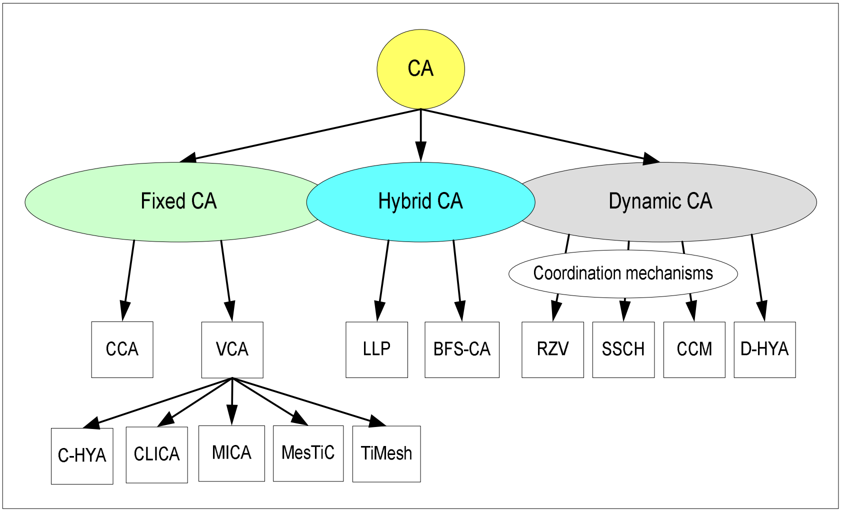

Figure 13 - Taxonomy of Channel Assignment Schemes in Wireless Mesh Networks

4.2 Fixed Channel Assignment Schemes

Fixed assignment schemes assign channels to radios either permanently, or for time intervals which are long with respect to the radio switching time. Such schemes can be further subdivided into *common channel assignment* and *varying channel assignment*.

4.2.1 Common Channel Assignment (CCA)

This is the simplest scheme. In CCA **[9]**, the radios of each node are all assigned the same set of channels. For example, if each node has two radios, then the same two channels are used at every node as shown in **Figure 14**. The main benefit is that the connectivity of the network is the same as that of a single channel approach, while the use of multiple channels increases network throughput. However, the gain may be limited in scenarios where the number of non-overlapping channels is much greater than the number of radios available in each node. Thus, although this scheme presents a simple CA strategy, it does not take into account all the various factors affecting the performance of a channel assignment in a WMN, thus producing an inefficient utilization of the network resources (i.e. interference).

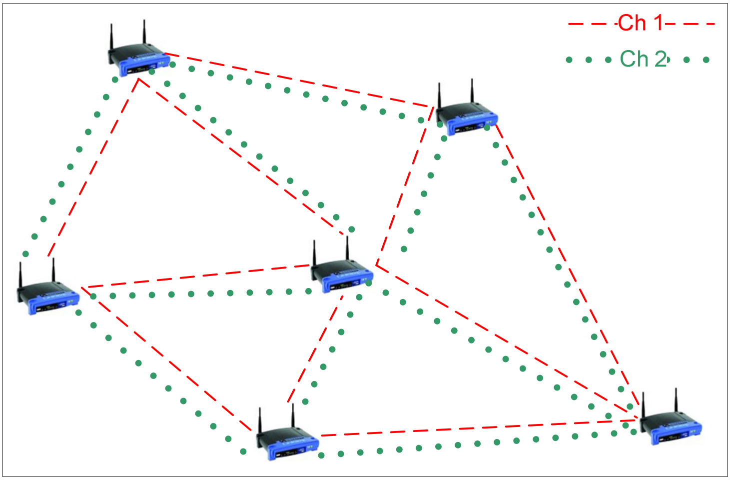

Figure 14 - Common channel assignment example

4.2.2 Varying Channel Assignment (VCA)

In the VCA scheme, radios of different nodes may be assigned different sets of channels **[15][43]**. However, the assignment of channels may lead to network partitions and/or topology changes which may increase the length of routes between mesh nodes. Therefore, in this scheme, the channels assignment needs to be carried out carefully. Below we discuss the VCA approach in more details by presenting five algorithms which belong to this sub-category.

4.2.2.1 Centralized Channel Assignment (C-HYA)

Based on *Hyacinth,* a multi-channel wireless mesh network architecture, a centralized channel assignment algorithm for WMNs is proposed in **[15]**, where traffic is mainly directed toward gateway nodes, i.e. the traffic is directed to/from the Internet. Assuming that the offered traffic load is known, this algorithm assigns channels thus ensuring the network connectivity and satisfying the bandwidth limitations of each link. It first estimates the total expected load on each virtual link by summing the load due to each offered traffic flow. Then, the channel assignment algorithm visits each virtual link in decreasing order of expected traffic load and greedily assigns it a channel. The algorithm starts with an initial estimation of the expected traffic load and iterates over channel assignment and routing until the bandwidth allocated to each virtual link matches its expected load. While this scheme presents a method for channel allocation that incorporates connectivity and traffic patterns, the assignment of channels on links may cause a *ripple effect* whereby already assigned links have to be revisited, thus increasing the time complexity of the scheme.

An example of node revisiting is illustrated in **Figure 15**. In this case, node *a* is assigned channels 1 and 6, and node *b* channels 2 and 7. Because *a* and *b* have no common channel, a channel re-assignment is needed. Specifically, link (*a-b*) needs to be assigned one of the channels from **[2][50][10][51]**. Based on the channel expected loads, link (*a-b*) is assigned channel 6, and channel 7 assigned already to link (*b-d*) is changed to channel 6.

The results **[15]** show that by deploying only two radios per node, it is possible to achieve a factor of up to 8 in the improvement of the overall network goodput when compared to single-radio case which is inherently limited to a single channel.

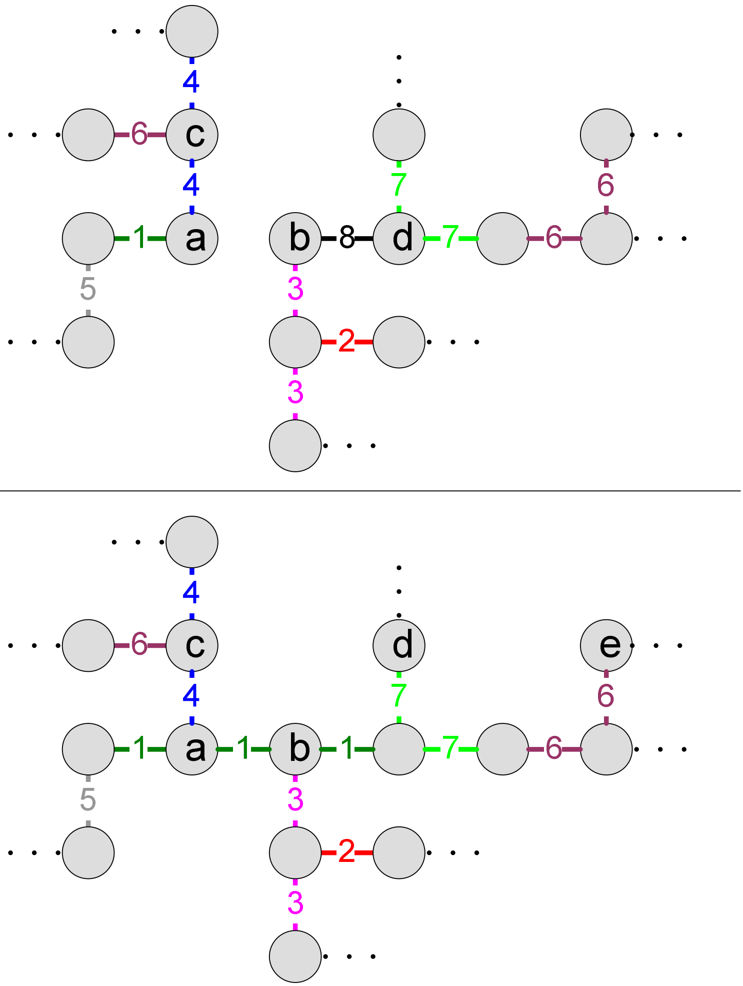

Figure 15 - An example of channel revisit in C-HYA

3.2.2.2 A Topology Control Approach (CLICA)

A polynomial time greedy heuristic, called *Connected Low Interference Channel Assignment (CLICA)*, is presented in **[43]** to enable an efficient and flexible topology formation, ease of coordination, and to exploit the static nature of mesh routers to update the channel assignment on large timescales.

CLICA is a traffic independent channel assignment scheme which computes the priority for each mesh node and assigns channels based on the connectivity graph and on the conflict graph. However, the algorithm can override the priority of a node to account for the lack of flexibility in terms of channel assignment and to ensure network connectivity. While this scheme avoids link revisits, it does not incorporate the role of traffic patterns (an example of traffic pattern is shown in **1**) in channel assignment for WMNs.

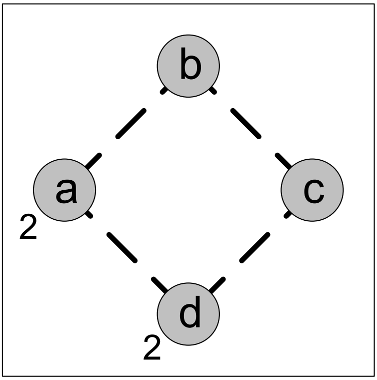

Figure 16 - Connectivity graph

To understand the functioning of the CLICA algorithm, let us consider the example in **Figure 16.** Suppose nodes *a* and *d* have two radios and the initial order of priorities is *a*, *d*, *c* and *b*. CLICA starts at *a* to color its incident links; it starts by coloring link ($a - b$) with channel C_1. As a result, *b* loses further flexibility in choosing channels for its other incident links. So, CLICA bumps *b*'s priority to the highest. Moreover, it recursively starts assigning channels at *b* which results in node *b* reusing channel C_1 for link (b–c). Same procedure as above (i.e., priority increase followed by recursive color reuse) repeats at node *c* forcing link (c–d) to use C_1. Now because *d* has two radios and only one of them is already assigned, the algorithm assigns link ($a - d$) with C_2 by using the additional radios. Note that CLICA is naturally *recursive* and follows a chain of the least flexible nodes to maintain network connectivity. Also note that it is a *one-pass* algorithm in that coloring decisions once made are not reversed later in the algorithm execution. Simulation results demonstrate the effectiveness of CLICA in reducing interference which represents the objective function for the CA optimization problem.

4.2.2.3 Minimum-Interference Channel Assignment (MICA)

In **[52]** the authors extended **[15]** and developed two new algorithms, the first one based on a popular heuristic search technique called Tabu search **[53]** originally designed for graph coloring problems. The second one is a greedy heuristic inspired by the greedy approximation algorithm for Max K-cut **[54]** problem in graphs. The Tabu-search based method starts with a random assignment; then a neighborhood search is run for a better solution by flipping the assignment of some nodes. At the same time, the method remembers the best solution seen so far and stops when the maximum number of iterations allowed is reached without a better solution found (an example of an output of the first phase is shown in **Figure 17(a)**). This solution is the best without taking into account the interface constraint, i.e., the total number of available channels at any network node is less than or equal to the number of radios on that node. Therefore the last step in the algorithm is to start from the node with maximum violations of the interface constraint, and combine any assignments of radios that share the same channel and share an edge between them in such a way to minimize the increase in conflicts.

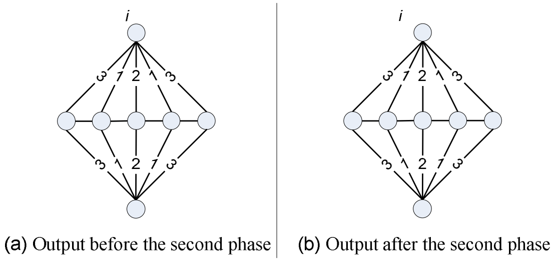

Figure 17 - Merge operation of second phase

In **Figure 17(a)**, let ***i*** be the node picked for the merge operation. The number of colors incident on ***i*** is reduced by picking two colors C1 and C2 incident on ***i***, and changing the color of all C1-colored links to C2. In order to ensure that such a change does not create interface constraint violations at other nodes, such a change will iteratively propagate to all C1-colored links that are connected to the links whose color has been just changed from C1 to C2 (two links are said to be connected if they are incident on a common node). Essentially the above propagation of color change ensures that for any node ***j***, either all or none of the C1-colored links incident on ***j*** are changed to color C2. The result of the merge operation after the second phase is shown in **Figure 17(b)**.

On the other hand, the second greedy heuristic developed in **[52]**, based on Max K-cut, takes care of the interface constraint at each iteration. The Max K-cut problem consists of how to partition the vertex set of a graph into k sets so as to maximize the number of edges crossing between partitions. Using linear programming and semi-definite programming formulations of this optimization problem, tight lower bounds on the optimal network interference have been obtained.

4.2.2.4 A Traffic and Interference Aware Channel Assignment Scheme (MesTiC)

MesTiC **[51]** stands for *Mes*h based *T*raffic and *i*nterference aware *C*hannel assignment. It is a fixed, rank-based, polynomial time greedy algorithm for centralized CA, which visits nodes once in the decreasing order of their rank. The rank of each node ***R*** is computed on the basis of its link traffic characteristics, topological properties and number of radios on a node according to the following ratio:

$$R(node) = \frac{Agg.Traffic(node)}{\min hops\ from\ gateway(node) * num\ of\ \ radios(node)} \qquad \text{Eqn. 4}$$

Clearly, the aggregate traffic flowing through a mesh node has an impact on the channel assignment strategy. The rationale is that if a node relays more traffic, assigning it a channel of least interference will increase the network throughput. Thus, aggregate traffic in the numerator in Eqn. 4 increases the rank of a node with its traffic. In addition, due to the hierarchical nature of a mesh topology, the nodes nearest to the gateway should have a higher preference (rank) in channel assignment, as they are more likely to carry more traffic. At the same time, the number of radios on a node gives flexibility in channel assignments and should inversely affect its priority (i.e. the lower the number of radios, the higher the priority in channel assignment).

MesTiC ensures the topological connectivity by using a common default channel deployed on a separate radio on each node, which can also be used for network management purposes. Fixed schemes alleviate the need for channel switching, especially when switching delays are large as is the case with the current 802.11 hardware. In addition, MesTiC is rank-based, which gives the nodes that are expected to carry heavy loads, more flexibility in assigning channels. Finally the use of a common default channel prevents flow disruption as discussed in **[47]**.

MesTiC algorithm traverses the mesh network nodes in descending order of their rank assigning channels to the radios. For further details on MesTiC, we refer the reader to **[51]** and **[55]**.

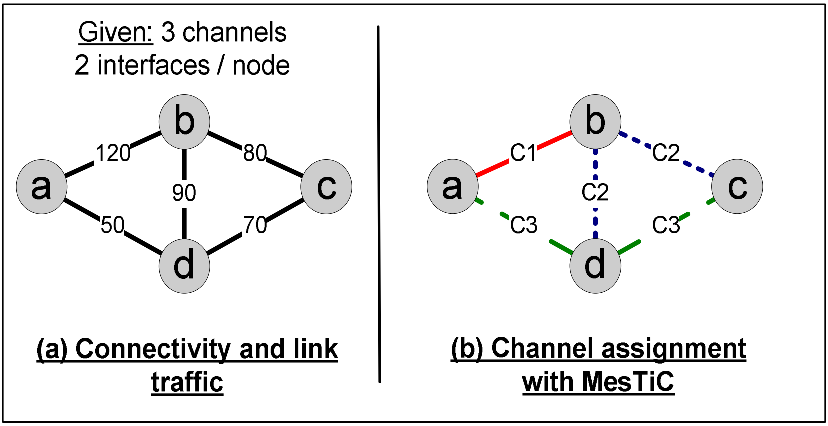

Figure 18 - Example illustrating how MesTiC works

Let us illustrate the working principle of *MesTiC* by considering the simple example in **Figure 18(a)** where the input connectivity graph and estimated link traffic (i.e., the estimated traffic between a node and its neighbors) are shown. In addition the network is configured with three channels and two radios per node. Assuming that node ***b*** is the gateway node, the rank of the remaining nodes, in decreasing order, is ***d***, ***a***, ***c***. The algorithm starts by visiting node ***b*** first, assigning channel **C1** to the link between (***b-a***) (which carries the highest traffic of 120), and then moves on to assign channel **C2** to the link (***b-d***). Now, while assigning a channel to link (***b-c***), it has to choose between **C1** and **C2**. However, as **C1** carries more traffic than **C2**, it assigns **C2** to link **(*b-c*)**. Similarly, at node ***d***, it assigns a previously unassigned channel **C3** to the link (***d-c***) and, as **C3** carries less traffic than **C2** (90 + 80 =170) or C1 (120), it assigns **C3** to the link (***d-a***). The algorithm proceeds until all links and radios are assigned channels as shown in **Figure 18(b)**. Simulation results show that MesTiC performs better than other CA algorithms for different topologies and traffic profiles.

4.2.2.5 Topology design and channel assignment (TiMesh)

In **[56]**, the authors present a decentralized channel assignment strategy that considers topology control and channel allocation as two separate but related problems. The former takes care of the problem of channel dependency and the latter deals with the interference issue.
The logical topology formation and radio assignment are formulated as a joint optimization problem based on a Multi-channel WMN (MC-WMN) architecture called *TiMesh*. The model formulation of the proposed solution takes into account the number of radios on each mesh router, the channel dependency among the nodes that share a common channel, the logical link degree, and the expected traffic load between the different source and destination nodes. The goals are: (1) to guarantee network connectivity, by supporting both internal traffic (among the wireless routers) and external traffic (to the internet); (2) to prevent ripple effects among the logical links sharing the same channel.
The MC-WMN is modeled by a physical topology graph G(N,E). Where N is the set of mesh routers (each equipped with I radios) and E is the set of links between the mesh routers.
The first constraint to the problem is that logical links are assumed to be bidirectional.
The second constraint considered is the channel dependency constraint; to restrict this dependency an upper bound on the number of additional logical links that may share a radio with a particular link is set. The larger this value, the smaller the proportion of time that each logical link can access the shared radio.
The third one is the ripple effect constraint; and the approach is to assign an exclusive radio to one end of each logical link. That is, if node x is responsible for the channel allocation on logical link (x,y), then the radio that is assigned by node y to attach to link (x,y) should not be used by any other logical link. For capacity planning, a statistical model of the network traffic is used and flow conservation is applied at each node which guarantees that there is at least one path available between each source and destination pair (s,d). Thus, the obtained topology is always connected.

The fourth constraint is the hop count constraint which states that for each source and destination pair (*s,d*), there exists at least one path with the hop count to be less than or equal to the shortest path + a tunable parameter Γ (a positive integer).
It is assumed that a power control algorithm maintains a constant data rate in the presence of fading and other channel imperfections. This implies a fixed nominal capacity associated to the logical links. However, the effective capacity depends on the number of additional logical links that are sharing the same channel. The utilization of the logical link is then defined as the total traffic load between source and destination (assumed to be known) divided by the effective link capacity.
The objective function for the optimization problem is to minimize the maximum utilization across all the links given the constraints defined earlier. For this paper, a fast greedy algorithm **[57]** was used to provide the solutions for the logical topology design and radio assignment problems. Moreover, the solution also determines which end node on each logical link is responsible for channel allocation.

4.3 Dynamic Channel Assignment Schemes

As in the fixed CA, dynamic CA strategies allow any radio to be assigned any channel but in the latter CA radios can frequently switch from one channel to another. Therefore, when nodes need to communicate with each other, in a dynamic CA, a coordination mechanism has to ensure they are on a common channel. For example, the coordination mechanism may require all nodes to visit a predetermined "rendezvous" channel **[58]** periodically to negotiate channels for the next phase of transmissions as shown in **Figure 19**.

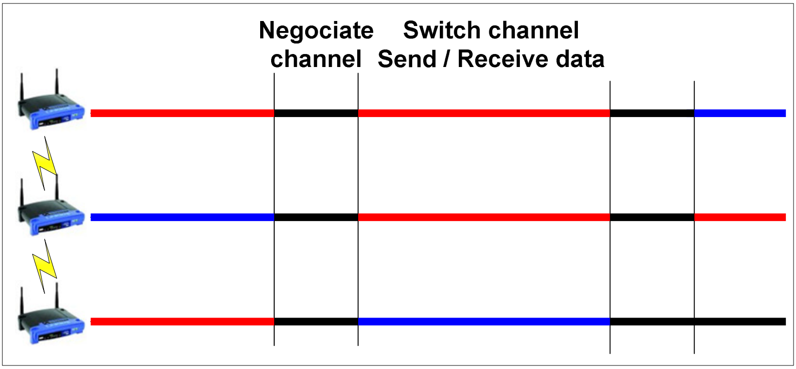

Figure 19 - Example of the synchronization "rendezvous" mechanism

Another mechanism, called the Slotted Seeded Channel Hopping (SSCH), consists of the use of pseudo-random sequences **[59]** in which each node should switch channels synchronously in a pseudo-random sequence so that all neighbors meet periodically in the same channel. In this approach the interfaces must be capable of fast synchronous channel switching. Specifically, time is divided into slots and the channels are switched at beginning of each slot according to:

New Channel = (Old Channel + seed) mod (Number of Channels) Eqn. 5

An example of the Slotted Seeded Channel Hopping (SSCH) mechanism is illustrated in **Figure 20.**

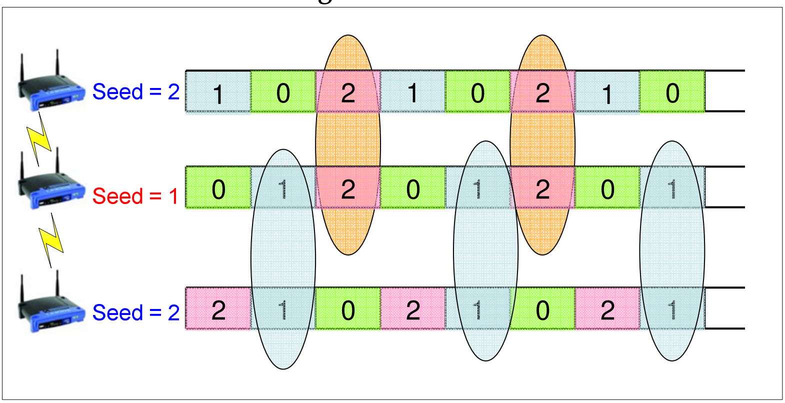

Figure 20 - Example of SSCH: Slotted Seeded Channel Hopping

Another approach to dynamic channel assignment is the control channel approach, shown in **Figure 21**, in which one radio is assigned to a common channel for control purposes, and the rest of radios are switched between the remaining channels and used for data exchange **[60]**.
The benefit of dynamic assignment is the ability to switch a radio to any channel, thereby offering the potential to utilize many channels with few radios. The key challenge with the dynamic switching approach is how to coordinate the decisions of when to switch radios as well as what channel to switch the radios to.

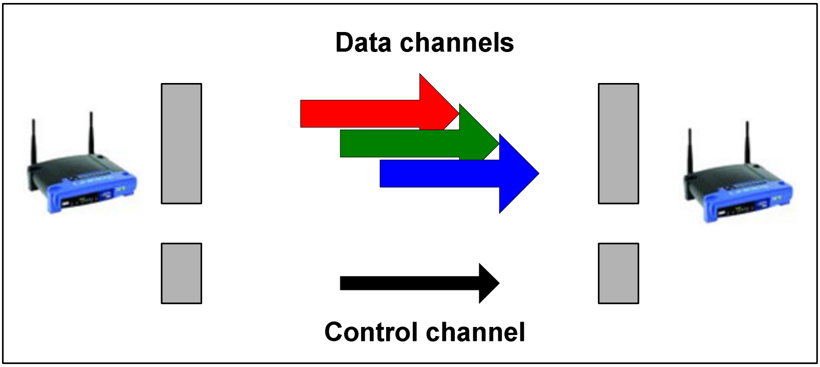

Figure 21 - Example of the control channel mechanism

4.3.1 A Distributed Channel Assignment Scheme (D-HYA)

A set of dynamic and distributed channel assignment algorithms is proposed in **[14][10]**, which can react to traffic load changes in order to improve the aggregate throughput and achieve load balancing. Based on the *Hyacinth* architecture, the algorithm (described in **[14]** as well as in **[10]** with a minor change) builds on a spanning tree network topology, similar in construction to that of IEEE 802.1D. The scheme works in such a way that each gateway node is the root of a spanning tree, and every mesh node belongs to one of these trees. The channel assignment problem consists of the following two steps.

(a) *neighbor-to-interface binding* (i.e. it selects the radio to communicate with every neighbor), where the dependency among the nodes is eliminated in order to prevent *ripple effects* in the network **[15]**. This is achieved by imposing a restriction that the set of radios that a node uses to communicate with its parent node, termed *UP-NICs*, is disjoint from the set of radios the node uses to communicate with its children nodes, called *DOWN-NICs*, as shown in **Figure 22**.

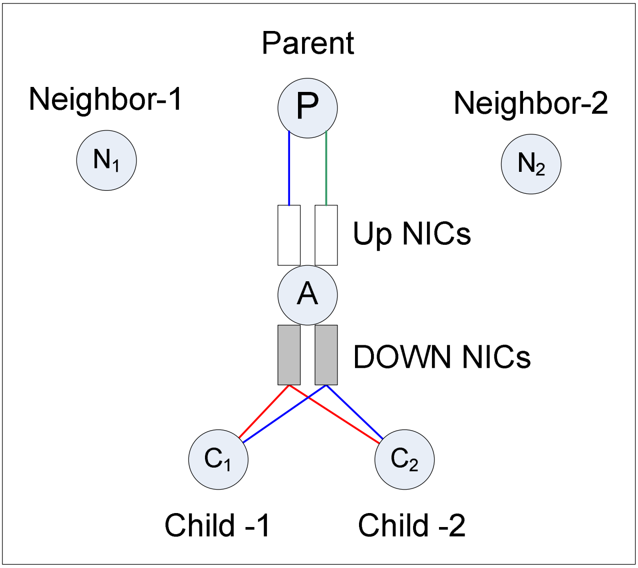

Figure 22 - Neighbor to interface binding in D-HYA

(b) *interface-to-channel binding* (i.e. it selects the channel to assign to every radio), where the goal is to balance the load among the nodes and relieve interference. The channel assignment of a WMN node's UP-NICs is the responsibility of its parent. To assign channels to a WMN node's DOWN-NICs, it needs to estimate the usage status of all the channels within its interference neighborhood. Each node therefore periodically exchanges its individual channel usage information as a CHNL USAGE packet with all its neighbors. Based on the per-channel total load information, a WMN node determines a set of channels that are least-used in its vicinity. As nodes higher up in the spanning trees need more relay bandwidth, they are given a higher priority in channel assignment. More specifically, the priority of a WMN node is equal to its hop distance from the gateway. When a WMN node performs channel assignment, it restricts its search to the channels that are not used by any of its interfering neighbors with a higher priority. The outcome of this priority mechanism is a *fat-tree* architecture where links higher up in the tree are given higher bandwidth. Because traffic patterns and thus channel loads can evolve over time, the radio-to-channel mapping is adjusted periodically, every Tc time units. Within a *channel load-balancing* phase, a WMN node evaluates its current channel assignment based on the channel usage information it receives from neighboring nodes. As soon as the node finds a relatively less loaded channel after accounting for priority and its own usage of current channel, it moves one of its DOWN-NICs operating on a heavily-loaded channel to use the less-loaded channel, and sends a CHNL CHANGE message with the new channel information to the affected child nodes, which modify the channels of their UP-NICs accordingly.

To summarize, in D-HYA channels are dynamically assigned to the radios based on their traffic load. However, the tree-topology constraint of the scheme poses a potential hindrance in leveraging multi-path routing in mesh networks.

4.4 Hybrid Channel Assignment Schemes

Hybrid channel assignment strategies combine both static and dynamic assignment properties by applying a fixed assignment for some radios and a dynamic assignment for other radios (see for example **[50][61][47]**). Hybrid strategies can be further classified based on whether the fixed radios use a common channel **[47]**, or a varying channel **[50][61]** approach. The fixed radios can be assigned a dedicated control channel **[14]** or a data and control channel **[47]**, while the other radios can be switched dynamically among channels. Hybrid assignment strategies are attractive because, as with fixed assignment, they allow for simple coordination algorithms, while still retaining the flexibility of dynamic channel assignment.
In the next two sections, we describe two hybrid CA schemes.

4.4.1 Link Layer Protocols for Radio Assignment (LLP)

In **[50][61]**, an innovative link layer radio assignment algorithm is proposed that categorizes available radios into fixed and switchable radios. Fixed radios are assigned, for long time intervals, specific fixed channels, which can be different for different nodes. On the other hand, switchable radios can be switched over short time scales among the non-fixed channels based on the amount of data traffic. By distributing fixed radios of different nodes on different channels, all channels can be used, while the switchable radio can be used to maintain connectivity. **Figure 23** illustrates how the protocol works where node A, B and C's fixed radios are assigned channel 1, 2 and 3 respectively. Now assume node A wishes to exchange data with nodes B and C. When A has to send a packet to B, A switches its switchable radio to channel 2 and transmits the packet. Since B is always listening to channel 2 with its fixed radio, B can receive the transmission of A. Now if B has to send a packet back to A, B switches its switchable radio to channel 1 and transmits the packet. Since A is listening to channel 1 with its fixed radio, the packet from B can be received. Similarly, if A has to subsequently send a packet to C, it switches to channel 3 and sends the packet. Note that B and C can at any time send a packet to A on channel 1. Thus, there is no need for coordination among A, B, and C on when to schedule transmissions.

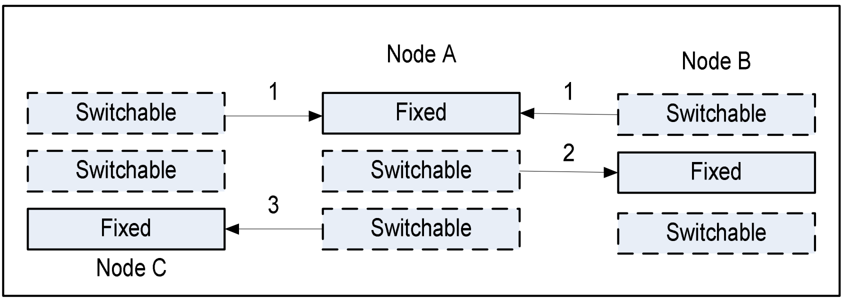

Figure 23 - Hybrid protocol operation

Two coordination protocols are proposed in **[50]** to decide which channels should be assigned to the fixed radio, and to manage communication between the nodes. The first one is the use of a well-known function that generates a hash based on the node identifier to select the channel to assign to the fixed radio. Neighbors of this node can use the same function to compute the channel to use to communicate with this node. The second strategy is the explicit exchange of "Hello" packets that contain information about the fixed channel used by a node. Based on the received "Hello" packets, nodes may (with some probability, to avoid oscillations) choose to set their fixed channel to an unused or a lightly loaded channel.

In **[61]**, the authors propose a hybrid CA scheme based on the second coordination protocol which works as follows. Periodically, each node broadcasts a "Hello" packet on every channel. The hello packet contains the fixed channel being used by the node, and its current *NeighborTable*. When a node receives a hello packet from a neighbor, it updates its *NeighborTable* with the fixed channel of that neighbor. The *ChannelUsageList* is updated using the *NeighborTable* of its neighbor. Updating *ChannelUsageList* with each neighbor's *NeighborTable* ensures that *ChannelUsageList* will contain two-hop channel usage information. An entry which has not been updated for a specified maximum lifetime is removed. This ensures that stale entries of nodes that have moved away are removed from the *NeighborTable* and *ChannelUsageList*.

The main benefit of this hybrid protocol is that it is fairly insensitive to radio switching delay, however the assignment of fixed channels has to be carefully balanced in order to achieve good performance.

4.4.2 Interference-Aware Channel Assignment (BFS-CA)

The channel assignment problem in WMNs in the presence of interference from co-located wireless networks is addressed in **[47]**. The authors propose a dynamic, centralized, interference-aware algorithm aimed at improving the capacity of the WMN backbone and at minimizing interference. This algorithm is based on an extension to the conflict graph concept called the multi-radio conflict graph (MCG) where the vertices in the MCG represent edges between radios instead of edges between mesh routers. To compensate for the drawbacks of a dynamic network topology, the proposed solution assigns one radio on each node to operate on a default common channel throughout the network. This strategy ensures a common network connectivity graph, provides alternate fallback routes and avoids flow disruption by traffic redirection over a default channel. This scheme computes interference and bandwidth estimates based on the number of *interfering radios*, where an interfering radio is a simultaneously operating radio that is *visible* to a mesh router but is external to its network. Moreover measurement of just the number of interfering radios is considered not sufficient because it does not indicate the amount of traffic generated by the interfering radios. For instance two channels could have the same number of interfering radios but one channel may be heavily utilized by the interfering radios compared to the other. Therefore each mesh router also estimated the bandwidth utilized by the interfering radios. Each mesh router then derives two separate channel rankings. The first ranking is according to increasing number of interfering radios. The second ranking is according to increasing channel utilization. The mesh router then merges the two rankings by taking the average of the individual ranks. The resulting ranking is used by the CA scheme. This scheme, called the *Breadth First Search Channel Assignment* (*BFS-CA*) algorithm, uses a breadth first search to assign channels to the radios. The search begins with links emanating from the gateway node; while links fanning outward toward the edge of the network are given lower priority.

The default channel is chosen such that its use in the mesh network minimizes interference between the mesh network and collocated wireless networks. This is achieved by computing the rank R_c of a channel as follows:

$$R_c = \frac{\sum_{i=1}^{n} Rank_c^i}{n} \qquad \text{Eqn. 6}$$

Where n is the number of routers in the mesh and $Rank_c^i$ is the rank of channel c at router i. The default channel is then chosen as the channel with the least R_c value.

The assignment of non default channels, on the other hand, is based on the information in the MCG where it is associated to every vertex its corresponding link delay value (computed based on the Expected Transmission Time or ETT **[9]**). The CA scheme also associated with each vertex a channel ranking derived by taking the average of the individual channel rankings of the two radios that make up the vertex. The average is important because the assignment of a channel to a vertex in the MCG should take into account the preferences of both end-point radios that make up the vertex.

Once channel assignments are decided, the mesh routers are notified to re-assign their radios to the chosen channels as described in details in **[47]**.

To adapt to the changing interference characteristics, the CA periodically re-assigns channels. The periodicity depends ultimately on how frequently interference levels in the mesh network are expected to change.

4.5 Comparisons of CA Schemes

The most important features of the existing CA algorithms for WMNs are summarized in **Table 4**. The key issues are: connectivity, topology control, interference minimization and traffic pattern. C-HYA is a traffic-aware CA scheme. While its distributed version, D-HYA, alleviates the effect of link revisits, stringent restrictions were imposed on the topology of the mesh network, thereby failing to leverage the advantages of multi-path routing in a mesh scenario. MesTiC is a fixed, centralized scheme that in the same way as C-HYA and D-HYA takes into account traffic load information, at the same time does not impose any strong constraints on the topology. Moreover, it is a greedy algorithm which does not suffer from ripple effects and ensures connectivity via a default radio. While the goal of LLP and CLICA was to minimize interference, the effect of traffic patterns on interference and thus on the CA scheme, was not taken into account. The effect of traffic in BFS-CA was considered, but only for traffic emanating from external wireless networks. From another perspective, some algorithms, such as CLICA, MICA and TiMesh considered topology control, which incurs overheads in the channel assignment algorithm but alleviates the need for an additional radio tuned to a common channel; while others (e.g. BFS-CA, MesTiC) assume default connectivity using a separate common channel on a separate radio.

Table 4 - Comparative Study of the salient features of channel assignment schemes

Property		Switching time	Connectivity	Ripple effect	Interference model	Traffic pattern	Topology control	Control philosophy
Fixed CA	CCA	No switching required	Ensured by the CA scheme	No	NA	Not considered	Fixed	NA
	C-HYA [15]	No switching required	Ensured by the CA scheme	Yes	Protocol model	Considered	Fixed	Centralized
	CLICA [43]	No switching required	Ensured by the CA scheme	No	Protocol model	Not considered	CA scheme defines the topology	Centralized
	MICA [52]	No switching required by both schemes	Ensured by the CA schemes	- Yes - No	Protocol but can be extended to physical	Can be considered	CA schemes define the topology	- Centralized - Centralized/ distributed
	MesTiC [51]	No switching required	Ensured by default radio	No	Protocol model	Considered	Fixed	Centralized
	TiMesh [56]	No switching required	Ensured by the CA scheme	No	Protocol model	Considered	CA scheme defines the topology	Distributed
Hybrid CA	LLP [50]	switching overhead involved	Ensured by channel switching	No	Protocol model	Considered from external radios	Dynamically chaging	Distributed
	BFS-CA [47]	Infrequent switching	Ensured by default radio	No	Trace driven	Not considered	Fixed	Centralized
Dynamic CA	D-HYA [10]	Infrequent switching	Ensured by the CA scheme	No	Trace driven	Considered	No, topology is defined by the routing tree	Distributed

Chapter 5

MesTiC: A Novel Channel Assignment Scheme

5.1 Introduction

As highlighted earlier, the central goal of channel assignment for multi-radio mesh networks is to improve the aggregate throughput of the network, taking into account the effects of traffic and interference patterns, as well maintaining topological connectivity. Based on our observations of the impact of traffic patterns and network connectivity on the performance of a WMN, below we propose an innovative scheme called *MesTiC*, which stands for *Mes*h based *T*raffic and *i*nterference aware *C*hannel assignment scheme.

As described in the previous chapter, the channel assignment problem has been studied by several researchers **[10][15][43][47][50][52][56]**. However only few of these algorithms **[10][15][56]** considered the traffic pattern which is considered very important criterion for the accuracy of a CA scheme. C-Hyacinth presented in **[15]** takes into consideration the traffic properties by incorporating a routing algorithm however it suffers from the ripple effect problem. Its distributed version D-Hyacinth **[10]** on the other hand, eliminates the ripple effect problem but the tree-topology constraint of the scheme poses a potential hindrance in leveraging multi-path routing.

MesTiC is a fixed, centralized scheme that in the same way as C-HYA and D-HYA takes into account traffic load information, at the same time does not impose any strong constraints on the topology. Moreover, it is a greedy algorithm which does not suffer from ripple effects and ensures connectivity via a default radio.

5.2 MesTiC Properties and features

MesTiC has the following important features:

- It is a fixed, rank-based, polynomial time greedy algorithm for centralized channel assignment, which visits every node once, thereby mitigating any *ripple effect;*
- The *rank* of each node is computed on the basis of its link traffic characteristics, topological properties and number of NICs on a node;
- Topological connectivity is ensured by a common default channel deployed on a separate radio on each node, which can also be used for network management purposes.

Fixed schemes alleviate the need for channel switching, especially when switching delays are large as is the case with the current 802.11 hardware. In addition, *MesTiC* is rank-based, which gives the nodes that are expected to carry heavy loads, more flexibility in assigning channels. Finally the use of a common default channel prevents flow disruption.

It should also be mentioned that the proposed scheme has been designed for a mesh network with a single gateway node, but it could be easily extended to multiple gateways with minor modifications to the basic scheme.

5.3 Proposed algorithm

The central idea behind *MesTiC* is to assign channels to the radios of a mesh node based on ranks assigned a priori to the nodes. The *rank* of a node, *Rank(node),* determines its priority in assigning channels to the links emanating from it. The rank encompasses the dynamics of channel assignment and is computed on the basis of three factors:

a) The aggregate traffic at a node based on the offered load of the mesh network as computed in **[15]**.
b) The distance of the node, measured as the minimum number of hops from the gateway node.
c) The number of radio interfaces available on a node.

Note that the gateway node is assigned the highest rank as it is expected to carry the most traffic. The rank for the remaining nodes is given by:

$$Rank(node) = \frac{Aggregate\,Traffic(node)}{\min hops\ \ from\,the\ gateway\ (node) * number\ of\ \ radios\ (node)} \quad \text{Eqn. 7}$$

Clearly, the aggregate traffic flowing through a mesh node has an impact on the channel assignment strategy. The rationale behind this observation stems from the fact that if a node relays more traffic, assigning it a channel of least interference will increase the network throughput. Thus, aggregate traffic in the numerator in **Eqn. 7** increases the rank of a node with its traffic. In addition, due to the hierarchical nature of a mesh topology, the nodes nearest to the gateway should have a higher preference (rank) in channel assignment, as they are more likely to carry more traffic. At the same time, the number of radios on a node gives flexibility in channel assignments and should inversely affect its priority (i.e. the lower the number of radios, the higher the priority in channel assignment). The aggregate traffic (total traffic traversing a node) is a key factor in computing the rank of the node. Such measure is subject to temporal variability due to the randomness of the wireless channel, routing protocols and application layer traffic profiles. We envisage that the traffic characterizations aggregated from a large number of network flows change over longer periods of time, whereas *MesTiC* can re-assign channels based on new traffic characteristics.

Once the rank of each node has been computed, the algorithm traverses the mesh network in decreasing order of *Rank(node)*, assigning channels to the radios as described in **Figure 24**. In this figure, the algorithm starts by calculating a fixed rank for every node

(I), and then every node is visited in decreasing order (II). If two nodes have already been assigned at least one common channel, by default there is a link between these nodes (II.1). If not, then for every possible unassigned link, the one that carries the higher traffic is assigned first (II.2) in the following manner: if the node visited still has an assigned radio, the least used channel is assigned to one of its free radios and a link is established with its neighbor (II.2.a). Otherwise, if all the visited node's radios have already been assigned, then the least used channel among those already assigned to its radios is assigned to the link (II.2.b). Following **Figure 24,** is the pseudo-code of MesTiC.

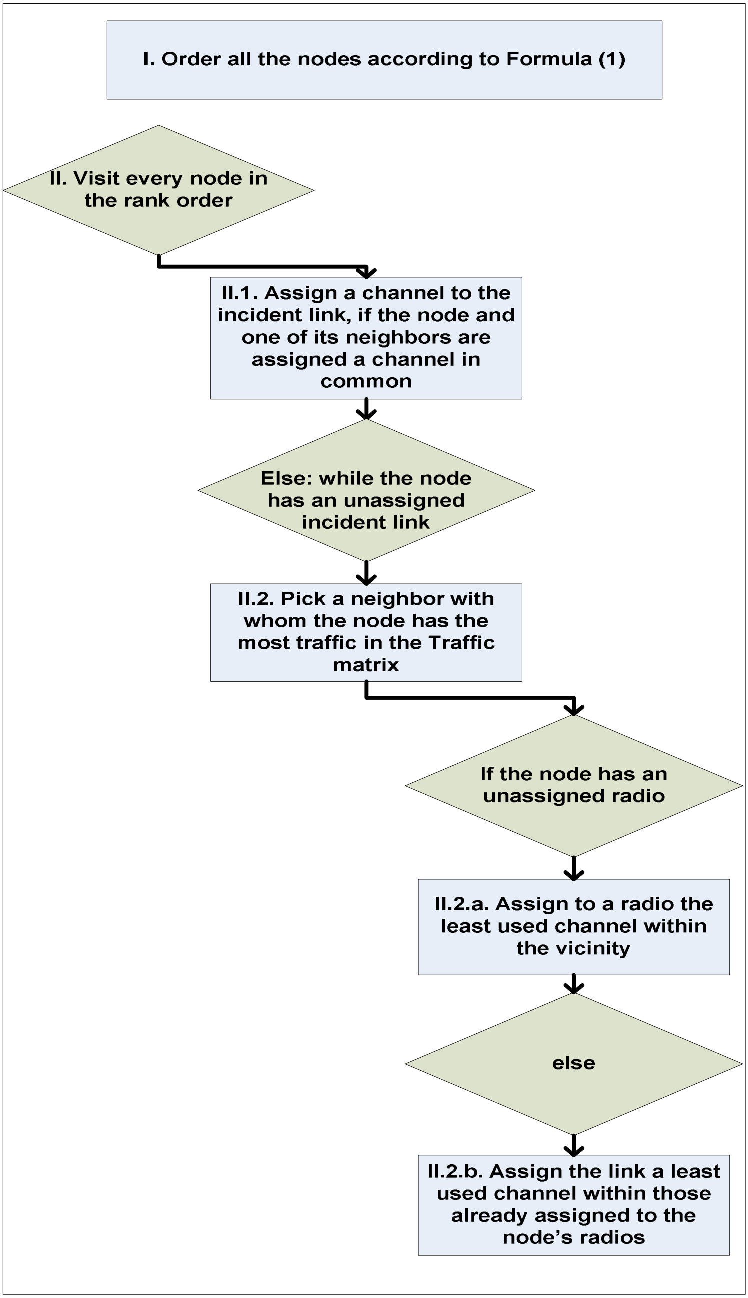

Figure 24 - Flow diagram of MesTiC

```
Input:
    Connectivity graph
    Traffic matrix
    Multi-radio conflict graph
    Number of radios at every node
    Number of non-overlapping channels

Ranking function:

Output:
    The assignment of channels to radios

Pseudo-code:
/* MesTiC visits every node based on its rank, the higher the Rank, the earlier a node is visited */
For each node V in the Rank order
/* For every link in the connectivity graph a channel has to be assigned to the link between the two nodes which both have a radio assigned a common channel */
For each unassigned incident link (V,W)
        If both V and W have a radio with a common channel C
                Assign C to link (V,W)
                Update the interference matrix
/* Now for every link not assigned a channel yet, MeTtiC will pick the link estimated to carry higher traffic first */
While V has an unassigned incident link
        Pick a neighbor W with whom V has the highest traffic in the Traffic matrix
/* If the visited node V has a radio still uncolored then its radio is either assigned a least used channel among those previously assigned to its neighbor W  if W has assigned all its radios. If not, both V's and W's unassigned radio are assigned the least used channel in the vicinity*/
        If V has an unassigned radio
                If W has all its radios assigned
                        Pick the least used channel C among those assigned to the radios at W
                        Assign C to a radio at V
                        Assign C to the link (V,W)
                        Update the interference matrix
                Else if W still has an unassigned radio
                        Pick the least used channel C within the vicinity
                        Assign C to a radio at V
                        Assign C to a radio at W
                        Assign C to the link (V,W)
                        Update the interference matrix
/* Similarly If all V's radios are already assigned a channel and W still has an unassigned radio, then W is assigned from among the radios already assigned to V */
        Else if V has all its radios assigned
                If a radio at W is still unassigned
                        Pick the least used channel C among those assigned to the radios at V
                        Assign C to a radio at W
                        Assign C to the link (V,W)
                        Update the interference matrix
/* Note that If the radios of both V and W are all assigned channels then MesTiC will not do anything because connectivity is already ensured with a radio dedicated to a common channel*/

For each node V in the network
    For each unassigned radio
        Pick a neighbor W with whom V has the highest traffic in the Traffic matrix
        Pick the least used channel C among those assigned to the radios at W
        Assign C to a radio at V
        Assign C to the link (V,W)
        Update the interference matrix
```

We illustrate the working principle of *MesTiC* by considering a simple example in **Figure 25(a)** where the input connectivity graph and estimated link traffic (estimated traffic between a node and its neighbors) are shown. In addition the network is configured with 3 channels and 2 interfaces per node. Assuming that node **b** is the gateway node, the rank of the remaining nodes, in decreasing order, is **d**, **a**, **c**. The algorithm starts by visiting node **b** first, assigning channel **C1** to the link between **b-a** (which carries the highest traffic of 120), and then moves on to assign channel **C2** to the link **b-d**. Now, while assigning a channel to link **b-c**, it has to choose between **C1** and **C2**. However, as **C1** carries more traffic than **C2**, it assigns **C2** to link **b-c**. Similarly, at node **d**, it assigns a previously unassigned channel **C3** to the link **d-c,** and as **C3** carries less traffic than **C2** (90 + 80 =170) or C1 (120), it assigns **C3** to the link **d-a**. The algorithm proceeds until all links and radios are assigned channels as shown in **Figure 25 (b)**

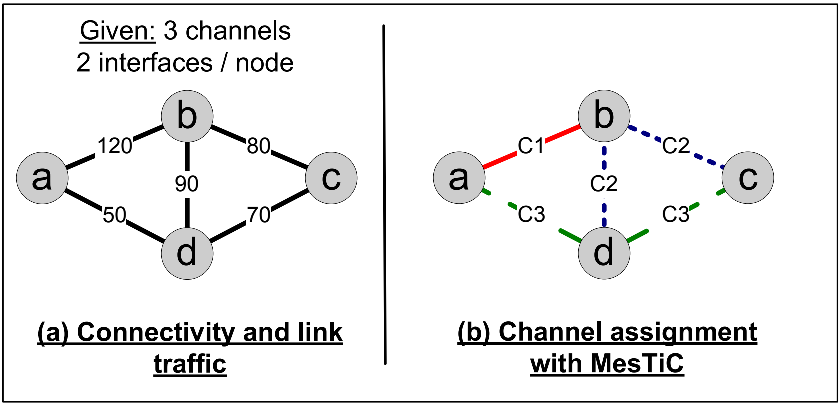

Figure 25 – Example illustrating how MesTiC works

In this manner, *MesTiC* assigns channels to the radio interfaces of the nodes in a WMN, while the connectivity of the network is ensured through a separate radio on a default channel. The cost dynamics of 802.11 based hardware and the availability of 12 non-overlapping channels in the IEEE 802.11a standard make a default connectivity scheme feasible under current scenarios for community mesh networks.

5.4 Performance Study

In this section, we study the performance of the proposed channel assignment scheme, *MesTiC,* in terms of overall throughput on a wireless mesh network. We present the details of the simulation platform and results of a comparison with the traffic-aware centralized scheme based on the *Hyacinth architecture* **[15]**, C-HYA.

In order to build a common platform for a comparative study, we developed our simulation on a modified version of ns-2 **[29]** software, which incorporates support for multiple radios and configurable routing protocols, such as dynamic source routing (DSR) and ad-hoc on demand distance vector routing (AODV). The simulation experiments were performed on a 5x5 grid topology[4] where each node could potentially communicate with 4 neighbors. With a randomly generated traffic profile, the traffic between any source-destination pair is chosen in the range [0-3] Mbps. Ns-2 was configured to emulate the traffic profile by running constant bit rate (CBR) UDP-flows. The conflict graph was created based on the interference-to-communication ratio set to 2, and the experiments reported in this paper were performed based on the DSR routing protocol. As mentioned earlier, the centralized CA scheme based on C-HYA, accounts for the link traffic matrix in their channel assignment algorithm. Moreover, their simulation analysis is based on a similar ns-2 based platform with similar settings. Thus, in this paper we report our results based on comparisons with C-HYA. However, our simulation platform can be easily extended to incorporate different routing and channel assignment schemes for mesh networks.

The WMN was simulated on ns-2 with the number of radios on each node set to 3, with 12 non-overlapping channels. The simulation was performed for 100 seconds for a given set of traffic profiles and ns-2 was configured to report the aggregate throughput obtained in the

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[4] Although simulations can be conducted on larger networks, we report on a 25-node mesh network, as community mesh networks are envisaged to contain typically 25-30 mesh routers.

network. The experiments were conducted on the mesh network topology with channel assignments generated by *MesTiC*, and repeated for the channel assignments generated by C-HYA. **Figure 26** reports the dynamics of the network in terms of aggregate throughput. The figure highlights that the simulation stabilizes around 40 seconds from the start of the simulation run, after which *MesTiC* reports a sustained higher aggregate throughput for the mesh network.

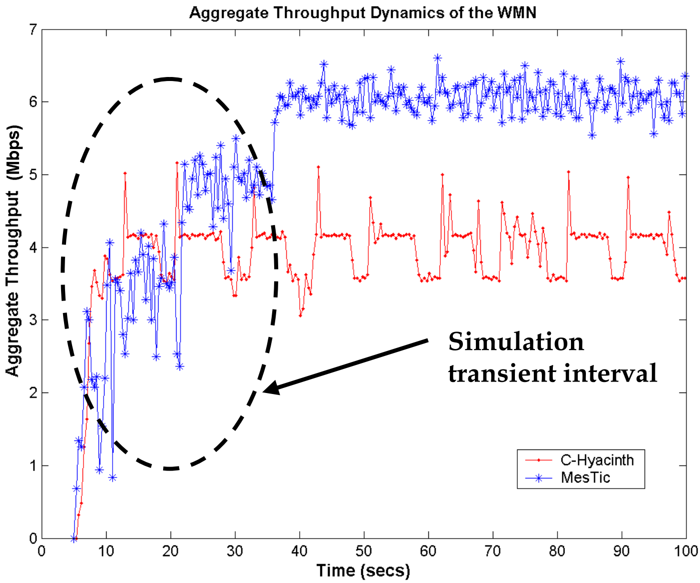


Figure 26 – Aggregate throughput dynamics of *MesTiC* vs. C-HYA

Similarly, at the stable region, with *MesTiC* there is enough bandwidth for a larger number of flows in the system, with an average value of 14 flows against an average of 9 flows in C-HYA **[15]**. Our extensive simulation results (not reported due to space constraints) conclude that *MesTiC* provides a significant improvement in aggregate throughput over C-HYA for various topologies and traffic profiles **[55]**.

Similarly, at the stable region, *MesTiC* supports larger number of active flows in the system, with an average value of 14 flows against an average of 9 flows in C-HYA, as seen from **Figure 27**. Based on these observations, we conclude that *MesTiC* gives significant improvement in aggregate throughput over C-HYA while sustaining more than 1.5 times the number of active flows in the network.

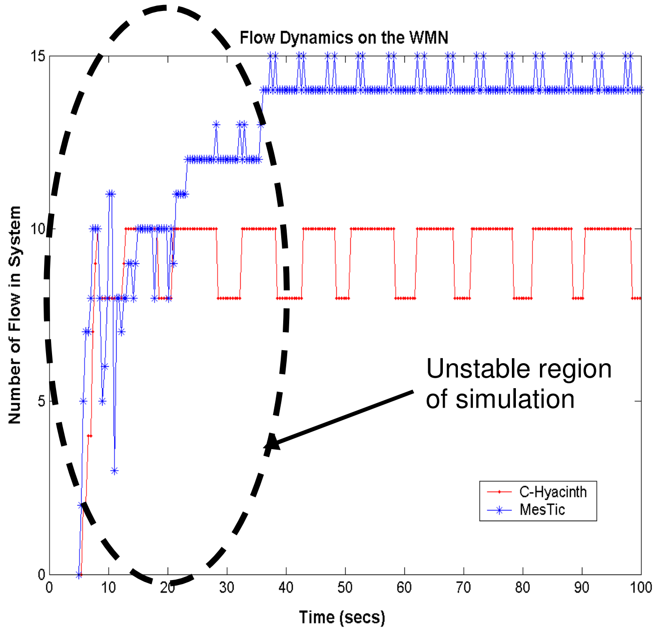


Figure 27 – Flow dynamics of *MesTiC* vs. C-HYA

In another experiment, we have measured throughput for different network topologies for both MesTiC and Hyacinth as illustrated in **Figure 28**. We observe that for seven different topologies MesTiC outperforms Hyacinth sometimes very significantly as in topology number 6 (5 times higher throughput).

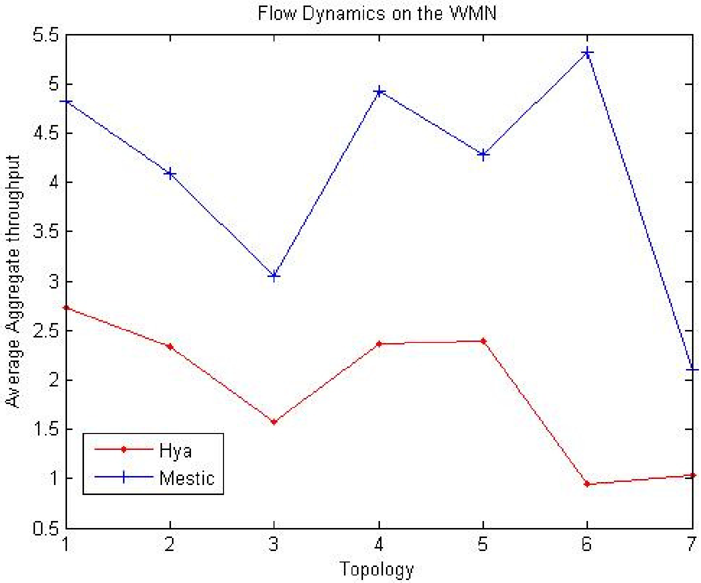


Figure 28 – Aggregate throughput versus network topologies – comparison between *MesTiC* and Hyacinth

Note that although the simulation experiments were performed with three radios per node, *MesTiC* essentially operates its channel assignment scheme on two radios, with the third configured on a default channel for connectivity. Thus, even with a lower degree of freedom in terms of radio flexibility, *MesTiC* was able to improve the overall network performance in terms of aggregate throughput.

Chapter 6

Routing, Interface Assignment and Related Cross-layer Issues in Multi-radio Wireless Mesh Networks

6.1 Introduction

Wireless Mesh Networks (WMNs) **[2][3]** are a network technology currently under development to provide end users with broadband wireless connectivity. In such systems, each mobile terminal owned by an end user, called Mesh Client (MC), is linked through a single radio hop to a Mesh Router (MR), a fixed infrastructure node. All the MRs are, in turn, interconnected to each other in a multi-hop fashion so as to form what is referred to as the network backbone. This kind of structure is easy to install since several low cost nodes can be added to improve the backbone connectivity. Moreover, MRs do not need to be battery-powered, since they can be easily placed in correspondence with a power outlet. Finally, the all-wireless structure does not require cable deployment, thus making WMNs appealing for connecting both vast rural regions and crowded urban areas where cable deployment is not cost-effective.

In general, to attach the WMN to the Internet, some special MRs, called Mesh Access Points (MAPs), are equipped with wired connections and therefore can take the role of Internet gateways. Therefore, they usually have better computational capabilities than the other MRs, which work as simple relay nodes; for this reason, it is sensible to think of MAPs as the centers of the network management operations. On the other hand, this determines a higher cost of such nodes and therefore their number is reasonably limited. In most cases, just one or two MAPs are used; this will be also the case for the examples discussed throughout this chapter.

Since the communication between a MC and its reference MR is single-hop, most of the challenges of the WMN management are at the backbone level. This part of the network is similar to other kinds of wireless multi-hop networks, such as Ad Hoc and Sensor Networks. Differently from them, however, the main problems in the inter-MR communication do not relate to mobility and energy saving problems, which are avoided due to the assumptions made above. Instead, other major technical issues arise especially when the network size grows (scalability problem). Among them, one of the most challenging is represented by routing **[62]**. In fact, the performance of WMNs in this sense is, similar to any other multi-hop network, limited by wireless interference. The placement of additional relay nodes yet mitigates the problem, since it gives additional opportunities for traffic forwarding; however, the performance improvement is often limited and does not linearly scale with the number of nodes. Thus, the design of efficient routing algorithms plays a key role among WMN research topics.

Moreover, WMN solutions are often thought as utilizing existing standards, such as IEEE 802.11 **[63]**, without any modification. On the one hand, this enables to use off-the-shelf network cards for the wireless mesh nodes, which keeps the infrastructure costs low. On the other hand, a straightforward adaptation of existing technologies, without taking into account the specific purposes of WMNs, will result in an inefficient management. In fact, these standards are commonly used in a different context; in particular, IEEE 802.11 is used almost exclusively in a single-hop fashion, whereas its collision avoidance mechanism is known to suffer from several problems in multi-hop scenarios, such as the decrease of network parallelism due to the exposed terminal problem **[64]**.

In general, a compromise shall be sought between this inefficient usage and the design of entirely new protocols. A possible solution, in this sense, can be the idea of finding new applications of possibilities already envisioned by the protocol but scarcely utilized in practice. An example where this concept can be applied concerns the possibility of exploiting multiple portions of the available wireless spectrum. For example, the IEEE 802.11a/b/g specifications provide multiple channels, some of which can be regarded, with a good degree of approximation, as non-overlapping (specifically, 3 channels for IEEE 802.11b/g and and 12 channels for IEEE 802.11a).

There are two possible approaches to deal with multiple channels. In the majority of the literature, it is assumed that they are perfectly non-overlapping; in this chapter we will consider this case only. There is also an interesting line of research, discussed in more detail in the following, where partial overlap of the channel is taken into account with the aim to exploit it **[65]**. However, this approach requires to entirely reformulate the routing problem. The case of perfect non-overlap is simpler, since it allows to regard the routing problem as a multi-commodity allocation or a graph coloring issue. Notice that models for studying networks exploiting frequency diversity date back prior to the success of wireless networks, since they were already investigated, e.g., for optical fiber networks **[66]**.

Although multiple channels can be introduced, and actually they are already available in existing standards, terminals are typically configured to operate on a single radio channel: in fact, in a single-hop scenario, this frequency diversity is mostly introduced to avoid collisions from different networks. In a WMN case, instead, this feature can be used to increase the number of transmissions which can be exchanged within a neighborhood. This imposes to differently tune the Network Interface Cards (NICs) of the involved MRs.

The opportunity given by multiple non-overlapping channels is better exploited if more than one NIC is available at a single node. In this way, one can avoid, or at least mitigate, the need for dynamically tuning to a common frequency the interfaces of MRs which are meant to communicate with each other. As will be discussed in the following, fast frequency-switching transceivers are in fact not always feasible. Actually, the cost decrease for commodity hardware makes multi-interface terminals economically sustainable, even though in general it is not possible, for many practical reasons to provide each node with a single NIC per every available channel. However, as shown in **[67]**, the largest advantage in terms of network capacity, intended as traffic which can be transmitted over the network in a collision-free manner, is present already for a limited (though larger than one) number of NICs per node. The relative performance improvement when the number of interfaces approaches the number of available channels becomes marginal.

Thus, we will focus on multi-radio, i.e., multi-channel *and* multi-interface, WMNs. The investigations carried out in the following concern the strategy to determine the channels to which the NICs of every node shall be tuned, which can be regarded as a multiple allocation optimization problem, and how this affects routing strategies over the WMN.

There is a two-fold relationship between the routing and the interface assignment problems. First, when the routing algorithm is applied, two nodes i and j can communicate, and therefore it is possible to route traffic through a network link from i to j, only if they share a common channel assigned to at least one of their NICs. Conversely, to be realized efficiently, the interface assignment should take into account the routing pattern of the network. In fact, since the use of different channels decreases not only the mutual interference but also the network connectivity, it should leave the possibility of connecting the nodes along the main traffic routes and possibly decreasing the number of interfering links.

Classic routing protocols for multi-hop networks **[7][8]** may be easily extended to support multiple interfaces at each node. However, those protocols typically select shortest-hop routes, which may not be suitable for multi-channel networks; as was noted in **[9]**, routing metrics based on hop count only should be integrated by also taking into account the network load. Moreover, longer paths may be preferable if they allow to decrease interference and increase transmission parallelism. At the same time, more bandwidth should be given to nodes that support higher traffic, i.e., channels assigned to these links should be shared among a fewer number of nodes. More in

general, the interface assignment strategy should be traffic-aware in the sense that it matches the distribution of traffic load in the mesh backbone.
For these reasons, in the following we will overview solutions presented in the literature and summarize basic criteria for routing and interface assignment in multi-radio WMNs, giving particular emphasis to the interaction between these two tightly related problems which can be efficiently managed with an adequate knowledge of the network traffic. In particular, we will discuss how to exploit the knowledge of the load on the links **[68]** and how to estimate it **[15]** and we give practical examples of application.

6.2 Background

The problem of frequency selection in a multi-channel networks inherits some approaches and methodologies, as well as the idea of using graph theory, from the problem of assigning channels in an optical network **[66]**. In this case however, the edges are fixed, since they correspond to a cabled connection between nodes. Thus, that topic resembles more closely the classic graph coloring problem. In the wireless case instead, the possibility of managing not only the frequency on which a connection is tuned to, but also the existence of the edge itself, requires an extended treatment. In this sense, another related problem is the frequency re-use planning in cellular networks, where graph representations have been also used **[44]**.
An interesting line of research dealing with multi-channel WMNs is based on the observation that most of the available channels are indeed partially overlapping. This, instead of being considered harmful, could be turned in an opportunity to achieve connectivity (though an imperfect one) in a less interference-prone way. It is also possible to have a fully connected network and decrease interference while using a single NIC for all nodes.
Such an approach, investigated for example in **[65]** and **[69]**, though very promising, implies to entirely re-formulate the network management, and is therefore out of the scope of the present chapter, where we deal instead with adapting existing routing approaches to

the multi-channel case, and we consider different channels as perfectly separate in frequency.

Approaches for multiple orthogonal resource allocation mainly deal with Time-Division Multiple Access (TDMA), as for instance done by the earlier work reported in **[70]**. In fact, this paper proposes to introduce multiple time slots, with a special control slot where the users can rendezvous to negotiate the access in a distributed manner. However, this case can be easily extended, with few modification, to a Frequency-Division Multiple Access (FDMA) case. For example, **[50]** reports a description of the issues which need to be faced when dealing with multi-radio multi-hop networks and proposes a similar strategy where a common control channel is used to coordinate a distributed assignment of multiple channels.

Due to the similarity between FDMA and TDMA multiplexing, some papers jointly investigate, together with routing, *both* channel assignment and packet scheduling over time **[71][72][73]**. In **[71]**, the goal of finding a joint channel assignment, routing and scheduling technique which optimizes throughput of the MCs is studied. The problem is formulated as a linear programming (LP) framework. The approach used by this paper for tackling multi-channel networks is similar to the one adopted in **[35]** where an analogous optimization framework is extended to the multi-channel case. Under specific interference assumptions, necessary and sufficient conditions are described, under which collision free link schedule can be obtained. In particular, as done by most of the papers related to this topic, the protocol interference model is used, as introduced in **[74]**. This dictates to model interference through collisions, and can be equivalently mapped through a so-called *conflict graph*. Actually, such a model is not perfect, since it implies some approximations in modeling interference as pointed out, for example, in **[75]**. Nevertheless, it is quite simple and is, in fact, often utilized by those papers modeling channel assignment through LP frameworks. However, since the problem of achieving the optimal allocation of scheduling times over several frequencies is shown to be NP-hard, the final solution proposed by **[71]** is an efficient heuristic approach, which can be proved to be at most a given factor away from the optimum.

In **[73]** a similar problem of joint routing, channel assignment and scheduling is investigated, where the goal is again on throughput maximization. Interference is again modeled through a K-dimensional version of the protocol interference model. After that, the feasibility of a schedule is verified by means of a sufficient condition, that is considering whether the conflict graph can be properly colored, by using as many colors as TDMA slots so that conflicting edges are differently colored (i.e., they are active over different time instants).
Another similar optimization is also considered in **[72]**; to deal with the high complexity of the resulting problem, the solution is sought through Simulated Annealing **[76]**, which is an evolutionary technique for LP problems offering a good trade-off between accuracy and computational complexity. The solution operates in two steps, i.e., the routing/channel assignment problem is split between two parts. First, routing is solved by means of a shortest-path strategy. Then, a simulated annealing algorithm tries to optimize the assignment of the NICs. Since this optimization technique needs a starting solution as input, channels are initially assigned randomly, provided that they satisfy interference constraints. Subsequently, the system evolves according to the simulated annealing procedure, which seeks to maximize the throughput.
An even simpler solution to overcome the NP-completeness of the problem is to propose efficient heuristic strategies. This methodology is adopted for example in **[67][43][51]**. In spite of their simplicity, these strategies can achieve good performance, especially in light of the fact that they do not need particularly complex computations. It is worth noting that, for the most, they employ the conflict graph model to represent interference, and therefore the proposed heuristic is related to graph coloring considerations.
All these approaches refer to a centralized solution, hence they assume the availability of a central controller (e.g., located in one of the MAPs) which takes care of solving the allocation problem and signalling the obtained solution to the other nodes. Instead, **[68]** proposes a decentralized maximization problem, where the interference constraints refer only to neighboring transmissions. An extended version, proposed in **[69]** by the same authors, investigates the case of partially non-orthogonal channels. This is done based on a technique in

which a channel weighing matrix is calculated. An original aspect of this approach is that, even though interference is still based on the protocol model, or, equivalently, on conflict graphs, instead of simply preventing collision from arising at all, it is taken into account how they affect (i.e., degrade) the capacity of the links, which allows for a more tunable problem characterization.

6.3 Thoughts for practitioners

In this section, we review some practical criteria which have been proposed to determine interface assignment in multi-radio WMNs. The technical contributions in this field are very heterogeneous for what concerns the depth of theoretical investigations. Thus, we try to discuss relevant points of interest which distinguish the existing proposals and we identify practical general criteria. The reported references can give further details on these topics.

6.3.1 Centralized vs. distributed assignment

As any other resource allocation strategy, interface assignment schemes can be generally realized in centralized or distributed fashion. In the centralized schemes the channels are assigned by a central controller, usually located in one of the MAPs. In the distributed schemes, instead, each node assigns channels to its interfaces in a more loosely coordinated fashion, since no global network knowledge is available. Thus, the decision is based on neighborhood information. The complexity of this latter case is much lower, at the cost of lower efficiency. Especially, the effectiveness of distributed strategy is critical in relationship with routing awareness, which demands for network-wise knowledge.

In general, most of the techniques reviewed in this chapter are directly applicable within a centralized management. Extensions to distributed management are also possible, but they usually require information exchange in order to acquire some global knowledge at each node. Similar techniques to obtain a distributed implementation of routing and interface-assignment can be found for example in **[70][67][10]**.

6.3.2 Heuristic vs. optimization strategies

As pointed out previously, the joint routing and interface assignment problem can be investigated through a proper optimization framework, but the resulting complexity is very high. It is then possible to draw another classification of possible approaches, even though it does not relate to design aspects, but rather on practical methodologies to solve the problem. In fact, in the literature several papers investigate the problem through LP approaches **[71][35][73][68]**, but also many contributions proposing a heuristic approach **[50][43][10][51]**.

From a general point of view, these two choices are extreme points of a trade-off. LP solutions offer better accuracy, heuristics have lower complexity. Intermediate solutions are also possible, such as meta-heuristic techniques like Simulated Annealing, as proposed in **[72]**. However, we remark that these two possibilities are not perfectly separated. In fact, though LP approaches are usually limited to smaller WMNs and suffer from scalability problems, they can shed light on heuristic techniques in a more rigorous and appropriate manner. As a matter of fact, the aforementioned papers which give an LP formalization also investigate heuristic criteria to solve the problem inspired by the theoretical findings.

6.4 The gateway bottleneck

A practical criterion to assign channels to interfaces, useful especially for heuristic procedures, is to consider the MAPs at first, since during the execution of an algorithm the first nodes to receive an assignment can usually select the frequencies in a less constrained manner. In **[77]**, where many inefficiencies possibly arising in WMNs are described, it was observed that the most congested nodes are likely to be the MAPs, where all the routes converge, a property referred to as *gateway bottleneck*. Also, the bottleneck is particularly limiting if a single gateway is present in the network; hence, it is suggested to always activate multiple MAPs (of course, this has beneficial effects not only in terms of network capacity, but also, e.g., in case of failure).

This implies that such nodes should be the ones where frequency diversity can be applied achieving the highest benefit. Especially if a single MAP is present, we could state a "rule of thumbs" of starting the channel assignment algorithm from it. Note also that in this case the property can be generalized, to some extent, by saying that the closer (in terms of number of hops) is a node to the MAP, the more critical can it be in terms of congestion. This is especially true for the node with the best connectivity to the gateway (e.g., in terms of highest rate, lowest interference, or both) among the neighbors of the gateway itself.
Actually, this strongly depends on the network topology. If the gateway has a single neighbor, the gateway bottleneck is simply translated to this node. On the other hand, if the network has a star topology, with all non-MAP nodes being neighbors of the gateway with relatively similar connectivity, there is no bottleneck whatsoever, or at least, no more than what dictated by the MAC, since all multiple transmissions collide. However, in practical scenarios, the distance to the MAP in terms of number of hops can be a good heuristic weight to determine the priority in receiving a channel assignment. To some extent, this criterion is implicitly taken into account by certain existing heuristic algorithms **[43][51]**.

6.5 Notation and terminology

As done by many related contributions, we adopt in the following a graph-based representation of the WMN backbone. All terminals belonging to the backbone, i.e., all the MRs also including the MAPs, can be represented as *nodes* included in a set N . If two nodes can communicate, i.e., there exist conditions where they can exchange packets with sufficiently high success probability, we consider them as linked through a graph edge. This may require that all the other nodes in the backbone do not transmit, since the condition of successful transmission can be violated in the presence of interference from other nodes. For this reason, the existence of an edge is a necessary condition, but not a sufficient one, to have an error-free communication. In addition to the existence of an edge, also certain interference conditions must be verified, which may vary according to the interference model adopted. In this way, a notation is commonly achieved in many radio allocation problems, where the network is represented as a graph $\mathsf{G} = (\mathsf{N}, \mathsf{E})$, where the set $\mathsf{E} \subseteq \mathsf{N} \times \mathsf{N}$ contains the network edges. Note that, from the physical point of view, the edges in E should be *directed*. This means that, given $i, j \in \mathsf{N}$, $(i, j) \in \mathsf{E}$ does not necessarily imply $(j, i) \in \mathsf{E}$. Even though rarely taken into account, link asymmetry is very frequent in radio networks **[78]**. However, there are certain MAC protocols, most notably the IEEE 802.11 one, which explicitly assume the links to be bidirectional, e.g., for handshake exchange. In this case, it is implicitly assumed that non-symmetric edges are discarded from E. This is actually a non-trivial assumption, as argued in **[79]**, but we take it since both simple and also very common in the literature. In the following, we will therefore refer to this case and take edges as bidirectional. Most of the reasonings can however be easily extended to more general scenarios where directed links are present as well.

We observe that the terminology used throughout the literature concerning graph representation of the network is rather assorted: the existence of an edge from i to j is also sometimes referred to as "j is within communication range of i" or "node j can hear node i". Even though these descriptions are not rigorous from the propagation point of view, as the radio transmission involves more parameters than just distance, they are often adopted in the exposition and we sometimes will use them as well. Similarly, notice that "topology" is a term often used as a synonym of "graph", in particular channel assignment seen on graph representations is often referred to as "topology control" problem.

In channel assignment problems there is an additional requirement for network representation, i.e., to describe radio interfaces, and whether they are tuned on the same frequency, otherwise no communication can occur between them. Note that interference conditions are entirely orthogonal to this latter issue, i.e., in order to exchange packets, two nodes must at the same time meet the requirement of having a shared NIC allocation *and* interference free communication.

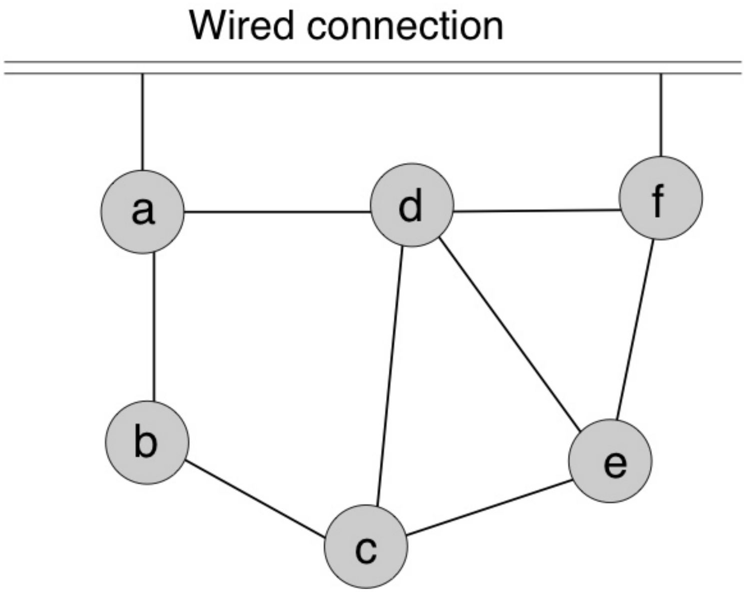


Figure 29 - Physical topology of a sample network.

Usually, to depict frequency allocation, the graph representation is split in two parts. In both of them, the set of nodes N is the same, but they differ in the set of the edges. In the first one, called *physical topology* $G_P = (N, E_P)$, the set of the edges consider all possible connections among nodes, with the only requirement of radio propagation. However, when the channels are assigned to the radio interfaces, it could happen that some nodes do not share a channel where to communicate, even though they are linked through an edge in E_P (and therefore they can hear each other). To represent the network connectivity after the channel assignments have been determined, a *logical topology* $G_L = (N, E_L)$ is employed, where E_L is determined by imposing the additional condition that only nodes sharing a common channel can be linked through an edge. Actually, since there may be nodes sharing *more than one channel*, there can also be *multiple edges* in E_L linking the same pair of nodes. In this sense, E_L is not strictly speaking a subset of E_P since the channel graph may contain more than one element corresponding to the same edge in the physical topology. We also remark that the symmetry considerations previously made apply to both physical and logical topologies, since the property of sharing a channel assignment on a network interface is a symmetric property for any pair of nodes.

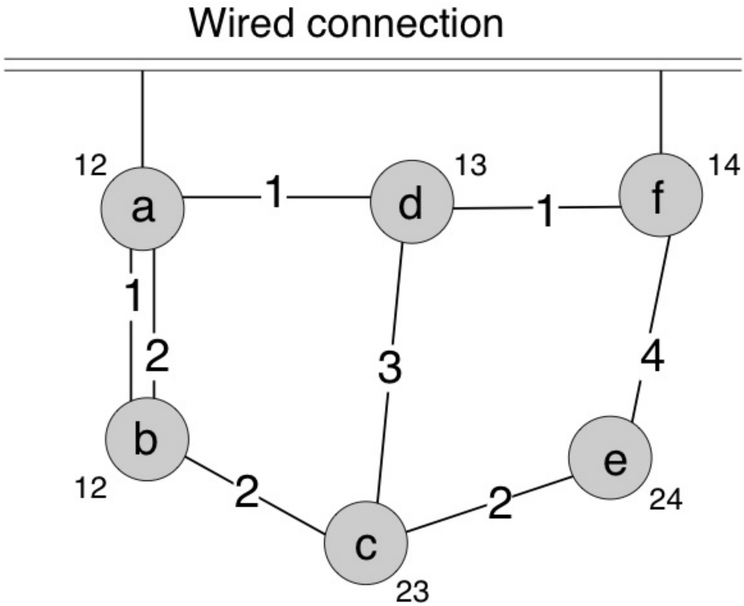


Figure 30 - Logical topology of a sample network.

Moreover, we need a notation to specifically represent the channel assignment. If there are K orthogonal channels available, without loss of generality we can use the set of integers $\mathsf{K} = \{1, 2, \ldots, K\}$ to denote them. For all $i \in \mathsf{N}$, we denote with $\nu(i)$ the number of NICs owned by node i. The exact channel assignment is represented by an *interface allocation variable* denoted as y_i^q, where $i \in \mathsf{N}$ and $q \in \mathsf{K}$, which is a binary variable equal to 1 if node i has a NIC tuned on channel q and 0 otherwise. Note that $\sum_{r=1}^{K} y_i^q = \nu(i)$ for all nodes $i \in \mathsf{N}$. Similarly, if $i, j \in \mathsf{N}$ and $q \in \mathsf{K}$, we define a binary *channel edge variable* called x_{ij}^q and defined as equal to 1 if i can transmit to j using the q the channel, and 0 otherwise. If the link symmetry assumption holds, it is reflected in that $x_{ij}^q = x_{ji}^q$. These variables are connected through the relationship $x_{ij}^q = y_i^q \cdot y_j^q$.

An example of graph representation is given in **Figure 29** and **Figure 30**, where the physical and the logical topologies, respectively, are shown for a sample network of 6 nodes with $K = 4$ channels. In this case, nodes a and f, which are shown to have wireline connection to the Internet, operate as MAPs, whereas the other nodes are ordinary MRs. For all nodes i, $\nu(i)$ is chosen equal to 2. In the logical topology (**Figure 30**) the numbers written on the edges indicate the frequency on which they are established, and small numbers beside a node denote its NIC assignment.

First of all, the aforementioned difference between the two topologies can be observed. Some links of the physical topology can be absent in the logical topology, as is the case, e.g., for the edge (d,e). In **Figure 30**, nodes d and e are not linked since they do not have a common interface assignment. On the other hand, all pairs of nodes in **Figure 29** are linked through one edge at most, whereas in Figure 30 two edges connect nodes a and b since they share both of their interface assignment on channels 1 and 2.

By looking at Figure 30, the interface allocation variables can be derived, for example $y_a^1 = y_a^2 = 1$, $y_a^3 = y_a^4 = 0$, or $y_e^2 = y_e^4 = 1$, $y_e^1 = y_e^3 = 0$. The channel edge variables are similarly determined, e.g., $x_{ab}^1 = x_{ab}^2 = x_{cd}^3 = 1$, $x_{ab}^3 = x_{ab}^4 = x_{de}^1 = 0$.

As discussed previously, in most of the investigations related to interface assignment, wireless interference is modeled through the so-called protocol model **[79]**. For our purposes this means that any edge $(i,j) \in \mathsf{E}_P$ is associated with a set $\mathsf{J}(i,j)$, called *conflicting link set*, containing all the edges $(x,y) \in \mathsf{E}_P$ whose activation on the same frequency than link (i,j) prevents a reliable transmission on it. For practical purposes, we adopt the convention of including also (i,j) in its own conflicting link set, i.e., $(i,j) \in \mathsf{J}(i,j)$, which simplifies the notation. The conflict relationship is mainly due to propagation phenomena; sometimes the conflicting link sets are defined based on simplified models, related for example to the distance between nodes. It is worth mentioning that this formulation is an abstraction useful for its conceptual simplicity, and for this reason will be used thereinafter. Yet, from the viewpoint of correctly modeling interference, more realistic descriptions, such as the so-called physical interference model **[79]** would be preferable. However, with some modifications, the reasonings presented in the following could be extended to alternative interference models as well. A detailed discussion about interference models is out of the scope of the present chapter. The interested reader can found overviews on this subject for example in **[80][81]**.

To instantiate the routing problem in the multi-channel environment, we need also to define for all links $(i,j) \in \mathrm{E}_P$ a parameter $c_{ij}^{(P)}$ which describes their *physical capacity*, i.e, their nominal data rate (e.g., expressed in Mbps). For completeness, we can introduce a value $c_{ij}^{(P)} = 0$ if $(i,j) \notin \mathrm{E}_P$. According to whether edge (i,j) is reflected in the logical topology also, $c_{ij}^{(P)}$ will be mirrored into a *logical capacity* value. Since there are several channels, this latter value depends also on the channel q. Thus, for $i,j \in \mathrm{N}$ and $q \in \mathrm{K}$, we define $c_{ij}^{(q)}$ which can be larger than zero only if $x_{ij}^{q} = 1$.

Moreover, we denote with $\gamma^{(s,d)}$ the expected end-to-end traffic to be delivered from source s to destination d. Typically, in WMN either s or d will coincide with one of the MAPs. We also call $\lambda_{i,j}^{q}$ the amount of traffic (involving any pair source-destination) which passes through edge (i,j) over channel q. To put these quantities in relationship, it is useful to introduce a *binary routing variable* called $a_{i,j}^{(m,n),q}$ defined as

$$a_{i,j}^{(s,d),q} = \begin{cases} 1 & \textit{if traffic from s to d is routed over (i, j) on channel q} \\ 0 & \textit{otherwise} \end{cases} \quad \text{Eqn. 8}$$

These variables will be put in relationship with each other in the next section, where we utilize them to characterize traffic aware routing strategies.

6.5 Link Load Estimation and Traffic-aware Interface Assignment

The task of assigning channels to the available NICs can benefit from the exploitation of traffic information. In fact, since the purpose of utilizing multiple channels at the same time is to decrease interference and promote network parallelism, this should be done especially around the most congested links. In this section we discuss possible strategies to retrieve this knowledge and exploit it.

6.5.1 Link load estimation

There are different methods for deriving a rough estimate of the expected link traffic load. These methods depend on the routing strategy used (e.g., load balanced routing, multi-path routing, shortest path routing and so on). A possible approach is based on the concept of load criticality **[15]**. This method assumes perfect load balancing across all acceptable paths between each communicating pair of nodes. Let $P(s,d)$ denote the number of loop-free paths between a source-destination pair of nodes $(s,d) \in \mathsf{N} \times \mathsf{N}$, and let $P_\ell(s,d)$ be the number of them that pass through a given link $\ell \in \mathsf{E}_P$. Then the expected traffic load Φ_ℓ on link ℓ is calculated as:

$$\Phi_\ell = \sum_{(s,d) \in \mathsf{E}_L} \frac{P_\ell(s,d)}{P(s,d)} \cdot \gamma^{(s,d)} \qquad \text{Eqn. 9}$$

This equation implies that the initial expected traffic on a link is the sum of the loads from all acceptable paths, across all possible node pairs, which pass through the link. Because of the assumption of uniform multi-path routing, the load that an acceptable path between a pair of nodes is expected to carry is equal to the expected load of the pair of nodes divided by the total number of acceptable paths between them.

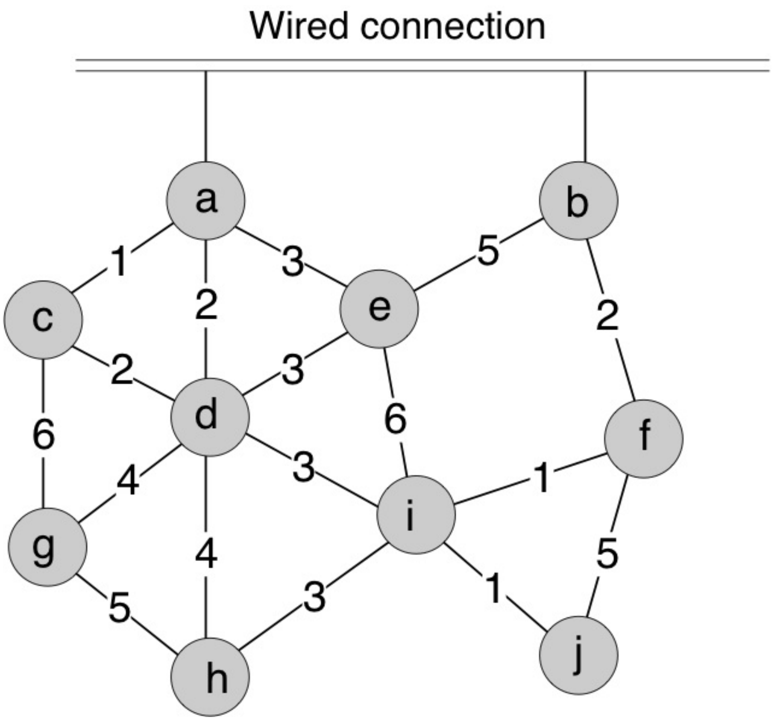


Figure 31 - Multi-Channel Wireless Mesh Network

Table 5 - Traffic profile with 3 flows

Source (s)	Destination (d)	$\gamma^{(s,d)}$ (Mbps)
a	g	0.9
i	a	1.2
b	j	0.5

Consider the logical topology as shown in **Figure 31** and assume that we have the three flows reported in **Table 5**.
Because we have three different sources and destinations, we have

$$\Phi_\ell = \frac{P_\ell(a,g)}{P(a,g)} \cdot \gamma^{(a,g)} + \frac{P_\ell(i,a)}{P(i,a)} \cdot \gamma^{(i,a)} + \frac{P_\ell(b,j)}{P(b,j)} \cdot \gamma^{(b,j)} \qquad \text{Eqn. 10}$$

Furthermore, we calculate $P(s,d)$ for each flow. To this end, we need to determine all the possible source-destination paths, which can be achieved through a Route Discovery procedure **[82]**. **Table 6** reports the results for the topology in Figure 31. For practicality reasons, we have set an upper limit for the path length to 5 hops, e.g., by imposing a Time-To-Live to the Route Discovery broadcast packets.

Table 6 - Possible flows between communicating nodes

(source,dest)	(*a*,*g*)	(*i*,*a*)	(*b*,*j*)
Possible paths	*a-c-g*	*i-e-a*	*b-f-j*
	a-c-d-g	*i-e-d-a*	*b-f-i-j*
	a-d-g	*i-d-a*	*b-e-i-j*
	a-d-c-g	*i-d-c-a*	*b-e-i-f-j*
	a-d-h-g	*i-d-e-a*	*b-e-d-i-j*
	a-d-i-h-g	*i-d-g-c-a*	
	a-e-d-g	*i-h-d-a*	
	a-e-i-h-g	*i-h-g-c-a*	
P(source,dest)	8	8	5

From the above information, we can now calculate how many paths pass a specific link in the network topology. These values and the corresponding link traffic load Φ_ℓ calculated using **Eqn. 10** are shown in **Table 7**.

Table 7- Possible flows between communicating nodes

ℓ	$P_\ell(a,g)$	$P_\ell(i,a)$	$P_\ell(b,j)$	Φ_ℓ(Mbps)
a-c	2	3	0	0.675
c-g	2	2	0	0.525
c-d	2	1	0	0.375
d-g	2	1	0	0.375
a-d	4	3	0	0.9
g-h	0	1	0	0.15
d-h	1	1	0	0.2625
a-e	2	2	0	0.525
d-e	1	2	1	0.5125
d-i	1	3	1	0.6625
h-i	2	2	0	0.525
e-i	1	2	2	0.6125
b-e	0	0	3	0.3
b-f	0	0	2	0.2
f-i	0	0	2	0.2
i-j	0	0	2	0.2
f-j	0	0	2	0.2

Based on these calculations, we can estimate the load between each neighboring node. The meaning of Φ_ℓ, which we have calculated throughout this example, is the expected traffic load of link ℓ, i.e., the amount of traffic expected to be carried over a specific link. The higher Φ_ℓ, the more critical the link. The idea is now to use this metric to decide which are the most congested points in the network, so as to assign possibly more than one frequency to heavily loaded links and fewer channels, or no channel at all, to less congested edges. Also, as Φ_ℓ can be seen as an estimated version, i.e., a measurement, of the the amount of traffic which passes through $(i,j)=\ell$, it holds

$$\Phi_\ell \approx \sum_{q=1}^{K} \lambda_\ell^q . \qquad \text{Eqn. 11}$$

Thus, if the variables λ_ℓ^q are available, they can be used in place of Φ_ℓ which depends on some a priori assumptions such as the perfect load balancing among the edges.
Moreover, several related issues open up. First of all, the strategy to weigh the different paths considers all of them as identical. Actually, there may be conditions which make a path less likely to be used for routing traffic, e.g., if it is very long. On the other hand, it is not true either that shortest hops are to be preferred. As discussed in **[9]**, simple hop count may not be the most appropriate metric to decide on the best routes toward the destination. Thus, in general the determination of quantities $P(s,d)$ is a possible interesting subject for further research.
At the same time, the Φ_ℓ metric can be used only as a rough estimate of the load. Importantly, since channel assignment may affect how E_P is reflected to E_L, there may be the case that some links are turned off by the absence of a common channel between the involved nodes. In this case, it is not possible to route traffic over them, and therefore the expected traffic load should be recomputed. Thus, also the study of these interactions and possible proposals about how to utilize similar metrics to infer where congestion is likely to arise are a possible challenging topic to investigate further.

6.5.2 Link capacity estimation

The link capacity, or the portion of channel bandwidth available to a link, is determined by the number of all physical links in transmission range of its transmitter or its receiver, i.e., in its conflicting link set, that are also assigned to the same channel. Obviously, the exact short-term instantaneous bandwidth available to each link is dynamic and continuously changing depending on several propagation and interference phenomena **[15]**. The goal here is to derive an approximation of the long-term bandwidth share available. Thus, the capacity $b_{ij}^{(q)}$ assigned to link (i,j) on channel q can be obtained using the following equation:

$$b_{ij}^{(q)} = \frac{\lambda_{ij}^{q}}{\sum_{(x,y)\in J(i,j)} \lambda_{xy}^{q}} \cdot c_{ij}^{(q)}. \qquad \text{Eqn. 12}$$

Note that if $\nu(i) = \nu$, constant for all the nodes,

$$\sum_{q=1}^{K} b_{ij}^{(q)} \approx \frac{\Phi_{ij}\, \nu \cdot c_{ij}^{(P)}}{\sum_{(x,y)\in J(i,j)} \Phi_{xy}}. \qquad \text{Eqn. 13}$$

In other words, the capacity share available to a link is approximately proportional to its expected load.

6.6 Traffic-aware joint interface assignment and routing

Giving the preliminaries defined before and the results reported previously, we may specify relationships among the variables which can be used, for example, in an LP context as done by **[68]**. We stress the important aspect that a comprehensive framework includes channel assignment (represented by variables y_i^q and x_{ij}^q), routing variables $a_{i,j}^{(m,n),q}$, and finally traffic information (variables $\gamma^{(s,d)}$). Thus, it is appropriate to refer to the resulting model as a Traffic-aware Joint Interface Assignment and Routing. We focus on the model only, whereas the solution techniques are out of the scope of the present analysis. Only, we remark here that the model is rather general and can be solved in a plethora of ways, including exact and approximate, centralized and distributed ones.
The variables of the model are related as per the following relationship, which can be seen as LP constraints. The aggregate traffic on a given link depends on the routing variables and the traffic requirements, so that

$$\lambda_{i,j}^{q} = \sum_{(s,d)\in \mathrm{N}\times\mathrm{N}} a_{i,j}^{(s,d),q} \gamma^{(s,d)} . \qquad \text{Eqn. 14}$$

The effective capacity $c_{ij}^{(q)}$ of link (i, j) on any channel q can not exceed the nominal capacity $c_{ij}^{(P)}$ and it is zero if i and j do not share channel assignment q. Thus,

$$c_{ij}^{(q)} = x_{ij}^{q} c_{ij}^{(P)} . \qquad \text{Eqn. 15}$$

Moreover, the aggregate traffic $\lambda_{i,j}^{q}$ must be less than $c_{ij}^{(q)}$. Actually, in [68] it is proposed to strengthen this constraint by including a parameter $\Lambda \le 1$. The motivation is that perfect capacity sharing among all interfering links is not true in practice. Thus, this constraint may be ineffective since it overestimates the effective capacity. Obviously, this is just an artifice and other solutions to cope with this problem are possible as well. Then, we impose

$$\lambda_{i,j}^{q} \le \Lambda c_{ij}^{(q)} . \qquad \text{Eqn. 16}$$

Finally, we impose a constraint describing conservation of the flows, i.e.,

$$\sum_{\substack{j\in \mathrm{N} \\ (i,j)\in \mathrm{E}_P}} \sum_{q=1}^{K} a_{i,j}^{(s,d),q} \gamma^{(s,d)} - \sum_{\substack{j\in \mathrm{N} \\ (i,j)\in \mathrm{E}_P}} \sum_{q=1}^{K} a_{j,i}^{(s,d),q} \gamma^{(s,d)} = \begin{cases} \gamma^{(s,d)} & \text{if } s = i \\ -\gamma^{(s,d)} & \text{if } d = i \\ 0 & \text{otherwis} \end{cases} \qquad \text{Eqn. 17}$$

At this point, several metrics can be chosen as the metric to optimize. For example, following again **[68]**, we can choose to minimize the ratio between load and available capacity share on the most congested link. This implies to optimize the utilization of the most congested link and results in the following objective:

$$\min_{(i,j)\in E_P} \max_{x_{ij}^q=1} \frac{\lambda_{i,j}^q}{b_{ij}^{(q)}}. \qquad \text{Eqn. 18}$$

This somehow determines a performance bound in terms of capacity, which is independent of the absolute values of load requirements $\gamma^{(s,d)}$. In fact, they can be re-scaled until constraint in **Eqn. 16** is violated. Therefore, the most congested link gives the capacity bottleneck for the throughput of the whole network. Of course, other objectives are possible as well, for example also introducing fairness considerations. Finally, once the objective function has been identified, the problem can be approached by both LP optimization frameworks and heuristic techniques, and both in a centralized and a distributed manner. The choice of the specific technique to use mostly relates to general design issues such as the computational capability of the terminals.

Chapter 7

Conclusions and Future Work

In this thesis we have identified the key challenges associated with assigning channels to radio interfaces in a multi-radio wireless mesh network. After presenting the channel assignment problem and its major constraints, we provided a taxonomy of existing channel assignment schemes and summarized our study with a comparison of the different schemes. One of the important challenges which are still to be solved is the question of how many interfaces to have on each mesh router. In other words, given the physical topology and the traffic profile of the network, how can we to optimize the number of radios on the different nodes. This question adds another dimension to the channel assignment problem and is still to be investigated in the future. Another important challenge is when the nature of traffic is not uniform; we talk about the case when there is a mixture of broadcast, multicast and unicast traffic in the same network. This problem was discussed in [85] where the authors investigated extensively the channel assignment problem in the broadcast case and discovered that for broadcast, a *common channel assignment* generally performs better than *variable channel assignment*. On the other end, CCA performs poorly for unicast flows and thus the challenge is to discover what channel assignment schemes can perform well for both.

We emphasize the importance of the interactions between interface assignment and routing for the capacity performance of multi-channel wireless mesh networks. Routing and interface assignment can benefit from simple information passing, where the two layers are still separated but cooperating. Moreover, if the terminal capabilities allow for it, one can also think of merging together the related strategies with a cross-layer approach.

To sum up, from a general viewpoint there are strong expectations about multi-radio WMNs providing end users with high network capacity. However, routing and interface assignment, require a careful, and possibly joint, investigation due to their tight interdependencies.

Traffic aware algorithms, which offer the opportunity to turn this relationship to an advantage, appear as very promising to make this goal easier to reach.

Appendix A

Routing and Channel Assignment in Wireless Mesh Networks: Related Work

A.1 Introduction

This related work chapter contains a detailed description of two important research studies conducted by leading research groups in routing in WMNs. The first work **[10]** is by Ashish Raniwala and Tzi-cker Chiueh from the Computer Science Department at Stony Brook University, NY. The authors mainly focus on the joint routing and channel assignment using ns-2 simulations. The second work **[9]** is by Richard Draves, Jitendra Padhye and Brian Zill from Microsoft Research at Redmond, WA. Their research is mainly focused on developing routing protocols for WMNs and the design of new routing metrics for improving the routing function. As motivation of this chapter, we emphasize the relationship between channel assignment, routing and routing metrics. The goal of this chapter is to present complementary parts from two different research groups which are very closely related to the research conducted in this thesis, that is why we chose to include it into an appendix.

A.2 Channel assignment [10]

A.2.1 Introduction

In this work **[10]**, the authors propose a multi-channel wireless mesh network (WMN) architecture whose central design issues are channel assignment and routing. They show that and intelligent channel assignment is critical to the performance of a WMN. They present distributed algorithms that utilize only local traffic load information to dynamically assign channels and to route packets. Through an extensive simulation study using ns-2, they show that even with just 2 NICs on each node, it is possible to improve the network throughput by a factor of 6 to 7 when compared with the conventional single-channel ad hoc network architecture. Although their 9-node prototype uses 802.11 interfaces, the architecture is also applicable to the *802.16a* networks, where customer premise equipments form a mesh connectivity to reach the base station. This paper makes the following research contributions:

- A fully distributed channel assignment algorithm that can adapt to traffic loads dynamically.
- A multiple spanning tree-based load-balancing routing algorithm that can adapt to traffic load changes as well as network failures automatically.

A.2.2 System architecture

Figure 32 shows the WMN architecture which consists of fixed wireless routers, each of which is equipped with a traffic aggregation access point that provides network connectivity to end-user mobile stations within its coverage area. In turn, the wireless routers form a multi-hop ad hoc network among themselves to relay the traffic to and from mobile stations. Some of the WMN nodes serve as gateways between the WMN and a wired network. All infrastructure resources such as file servers, Internet gateways and application servers, reside on the wired network and can be accessed through any of the gateways.

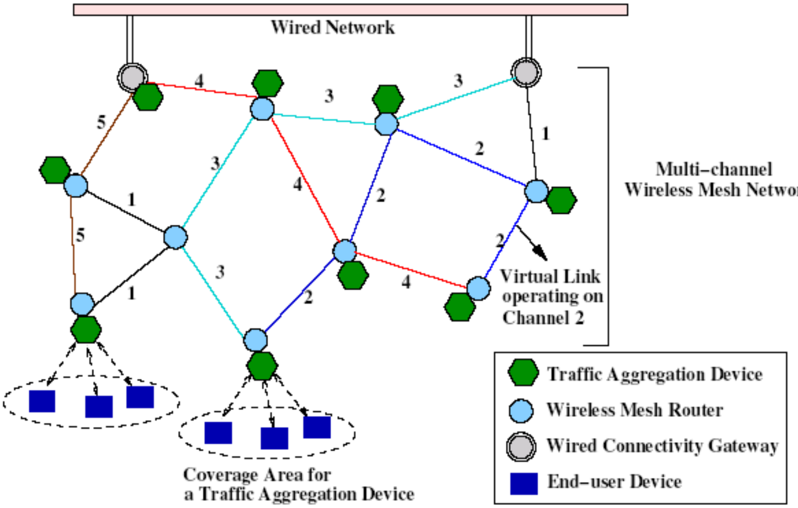


Figure 32 – System architecture [10]

Each node in a multi-channel WMN is equipped with multiple 802.11-compliant NICs, each of which is tuned to a particular radio channel for a relatively long period of time, such as several minutes or hours.
For direct communication, two nodes need to be within communication range of each other, and need to have a common channel assigned to their interfaces. A pair of nodes that use the same channel and are within interference range may interfere with each other's communication, even if they cannot directly communicate.
Node pairs using different channels can transmit packets simultaneously without interference. Note that mobile nodes have only a single NIC, and the interaction between mobile nodes and a traffic aggregation device is similar to the infrastructure mode operation of the IEEE 802.11 standard.

A.2.3 Channel assignment problem

The goal of channel assignment in a multi-channel WMN is to bind each network interface to a radio channel in such a way that the available bandwidth on each virtual link is proportional to the load it needs to carry.

The channel assignment problem can actually be divided into two sub-problems: (1) neighbor-to-interface binding, and (2) interface-to-channel binding. Neighbor-to-interface binding determines through which interface a node uses to communicate with each of its neighbors with whom it intends to establish a virtual link. Because the number of interfaces per node is limited, each node typically uses one interface to communicate with multiple of its neighbors. Interface-to-channel binding determines which radio channel a network interface should use. The main constraints that a channel assignment algorithm needs to satisfy are:

- The number of distinct channels that can be assigned to a WMN node is bounded by the number of NICs it has.
- Two nodes that communicate with each other directly should share at least one common channel.
- The raw capacity of a radio channel within an interference zone is limited.
- The total number of non-overlapped radio channels is fixed.

Conceptually, links that need to support higher traffic load should be given more bandwidth than others. This means that these links should use a radio channel that is shared among a fewer number of nodes. An ideal load-aware channel assignment would distribute radio resource among links in a way that matches their expected traffic loads.

A.2.4 Load-balancing routing problem

Channel assignment depends on the load on each virtual link, which in turns depends on routing. The traffic distribution of a WMN is skewed. In other words, most of the WMN nodes communicate primarily with nodes on the wired network. This is the case because most users are primarily interested in accessing the Internet or enterprise servers, both of which are likely to reside on the wired network. The goal of the routing algorithm is thus to determine route(s) between each traffic aggregation device and the wired network in such a way that balances the load on the mesh network, including the links to the wired network. Load balancing helps avoid bottleneck links, and increases the network resource utilization efficiency.

A.2.5 Evaluation Metric

The main goal of the channel assignment and routing algorithms is to maximize the overall network goodput, or the number of bytes it can transport between the traffic aggregation devices and the wired connectivity gateways within a unit time. To formalize this goal, the authors define the *cross-section goodput* of a network as:

$$X = \sum_{a} \min\left(\sum_{i} C(a, g_i), B(a)\right) \qquad \text{Eqn. 19}$$

where $C(a, g_i)$ is the useful network bandwidth available between a traffic aggregation device a and a gateway node g_i. If the bandwidth requirement between a traffic aggregation device a and the wired network is B(a), then only up to B(a) of the bandwidth between node a and all the gateway nodes is considered useful. This criteria ensures that only the usable bandwidth of a network is counted towards its cross-section throughput, hence the term cross-section goodput. The goal of the channel assignment and routing algorithms is to maximize this cross-section goodput X.

A.2.6 Distributed routing / Channel assignment algorithm

This distributed routing/channel assignment algorithm utilizes only local topology and local traffic load information to perform channel assignment and route computation. The information is collected from (k+1)-hop neighborhood, where k is the ratio between the interference and communication ranges which is typically between 2 and 3.

- ***Load-Balancing Routing***
  As most of the traffic on a WMN is directed to/from the wired network, each WMN node needs to discover a path to reach one or multiple wired gateway nodes. Logically, each wired gateway node is the root of a spanning tree, and each WMN node attempts to participate in one or multiple such spanning trees. These spanning trees are connected to each other through the wired network. When each WMN node joins multiple spanning trees, it can distribute its load among these trees and also use them as alternative routes when nodes or links fail. However, a WMN node may need additional wireless network interfaces to join multiple trees. In this paper, the authors restrict their focus on the case where each node is actively associated with only one of the trees and uses the other trees only for failure recovery.
- ***Routing Tree Construction***

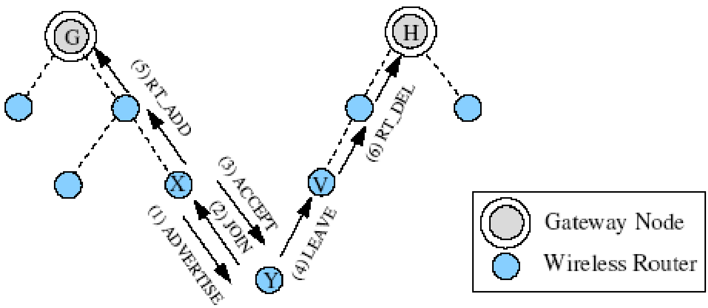


Figure 33 – Spanning tree construction [10]

The basic tree construction process as shown in **Figure 33** is similar to IEEE 802.1D's spanning tree formation algorithm with two major differences. First one is that the metric used by each WMN node to determine a parent is dynamic to achieve better load balancing. Second one is that load-aware channel assignment technique is used to automatically form a fat-tree where more relay bandwidth is available on virtual links closer to the roots of the trees, namely, the wired gateways.

Assume a node X has already discovered a path to the wired network. It periodically, every T_a time units, broadcasts this reachability information to its one-hop neighbors using an ADVERTISE packet. Initially, only the gateway nodes can send out such advertisements because of direct connectivity to the wired network. Over time, intermediate WMN nodes that have a multi-hop path to one of the gateway nodes can also make such advertisements. The ADVERTISE packet that X sends out contains the cost of reaching the wired network through X. Upon receiving an advertisement, X's neighbor, say node Y, can decide to join X if Y does not have a path to the wired network, or the cost to reach the wired network through X is less than Y's current choice. To join node X, Y sends a JOIN message to X. On receiving the JOIN message, X adds Y to its children list, and sends an ACCEPT message to Y with information about channel(s) and IP address to use for forwarding traffic from Y to X. In terms of the routing tree, X is now the parent of Y, and Y is one of the children of X.

Finally, Y sends a LEAVE message to its previous parent node, say V. From this point on, Y also broadcasts ADVERTISE packets to its own one-hop neighbors to further extend the reachability tree.

As a result of the exchange of JOIN/ACCEPT/LEAVE messages, the routing tables on the involved nodes are updated. First, the default routing entry of Y points to X as the next hop. All nodes in the tree from V upwards to the corresponding gateway node delete the forwarding entries pointing to Y and its children, if any. On the other hand, all nodes in the tree from X upwards to the gateway node add a forwarding entry for packets destined to Y and its children. To perform these route updates, the RT_ADD / RT_DEL messages are sent up to the root of the corresponding trees.

- ***Routing Metric***

  The cost metric carried in the ADVERTISE messages determines the final tree/forest structure.

  The authors explore three different cost metrics. First is the *hop count* between a WMN node and the gateway node associated with an ADVERTISE message. This metric enables a WMN node to reach the wired network using the minimum number of hops, but does nothing to balance network load. An advantage of using the hop-count metric is rapid convergence, as the minimum hop-count from a node to a wired network is determined by physical topology and is thus mostly static.

  The second cost metric is the *gateway link capacity*, which indicates the residual capacity of the uplink that connects the root gateway of a tree to the wired network. Residual capacity of any link is determined by subtracting the current usage of the link from its overall capacity. In case the total bandwidth of a gateway's wireless links is smaller than its uplink, we take the wireless links' bandwidth as the gateway link capacity.

  The third cost metric is the *path capacity*, which represents the minimum residual bandwidth of the path that connects a WMN node to the wired network. Path capacity is more general than gateway link capacity because the former assumes that the bottleneck of a path can be any constituent link on the path, rather than always the gateway link. The capacity of a wireless link is approximated by subtracting the aggregate usage of the link's channel within its neighborhood from the channel's raw capacity which is assumed to be fixed within any collision domain.

- ***Distributed Load-Aware Channel Assignment***

  The neighbor discovery and routing protocol allows each WMN node to connect with its neighbors and identify a path to the wired network. We now discuss the mechanisms through which a WMN node can decide how to bind its interfaces to neighbors and how to assign radio channels to these interfaces in the absence of global coordination.

The key problem in the design of a distributed channel assignment algorithm is channel dependency among the nodes, which is illustrated in **Figure 34**.

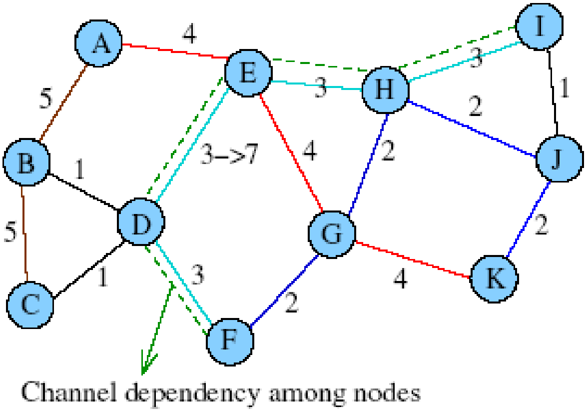


Figure 34 - Example shows how a change in a channel assignment could lead to a series of channel re-assignments across the network because of the channel dependency problem [10]

In this example, assume node D finds that the link D-E is heavily loaded and should be moved to a lightly loaded channel 7. As D only has 2 NICs, it can only operate on two channels simultaneously. To satisfy this constraint, link D-F also needs to change its channel. The same argument goes for node E, which needs to change the channel assignment for link E-H. This ripple effect further propagates to link H-I. Similar ripple effects would ensue if link A-E were to change its channel.

In this case, link E-G and G-K will need to change their channels as well. This channel dependency relationship among network nodes makes it difficult for an individual node to predict the effect of a local channel re-assignment decision.

To bound the impact of a change in channel assignment, the authors impose a restriction on the WMN nodes. Specifically, the set of NICs that a node uses to communicate with its parent node, termed **UP-NICs**, is disjoint from the set of NICs the node uses to communicate with its children nodes, called **DOWN-NICs**, as shown in **Figure 35**.

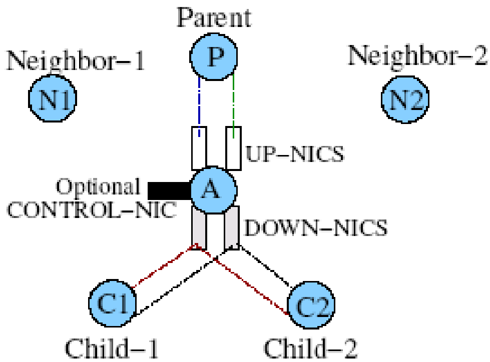


Figure 35 – Elimination of channel dependency [10]

Each WMN node is responsible for assigning channels to its DOWN-NICs. Each of the node's
UP-NICs is associated with a unique DOWN-NIC of the parent node and is assigned the same channel as the parent's corresponding DOWN-NIC. This restriction effectively prevents channel dependencies from propagating from a node's parent to its children, and thus ensures that a node can assign/modify its DOWN-NICs' channel assignment without introducing ripple effects in the network.
Once the neighbor-to-interface mapping is determined, the final question is how to assign a channel to each of the NICs. The channel assignment of a WMN node's UP-NICs is the responsibility of its parent. To assign channels to a WMN node's DOWN-NICs, it needs to estimate the usage status of all the channels within its interference neighborhood. Each node therefore periodically exchanges its individual channel usage information as a CHNL_USAGE packet with all its (k + 1)-hop neighbors. Because all the children and parent of a node, say A,

can interfere with their own k-hop neighbors, A's (k + 1)-hop neighborhood includes all the nodes that can potentially interfere with A's communication. The aggregate traffic load of a particular channel is estimated by summing up the loads contributed by all the interfering neighbors that happen to use this channel. To account for the MAC-layer overhead such as contention, the total load of a channel is a weighted combination of the aggregated traffic load and the number of nodes using the channel.

Based on the per-channel total load information, a WMN node determines a set of channels that are least-used in its vicinity. As nodes higher up in the spanning trees need more relay bandwidth, they are given a higher priority in channel assignment. More specifically, the priority of a WMN node is equal to its hop distance from the gateway. When a WMN node performs channel assignment, it restricts its search to those channels that are not used by any of its interfering neighbors with a higher priority.

Because traffic patterns and thus channel loads can evolve over time, the interface-to-channel mapping is adjusted periodically, every T_c time units. Within a channel load-balancing phase, a WMN node evaluates its current channel assignment based on the channel usage information it receives from neighboring nodes. As soon as the node finds a relatively less loaded channel after accounting for priority and its own usage of current channel, it moves one of its DOWN-NICs operating on a heavily-loaded channel to use the less-loaded channel, and sends a CHNL_CHANGE message with the new channel information to the affected child nodes, which modify the channels of their UP-NICs accordingly.

A.2.7 Performance Evaluation

The performance of the proposed multi-channel WMN architecture and the effectiveness of the proposed channel assignment and routing algorithms are studied through extensive ns-2 simulations. The

evaluation metric for most experiments is cross-section goodput X defined previously and the RTS/CTS mechanism is enabled.
In the first experiment, the authors measured the throughput improvement achieved by their architecture using different channel assignment algorithms. They used Ten different 60-node network topologies randomly sampled from a 9x9 square grid network.

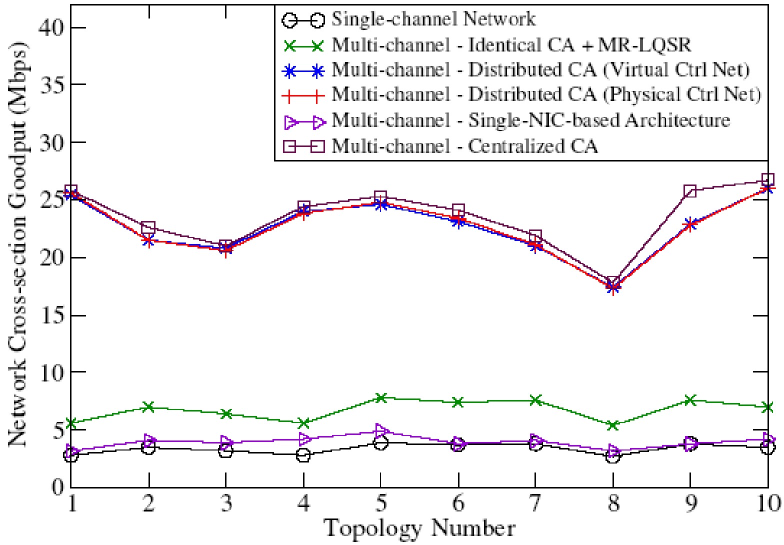


Figure 36 – Network cross-section goodput for different architectures and channel assignment strategies [10]

The results in **Figure 36** show that even with identical channel assignment scheme **[9]**, deploying 2 NICs on each node improves the network goodput by a factor of 2 compared with conventional single-channel network. With the proposed distributed channel assignment algorithm the network throughput becomes 6 to 7 times that of single-channel network.
The first distributed channel assignment scheme **[14]**, called *physical control network*, uses a dedicated control channel for communicating all control traffic. This requires an additional WLAN interface on each node specifically for control traffic. The second distributed channel assignment scheme, called *virtual control network*, multiplexes the

control traffic over data NICs thereby reducing the per-node hardware cost.

Finally, the centralized channel assignment/routing algorithm **[15]** does not perform much better than the distributed versions; this shows that the performance loss due to distribution of intelligence is very small.

An alternate design for a multi-channel mesh networking is to equip each node with a single interface and operate the sub-network rooted at each gateway at a different channel. Logically, this should reduce the contention among nodes and thus improve the network goodput. However, this scheme does not give much throughput improvement over a single-channel mesh network as shown in **Figure 36**. The fact that only a single channel is used within a tree means that there is still heavy collision and interference on the wireless links around each gateway, which is most likely where the bottleneck is.

The second experiment simulated a 64-node network to measure the response time observed by web users.

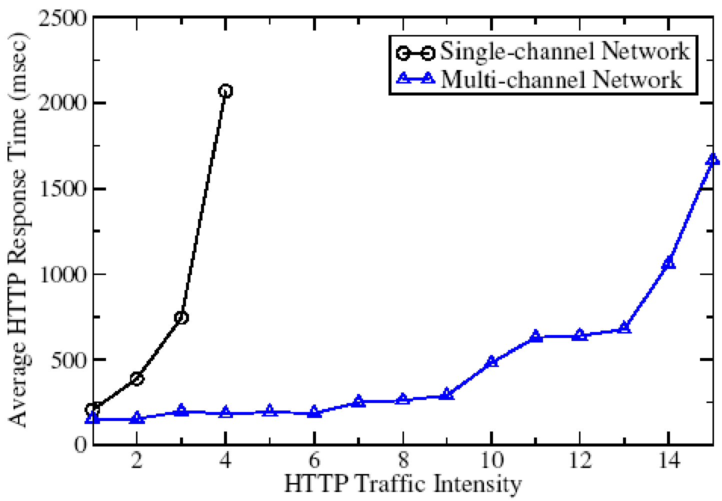


Figure 37 - Web browsing (HTTP) response time versus traffic intensity [10]

The result shown in **Figure 37** is that with just 2 NICs on each node, the multi-channel mesh network reduces the HTTP response time substantially. Additionally, at saturation the multi-channel WMN can support over 4 times as much web traffic as compared with the single-channel WMN, and consequently a much larger number of users.

It was already mentioned that the number of non-overlapped radio channels is 3 for 802.11b/g and 12 for 802.11a. **Figure 38** shows the effects of varying the number of radio channels on the network goodput.

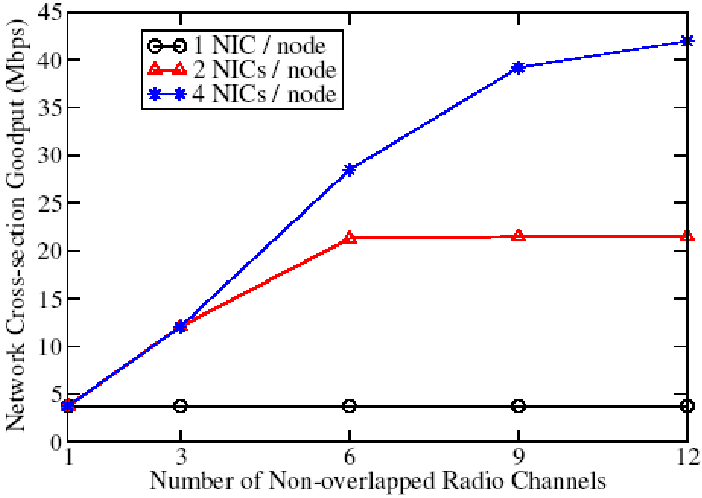


Figure 38 - Effects of varying the number of WLAN interfaces [10]

When each node has 2 NICs, the network goodput saturates at about 6 channels. When the number of NICs on each node is increased to 4, the network can use up to 12 channels before its performance starts to saturate.

In this last experiment, the authors compare the impact of various routing metrics on the overall network performance.

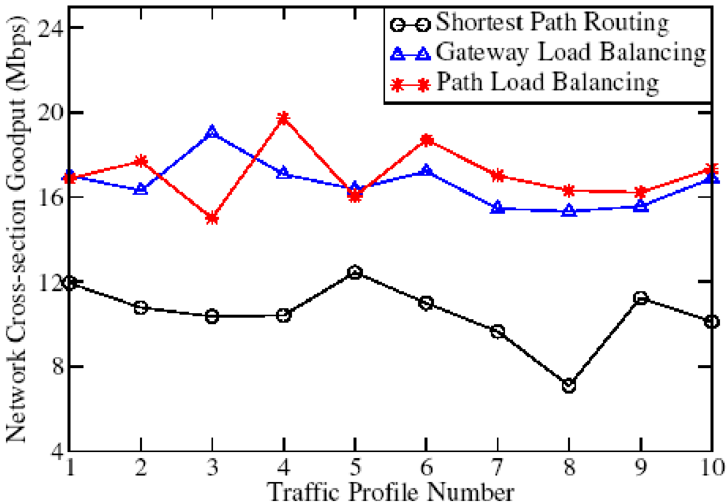


Figure 39 - Performance comparison among load balancing routing metrics [10]

Figure 39 shows that shortest path routing does not utilize the gateways' bandwidth effectively. It also shows that the performance of path load balancing is only slightly better than that of gateway load balancing, suggesting that gateways are the main bottlenecks.

A.3 Routing metrics [9]

A.3.1 Introduction

A routing metric is a very important aspect of the routing protocols, the goal of a metric is to choose a high-throughput path between a source and a destination. The metric proposed in this work assigns weights to individual links based on the Expected Transmission Time (ETT) of a packet over the link. The ETT is a function of the loss rate and the bandwidth of the link. The individual link weights are combined into a path metric called Weighted Cumulative ETT (WCETT) that explicitly accounts for the interference among links that use the same channel. The WCETT metric is incorporated into a routing protocol called Multi-Radio Link-Quality Source Routing (MR-LQSR).

A.3.2 Assumptions

- All nodes in the network are stationary.
- Each node is equipped with one or more 802.11 radios.
- If a node has multiple radios, they are tuned to different, non-interfering channels.

A.3.3 Routing metric

Much prior research has recognized the shortcomings of shortest-path routing in multi-hop wireless networks. Based on that, the authors of this work proposed a new metric for routing in multi-radio, multi-hop wireless networks. But before discussing the routing metric the proposed metric ETT, we will focus on the Expected Transmission Count (ETX), the routing metric developed by De Couto *et al.* (MIT, 2003) **[11]**. The ETX metric measures the expected number of transmissions, including retransmissions, needed to send a unicast packet across a link. The derivation of ETX starts with measurements of the underlying packet loss probability in both the forward and reverse directions; denoted by p_f and p_r, respectively; and then calculates the expected number of transmissions.

We begin by calculating the probability that a packet transmission is not successful. The 802.11 protocol requires that for a transmission to be successful, the packet must be successfully acknowledged. Let p denote the probability that the packet transmission from x to y is not successful:

$$p = 1 - (1 - p_f) * (1 - p_r) \qquad \text{Eqn. 20}$$

The 802.11 MAC will retransmit a packet whose transmission was not successful. Let the probability that the packet will be successfully delivered from x to y after k attempts be denoted by $s(k)$. Then:

$$\boldsymbol{s(k) = p^{k-1} * (1 - p)} \qquad \text{Eqn. 21}$$

Finally, the expected number of transmissions required to successfully deliver a packet from x to y is denoted by ETX:

$$ETX = \sum_{k=1}^{\infty} k * s(k) = \frac{1}{1-p} \qquad \text{Eqn. 22}$$

The path metric is the sum of the ETX values for each link in the path. The routing protocol selects the path with minimum path metric. The definition of ETX assumes that the probability that a given packet is lost in transmission is independent of its size, and is independent and identically distributed. It also implies that the ETX metric is bidirectional—the metric from x to y is the same as the metric from y to x.

Although ETX does very well in homogeneous single-radio environments, it does not perform as well in environments with multiple radios or different data rates.

The Expected transmission Time (ETT) of a link **[9]** is defined as a "bandwidth-adjusted ETX" and expressed as:

$$ETT = ETX * \frac{S}{B} \qquad \text{Eqn. 23}$$

where S is the packet size and B is the link bandwidth and ETX is exactly the same as defined in **[11]** by **Eqn. 22** and uses the same notation.

To calculate ETT according to Eqn. 22 and Eqn. 23, we need to know the forward and reverse loss rates (p_f and p_r) and the bandwidth of each link. The values of p_f and p_r can be approximated by using the broadcast packet technique described by De Couto *et al.* **[11]**. In this technique, each node periodically (once every one second) sends out a broadcast probe packet. Broadcast packets are not retransmitted by the 802.11 MAC. Nodes track the number of probes received from each neighbor during a sliding time window (ten seconds) and include this information in their own probes. Nodes can calculate p_r directly from the number of probes they receive from a neighbor in the time window, and they can use the information about themselves received in the last probe from a neighbor to calculate p_f .

The problem of determining the bandwidth of each link is more complex. Here the bandwidth is measured using the technique of packet pairs. In this technique, each node sends two back-to-back probe packets to each of its neighbors every one minute. The first probe packet is small (137 bytes), while the second probe packet is large (1137 bytes). The neighbor measures the time difference between the receipt of the first and the second packet and communicates the value back to the sender. The sender takes the minimum of 10 consecutive samples and then estimates the bandwidth by dividing the size of the second probe packet by the minimum sample.

The path metric is called Weighted Cumulative ETT (WCETT). It is set to be the sum of the ETTs of all hops on the path; thus, for a path consisting of *n* hops, WCETT is defined by:

$$WCETT = \sum_{i=1}^{n} ETT_i \qquad \text{Eqn. 24}$$

However, we also want WCETT to consider the impact of channel diversity. Simply adding up ETTs will not ensure this property, since we are not distinguishing between hops that are on different channels. To reflect this, the metric will require an additional term.

Consider an *n*-hop path. Assume that the system has a total of *k* channels. Define X_j as:

$$X_j = \sum_{\text{hop } i \text{ is on channel } j} ETT_i \qquad \text{Eqn. 25}$$

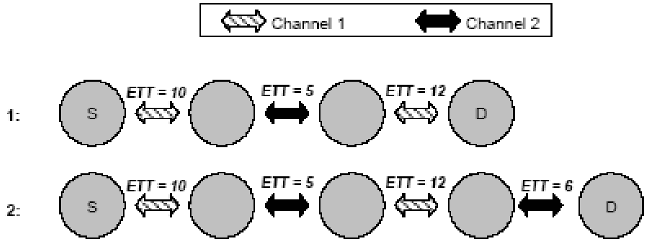
Thus, X_j is the sum of transmission times of hops on channel j. The total path throughput will be dominated by the bottleneck channel, which has the largest X_j. Thus, it is tempting to simply use the following definition for WCETT:

$$WCETT = \max_{1 \le j \le k} X_j \qquad \text{Eqn. 26}$$

We can combine the desirable properties of the two metrics by taking their weighted average:

$$WCETT = (1-\beta)\sum_{i=1}^{n} ETT_i + \beta \max_{1 \le j \le k} X_j \qquad \text{Eqn. 27}$$

Where β is a tunable parameter subject to $0 \le \beta \le 1$.
This equation can be seen as a tradeoff between throughput and delay. The first term can be considered as a measure of the latency of this path. The second term can be viewed as a measure of path throughput. The weighted average is an attempt to strike a balance between the two. An example is show in **Figure 40**.



Path	Sum	Max	WCETT ($\beta = 0.9$)	WCETT ($\beta = 0.1$)
1	27	22	22.5	26.5
2	33	22	23.1	31.9

Figure 40 – WCETT Examples [9]

A.3.4 The MR-LQSR routing protocol

MR-LQSR is a combination of the LQSR protocol with WCETT. LQSR is a source-routed link-state protocol derived from DSR **[7]**. LQSR implements all the basic DSR functionality, including Route Discovery and Route Maintenance. LQSR uses a link cache instead of a route cache, so fundamentally it is a link state routing protocol like OSPF.

DSR is modified in several ways to support routing according to link-quality metrics. These include modifications to route discovery and route maintenance plus new mechanisms for metric maintenance. Additionally, this design does not assume that the link-quality metric is symmetric. That is a very important characteristic desired in the routing metric.

LQSR route discovery supports link metrics. When a node receives a Route Request and appends its own address to the route in the Route Request, it also appends the metric for the link over which the packet arrived. When a node sends a Route Reply, the reply carries back the complete list of link metrics for the route. LQSR also uses a reactive mechanism to maintain the metrics for the links which it is actively using. When a node sends a source-routed packet, each intermediate node updates the source route with the current metric for the next link. This carries up-to-date link metrics forward with the data **[12]**.

A.3.5 Testbed

The experimental data reported in this work are the results of measurements taken on a 23-node wireless testbed similar to MIT's Roofnet **[13]**. Each node has two 802.11 NIC cards which all perform autorate selection and have RTS/CTS disabled. The nodes are located in fixed locations and did not move during testing. The node density was deliberately kept high enough to enable a wide variety of multi-hop path choices.

A.3.6 Performance evaluation

The goal of the first experiment (**Figure 41**) was to measure the accuracy of the packet-pair technique.

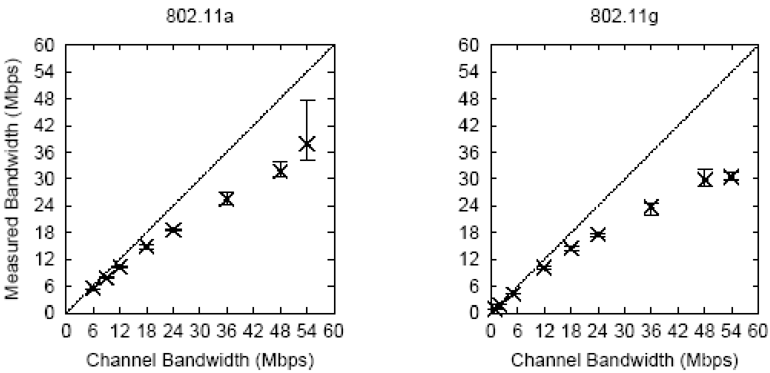


Figure 41 - Accuracy of packet-pair estimations [9]

The two plots in **Figure 41** show that the packet-pair estimate is accurate for low channel data rates, while at high data rates it underestimates the channel bandwidth. So the question that can be

asked here, is: Does the packet-pair technique produce sufficiently accurate estimates of channel bandwidth?
In the second experiment (**Figure 42**), the authors first compared the performance of the different metrics: WCETT, ETX and shortest path in the baseline scenario using one radio per node and then using two radios per node.

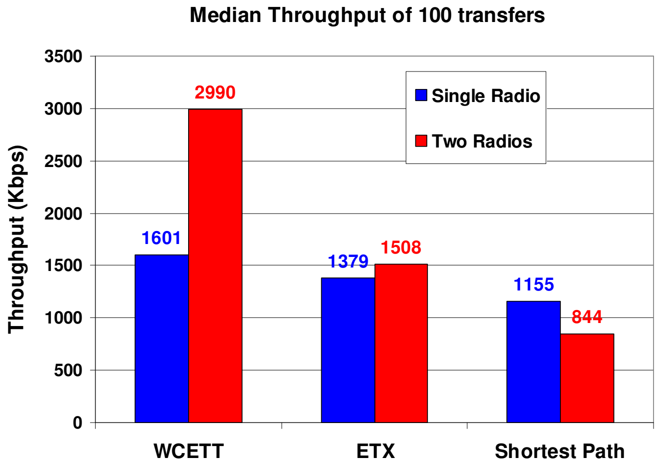


Figure 42 - Comparison of median TCP throughput with one and two radios [9]

This graph shows that WCETT works well in single-radio environments, and its performance is comparable to and even a little better than that of ETX.
In the two radio scenario in which β was set to 0.5, WCETT significantly outperforms both ETX (89%) and shortest path (254%). Also WCETT metric takes much better advantage of the additional capacity provided by the second radio (86%).
The next experiment (**Figure 43**) depicts the ability of WCETT to select good paths which means paths with highest throughput.

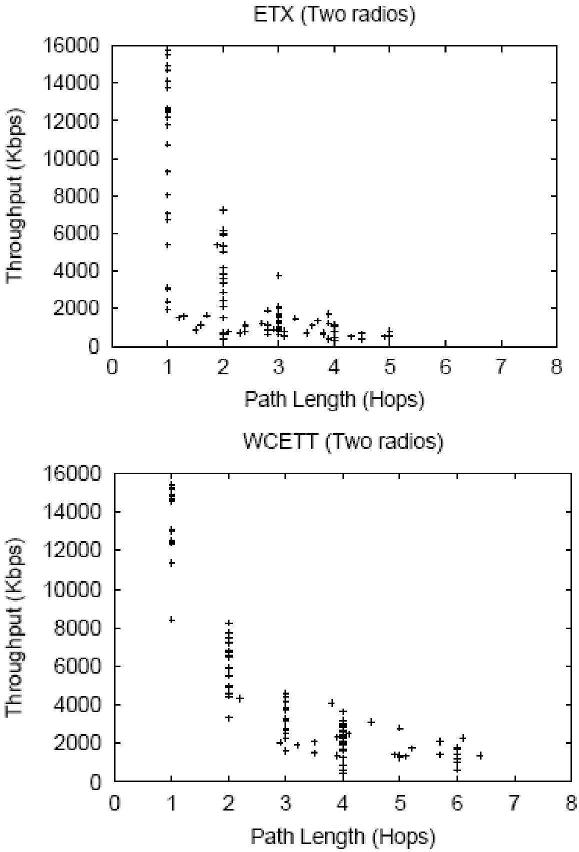


Figure 43 - Relationship between path length and throughput of individual connections with two radios [9]

The fourth experiment (**Figure 44**) considers the performance of WCETT in more detail. It tries to address whether the use of two radios provides performance improvement on connections of all path lengths, and if so, does the gain vary depending on path length.

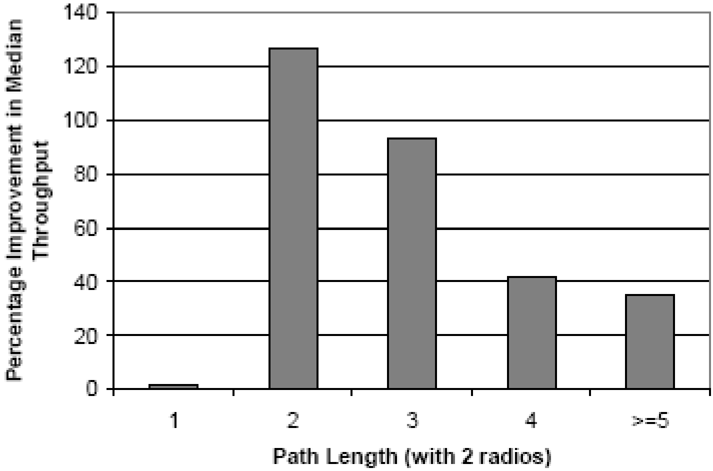


Figure 44 - Improvement in median throughput over single-radio case for various path lengths using WCETT [9]

First observation is that WCETT provides no improvement for single-hop connections. For multi-hop connections, we see that the performance improvement drops with increase in path length. The problem is that on long, multi-hop wireless paths, TCP performs poorly due to many reasons. These include increases in RTT, higher probability of packet loss due to channel errors, and contention between hops that are on the same channel.
In summary, the benefit provided by WCETT is higher for shorter paths, but even on paths that are 5 hops or longer, WCETT provides over 35% gain in performance.
In all the previous experiments, the authors had set the value of β to 0.5 while evaluating the performance of WCETT. Recall that that β is the weight given to the channel-diversity component of WCETT.
In the next experiments, we will study the impact of β under different traffic loads and study its impact on the performance.
In this experiment (**Figure 45**), the authors reproduced the previous experiment but multiple values of β.

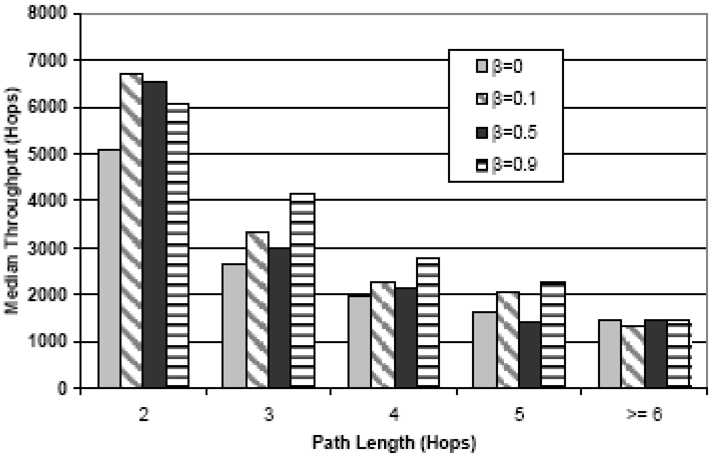


Figure 45 - Comparison of median throughputs of connections grouped by path lengths using various values of β [9]

At first glance, it would appear that β does not have significant impact on throughput. The only conclusion we can obtain from this experiment is that to select high-throughput paths in a multi-radio network, it is important to consider channel diversity in addition to the loss rate and bandwidth of individual links. The advantages of channel diversity are more apparent on shorter paths, since on longer paths factors such as increased RTT tend to limit performance.

In this last experiment (**Figure 46**), we consider two simultaneous active TCP transfers and was repeated using both the ETX and the WCETT metrics. The median throughput is multiplied by 2 and named Multiplied Median Throughput (MMT).

First observation is that WCETT performs better than ETX for all values of β in this scenario.

Second, compare the ETX and WCETT (β = 0.5) bars with the corresponding bars from **Figure 46**. We see that the MMT values are roughly equal to the median throughputs of single connections. This means that two simultaneous TCP connections constitute a fairly high load for this network. And in this case, we see that the performance of WCETT is dependent on the value of β. So the conclusion to draw from this experiment is that at high load levels, the total network throughput is maximized by using lower values of β.

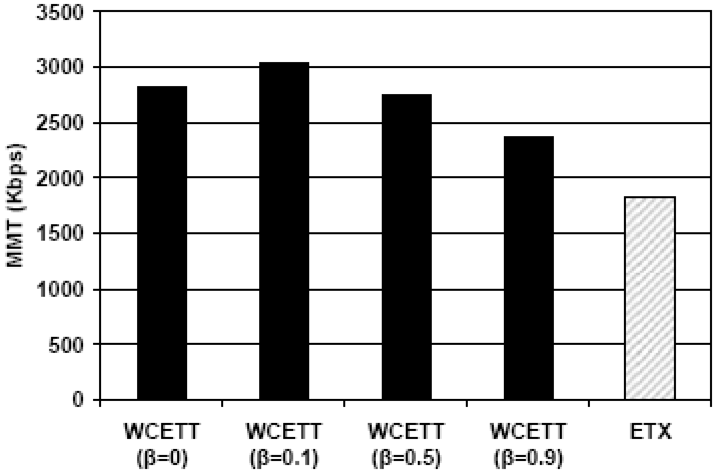


Figure 46 - Multiplied Median Throughput for WCETT and ETX with two transfers are active simultaneously [9]

Appendix B

Routing in mobile ad hoc networks (MANETs)

The highly dynamic nature of a MANET results in frequent and unpredictable changes of network topology, adding difficulty and complexity to routing among the mobile nodes. The challenges and complexities, coupled with the critical importance of routing protocol in establishing communications among mobile nodes, make routing area the most active research area within the MANET domain. MANET environment and characteristics, such as mobility and bandwidth/energy limitations, led to defining a set of desirable characteristics that a routing protocol should have to optimize the limited resources such as scalability and reliability. MANET routing protocols are typically subdivided into two main categories: proactive routing protocols and reactive on-demand routing protocols.

- **Proactive routing protocols:**
  Proactive routing protocols are derived from legacy Internet link-state and distance-vector protocols. They attempt to maintain consistent and updated routing information for every pair of network nodes by propagating, proactively, periodic and event-driven (triggered by links breakages) route updates.
  Examples of proactive protocols are: Destination-Sequenced Distance-Vector (DSDV), Optimized Link State Routing (OLSR), and Topology Dissemination Based on Reverse- Path Forwarding (TBRPF).
  Very briefly, DSDV protocol is a distance-vector protocol with extensions to make it suitable to MANETs. OLSR and TBRPF protocols are both derived from legacy link-state and represent an optimization to MANET.

- **Reactive on demand routing protocols:**

  Reactive on demand routing protocols establish the route to a destination only when there is a demand for it. Through a route discovery process, the source node usually initiates the route requested. Once a route has been established, it is maintained until this destination becomes inaccessible through this path.

  Examples of reactive protocols are Dynamic Source Routing (DSR), Ad hoc On Demand Distance Vector (AODV), Temporally Ordered Routing Algorithm (TORA), Associativity Based Routing (ABR), Signal Stability Routing (SSR) **[1]**.

  DSR is a loop-free, source based, on demand routing protocol. Each node in the network, maintains a route cache that contains the source routes learned by the node. The route discovery process is only initiated when a source node does not already have a valid route to the destination in its route cache; entries in the route cache are continually updated as new routes are learned. More details on DSR can be found in **[7]**. AODV is a reactive improvement of the DSDV protocol. AODV minimizes the number of route broadcasts by creating routes on-demand. Similar to DSR, route discovery is initiated on-demand, the route request is then forward by the source to the neighbors, and so on, until either the destination or an intermediate node with a fresh route to the destination, are located **[8]**.

  DSR has a potentially memory requirements and larger control overhead than AODV since each DSR packet must carry full routing path information, whereas in AODV packets only contain the destination address. On the other hand, DSR can utilize both symmetric and asymmetric links during routing, while AODV only works with symmetric links which is a high constraint in wireless environments. Moreover, nodes in DSR maintain multiple routes to a destination in their cache, a feature helpful during link failure.

  In general, reactive protocols such as AODV and DSR work well in small to medium size networks with moderate mobility, whereas proactive protocols more suitable for small scale static networks **[1]**.

Appendix C

Implementation Experiences

NS-2 simulator makes the assumption that there is no interference between non-overlapping channels. This assumption, however, is not entirely true in practice. In this appendix, we discuss some implementation experiences with real 802.11 hardware; specifically, some empirical measurements of inter-channel interference for two cards residing on a single node, and techniques to overcome such interference.

Experiments with real 802.11b hardware, conducted by the authors of **[15]** on a 4-node testbed, show substantial interference between two cards placed on the same machine despite operating on non-overlapping channels (see **Table 8**). The extent of interference depends on the relative positions of the cards. Placing cards right on top of each other lead to maximum interference, and achieves only a maximum 20% gain in aggregate goodput over the single channel case.

Table 8 - Interference between two internal-antenna equipped 802.11b cards placed on the same machine and operating on channels 1 and 11.

NIC-1 Action	NIC-2 Action	NIC-1 Goodput	NIC-2 Goodput	% of Max Goodput
send	silent	5.52	-	-
recv	silent	5.23	-	-
silent	send	-	5.46	-
silent	recv	-	5.37	-
send	send	2.44	2.77	47.6%
recv	send	2.21	4.02	58.3%
send	recv	4.22	2.42	61.0%
recv	recv	4.02	1.89	55.8%

If the cards are placed horizontally next to each other, the interference is minimum leading to almost 100% gain in aggregate goodput. In addition, the degradation due to inter-channel interference was found independent of the guard band, i.e. the degradation was almost the same when channel 1 and 6 were used as compared to the case when channel 1 and 11. One explanation might be that this interference arises because

of the imperfect frequency-filter present in the commodity cards.

One possible solution is to equip cards with external antennas and place the external antennas slightly away from each other. It is also necessary that the internal antenna of the card is disabled. **Table 9** shows the results **[15]**.

Table 9 - Reduced interference with the use of external antennas. The cards were operated on closer channels 1 and 6.

NIC-1 Action	NIC-2 Action	NIC-1 Goodput	NIC-2 Goodput	% of Max Goodput
send	silent	5.93	-	-
recv	silent	5.75	-	-
silent	send	-	5.96	-
silent	recv	-	5.78	-
send	send	5.52	5.96	96.6%
recv	send	5.37	5.89	96.2%
send	recv	5.42	5.41	92.5%
recv	recv	5.66	5.17	93.9%

The second experience was conducted by the authors of **[9]** on three dual-radio nodes: 1, 2 and 3. Using one card on 802.11a channel 36 between node 1 and 2, an average throughput of 15351Kbps was measured. Likewise, using the second card on 802.11a channel 64 between node 2 and 3, they saw 13483Kbps. When run simultaneously, however, these throughputs dropped to 4155Kbps and 9143Kbps, respectively. This is a reduction in throughput of 73% between node 1 and 2 and 32% between node 2 and 3.

In subsequent tests using 802.11g with 802.11a, they measured an average throughput of 15329Kbps between node 1 and 2 (using 802.11a channel 36) and 9743Kbps between node 2 and 3 (using 802.11g channel 10) when run independently. Simultaneously, the respective results were 14898Kbps and 9685Kbps. The reduction in throughput for this situation is only 3% between node 1 and 2 and 1% between node 2 and 3. They also verified that two 802.11g radios or two 802.11b radios in the testbed interfere, regardless of channel. The only explanation is that the physical proximity of the two antennas on each node is contributing to this interference problem. Therefore they decided not to use two channels in the same band when running experiments to evaluate the metric. Instead, they chose to use one 802.11a and one 802.11g channel for each node **[9]**.

Appendix D

Network Simulator - 2

Ns is a discrete event simulator targeted at networking research. Ns provides substantial support for simulation of TCP, routing, and multicast protocols over wired and wireless (local and satellite) networks. Ns began as a variant of the REAL network simulator in 1989 and has evolved substantially over the past few years. Since 1995, ns development was supported by DARPA **[29]**.

Ns is an object oriented simulator, written in C++, with an OTcl interpreter as a front-end. The simulator supports a class hierarchy in C++ (also called the compiled hierarchy in this document), and a similar class hierarchy within the OTcl interpreter (also called the interpreted hierarchy in this document). The two hierarchies are closely related to each other; from the user's perspective, there is a one-to-one correspondence between a class in the interpreted hierarchy and one in the compiled hierarchy. The root of this hierarchy is the class TclObject. Users create new simulator objects through the interpreter; these objects are instantiated within the interpreter, and are closely mirrored by a corresponding object in the compiled hierarchy. The interpreted class hierarchy is automatically established through methods defined in the class TclClass and user instantiated objects are mirrored through methods defined in the class TclObject.

Ns uses two languages because the simulator has two different kinds of things it needs to do. On one hand, detailed simulations of protocols requires a systems programming language which can efficiently manipulate bytes, packet headers, and implement algorithms that run over large data sets. For these tasks run-time speed is important and turn-around time (run simulation, find bug, fix bug, recompile, re-run) is less important.

On the other hand, a large part of network research involves slightly varying parameters or configurations, or quickly exploring a number of scenarios. In these cases, iteration time (change the model and re-run) is more important. Since configuration runs once (at the beginning of the simulation), run-time of this part of the task is less important.

Ns meets both of these needs with two languages, C++ and OTcl. C++ is fast to run but slower to change, making it suitable for detailed protocol implementation. OTcl runs much slower but can be changed very quickly (and interactively), making it ideal for simulation configuration. Ns (via tclcl) provides glue to make objects and variables appear on both languages **[30]**.

In the OTcl script provided by the user, we can define a particular network topology, the specific protocols and applications that we wish to simulate (whose behavior is already defined in the compiled hierarchy) and the form of the output that we wish to obtain from the simulator.

Ns is a discrete event simulator, where the advance of time depends on the timing of events which are maintained by a scheduler. An event is an object in the C++ hierarchy with a unique I, a scheduled time and the pointer to an object that handles the event. The scheduler keeps an ordered data structure with the events to be executed and fires them one by one, invoking the handler of the event **[31]**.

Ns-2 is the simulator used for most if not all simulation studies for WMNs. There is an extension to Ns-2 called the Rice Monarch Wireless and Mobility Extensions to ns-2 developed at the Department of Computer Science at Rice University **[32]**. It has made substantial extensions to the Ns-2 network simulator that enable it to accurately simulate mobile nodes connected by wireless network interfaces, including the ability to simulate multi-hop wireless ad hoc networks.

A snapshot of this extension features **[32]** is:

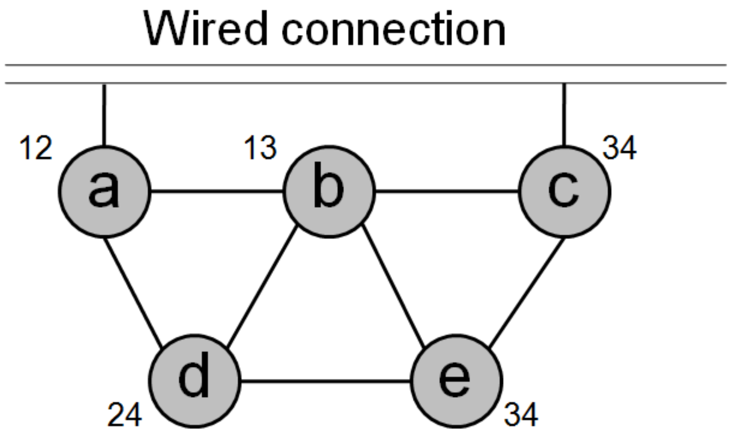
- Several fixes which should enable use on non-Intel x86 platforms
- Mobile Nodes with programmable trajectories
- Complete implementation of the IEEE 802.11 DCF MAC protocol
- Complete implementation of the Address Resolution Protocol (ARP)
- Implementations of the following multi-hop ad hoc network routing protocols:
    - Dynamic Source Routing(DSR)
    - Destination Sequenced Distance Vector(DSDV)
    - Temporally Ordered Routing Algorithm (TORA)
    - Ad hoc On-demand Distance Vector (AODV)
- Wireless network interface modeling the Lucent WaveLAN DSSS radio
- Modeling of signal attenuation, collision, and capture

- Two Ray Ground Reflection radio propagation model
- Visualization tool for creating scenario files and playing back simulation traces
- A calcdest program that annotates scenario files generated by ad-hockey with the optimal path length information
- Trace analysis scripts for protocol evaluation
- Support for new MAC layers:
    - Model of the WaveLAN-I CSMA/CA MAC
    - ``Null'' MAC layer that provides NO collisions, congestion, etc.
- Early support for ad hoc network emulation
- New features for ad-hockey, including
    - The ability to slave it to a running emulation
    - Ability to use jpegs as background images

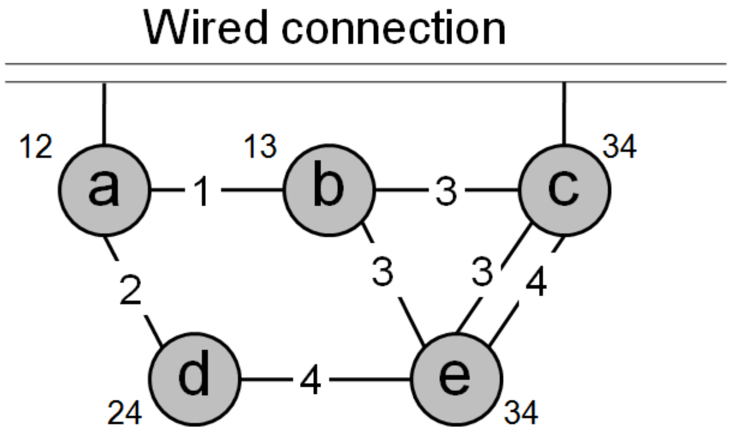
Appendix E

Comprehensive material for chapter 6

Question 1
Determine the logical topology for the physical topology shown in the picture below.

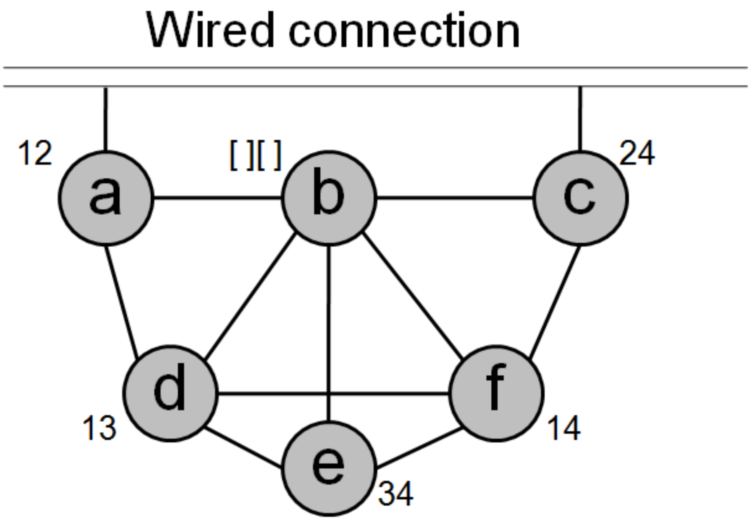


Answer:
The logical topology is as derived below. Note that, differently from the physical topology there is no link between nodes *b* and *d*, whereas there is a double link between *c* and *e*.



Question 2

Consider the physical topology reported in the figure below. Channel assignment has been performed for all nodes but node *b*, which has two NICs. How can these two interfaces tuned so that every edge of the physical topology corresponds with at least one edge in the logical topology?



Answer:
The two NICs of node *b* have to be set to channels 1 and 4.

Question 3
Discuss pros and cons of the dynamic channel assignment approach.

Answer:
The main advantage of the dynamic channel assignment is that network capacity may be better exploited. In fact, dynamic assignment can react to topology changes or to variable load in the network. On the other hand, this requires expensive terminals, able to switch rapidly from channel to channel. Also, deafness problems arise and the medium access scheme becomes more complicated.

Question 4
What is the "gateway bottleneck" and what does it imply, both in terms of limitations and practical approaches?

Answer:
The gateway bottleneck is the phenomenon, observed in practice, according to which the gateways are more congested than other nodes because the routes converge at them. This means that a single network gateway may become extremely congested and it is therefore suggested to have more than one MAP. Also, it is recommended to leverage channel assignment to give frequency diversity especially around the gateways.

Question 5
Consider a 7-node physical topology $G_P = (N, E_P)$, i.e., where $|N| = 7$. Assume all nodes have 3 NICs and the network is fully connected, that is, there is an edge between any two nodes in N. Further, assume all links are symmetric and bi-directional. Determine:
a. The number of edges $|E_P|$ in the physical topology.

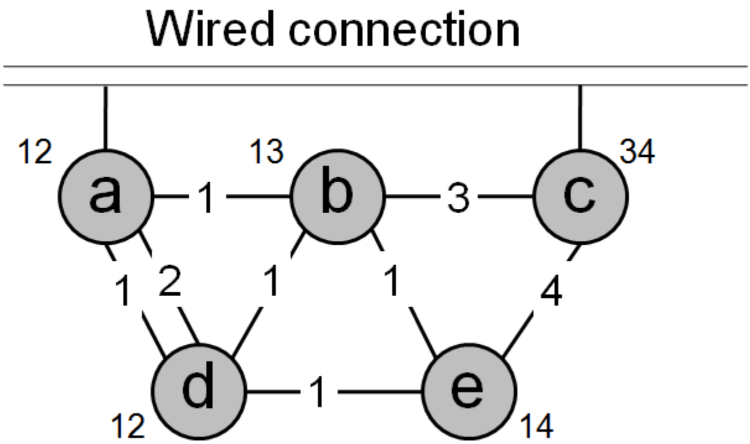
b. The number of edges $|E_L|$ in the logical topology which results from CCA (common channel assignment), i.e., the same channel for all NICs even belonging to the same node.
c. The number of edges $|E_L|$ in the logical topology which results from a channel assignment procedure imposing the same triplet of different channels (say, (1,2,3)) for the 3 NICs belonging to any node.
d. The number of edges $|E_L|$ in the logical topology which results from a channel assignment procedure where 5 nodes have their NICs set to (1,2,3) and 2 nodes have their NICs set to (1,2,4).

Answer:

a. Since the network is fully connected, there are $7\times6/2=21$ edges in E_P.
b. The number of edges in the logical topology derived from CCA is the same as $|E_P|$, i.e., 21 edges.
c. This assignment yields three times more edges than $|E_P|$, so $|E_L|=63$.
d. The shared channels 1 and 2 create, similarly to before, 42 edges. Additionally, there is a clique of 5 nodes sharing also channel 3, for $5\times4/2=10$ further edges. Finally, a single edge operates on channel 4 between the two nodes which have a NIC assigned to it. The grand total is 53 edges in this logical topology.

Question 6

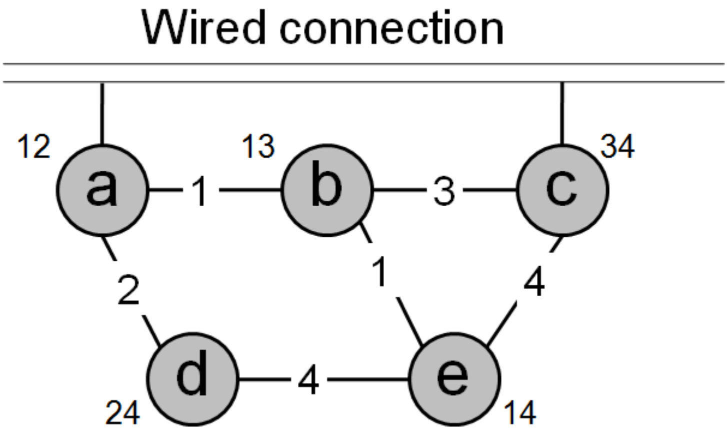
Consider the logical topology reported in the figure below.



For every $i, j \in \mathrm{N}$, $q \in \mathrm{K}$, determine the interface allocation variables y_i^q, and the channel edge variables x_{ij}^q.

Answer:
$y_a^1 = y_a^2 = y_b^1 = y_b^3 = y_c^3 = y_c^4 = y_d^1 = y_d^2 = y_e^1 = y_e^4 = 1$. Any other $y_i^q = 0$.
$x_{ab}^1 = x_{ad}^1 = x_{bd}^1 = x_{be}^1 = x_{de}^1 = x_{ad}^2 = x_{bc}^3 = x_{ce}^4 = 1$. Any other $x_{ij}^q = 0$.

Question 7
Consider the logical topology reported in the figure below.



Determine all the loop-free paths between *a* and *e*, called *P*(*a*,*e*), and between *c* and *d*, called *P*(*c*,*d*).

Answer:

(source, dest)	(*a*,*e*)	(*c*,*d*)
Possible paths	*a-b-e*	*c-e-d*
	a-b-c-e	*c-b-a-d*
	a-d-e	*c-e-b-a-d*
P(source,dest)	3	3

Question 8
Consider the same logical topology of Question 7. Assume two flows are present in the network: from *a* to *e*, with expected end-to-end traffic $\gamma^{(a,e)} = 1.8 \text{ Mbps}$, and from *c* to *d*, with expected end-to-end traffic $\gamma^{(c,d)} = 1.5 \text{ Mbps}$.
According to the load criticality method with uniform traffic repartition over all paths, determine the expected load on each of the links below.

Answer:

ℓ	$P_\ell(a,e)$	$P_\ell(c,d)$	Φ_ℓ (Mbps)
a-b	2	2	2.2
a-d	1	2	1.6
d-e	1	1	1.1
b-c	1	1	1.1
b-e	1	1	1.1
c-e	1	2	1.6

Question 9
Consider a pair of nodes i, j whose conflicting set $\mathsf{J}(i, j)$ includes, beyond (i, j), the following edges of the physical topology: $e_1, e_2, e_3, e_4, e_5, e_6$. In the logical topology e_1, e_2, e_3 are tuned on channel 1, e_4, e_5 are tuned on channel 2 and e_6 is tuned on both. Assume that $c_{xy}^{(P)}$ = 10 Mbps for any *x*, *y*.

Traffic is 2.0 Mbps between i and j, and as reported below on edges e_k.

index k	1	2	3	4	5	6
load of e_k on channel 1	3.0	1.2	0.8	0	0	1.0
load of e_k on channel 2	0	0	0	2.4	1.1	2.0

Assuming fair bandwidth share, determine $b_{ij}^{(q)}$ for q = 1,2 in the following cases:

a. Nodes i and j share one NIC assignment on channel 1.
b. Nodes i and j share one NIC assignment on channel 2.
c. Nodes i and j share two NIC assignments on both channels 1 and 2, and the traffic is equally split between the resulting two links in the logical topology.

Answer:

Recall Eqn. 12: $b_{ij}^{(q)} = \dfrac{\lambda_{ij}^{q}}{\sum_{(x,y)\in J(i,j)} \lambda_{xy}^{q}} \cdot c_{ij}^{(q)}$.

This means that the share of $c_{xy}^{(P)}$ assigned to (i, j) on channel q is proportional to the ratio of the loads of the links involved in the conflicting set. Thus:

a. $b_{ij}^{(1)}$ = 2.5 Mbps, $b_{ij}^{(2)}$ = 0 Mbps.
b. $b_{ij}^{(1)}$ = 0 Mbps, $b_{ij}^{(2)}$ = 2.667 Mbps.
c. $b_{ij}^{(1)}$ = 1.429 Mbps, $b_{ij}^{(2)}$ = 1.538 Mbps.

Question 10

Consider the same setup of Question 9 (point c) but now assume we want to take the objective of optimal utilization into account, as per Eqn. 18. Assume link (i, j) is the most critical of the network. How should its traffic be split between channels 1 and 2?

Answers:

The traffic of 2.0 Mbps has to be split between $\lambda_{ij}^{(1)}$ and $\lambda_{ij}^{(2)}$, so we impose $\lambda_{ij}^{(1)} + \lambda_{ij}^{(2)} = 2.0 \text{ Mbps}$. To obtain admissible values we also impose $0 \le \lambda_{ij}^{(q)} \le 2$. Again from Eqn. 12 we derive the expressions for $b_{ij}^{(1)}$ and $b_{ij}^{(2)}$ as functions of $\lambda_{ij}^{(1)}$ and $\lambda_{ij}^{(2)}$, respectively. We want to minimize the maximum over q = 1,2 for $\lambda_{ij}^{(q)} / b_{ij}^{(q)}$, which means that $\lambda_{ij}^{(1)} / b_{ij}^{(1)}$ must be equal to $\lambda_{ij}^{(2)} / b_{ij}^{(2)}$, which means $\lambda_{ij}^{(2)} - \lambda_{ij}^{(1)} = 0.5 \text{ Mbps}$. Solving the resulting equations, we obtain the optimal split to be $\lambda_{ij}^{(1)}$ = 0.75 Mbps and $\lambda_{ij}^{(2)}$ = 1.25 Mbps, which in turn gives $b_{ij}^{(1)}$ =1.111 Mbps and $b_{ij}^{(2)}$ =1.852 Mbps.

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