Channel Assignment in Wireless Mesh Networks

A State-of-Art

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Abstract

Wireless mesh networks offer many advantages in terms of connectivity and reliability. They provide multiple paths between nodes and are self healing. Traditionally, wireless mesh networks were used with nodes equipped with a single radio. There are however, limitations in single radio wireless mesh networks, such as lower throughput and its limited use of the available wireless channels. This report focuses on the Channel Allocation scheme which efficiently utilizes multiple wireless interfaces to achieve better throughput thereby increasing the network capacity considering the presence of co-located wireless networks. We introduce and evaluate different methods to improve the network throughput in a multi radio wireless mesh network. We present some channel assignment protocols which utilize multiple radio interfaces to improve the throughput and minimize the radio interference of the wireless network.
Chapter 1

Introduction

Traditionally in wireless networks, nodes were operating with a single radio, due to the cost associated with having multiple radios on a node, which was high. Several methods were proposed which aimed to improve the network throughput, for single-radio wireless mesh networks. However, with lowering costs, it has become possible to equip a node with multiple radios. Having multiple radios on a node opens several possibilities and options as to how these radios can be utilized to improve some of the important characteristics of the nodes and the performance of the network. Several interesting studies have been performed on multi-radio nodes and have concluded that in some cases, having multiple radios can considerably improve the throughput and network performance. In this thesis, we use the concept of a multi-radio mesh node to analyze the performance of wireless mesh networks in different conditions with different channel assignment schemes. We look at new ways to try and improve the network throughput in wireless mesh networks.
Overview of IEEE 802.11 and WMN

In this section, we describe the actual state of art related to channel assignment in wireless mesh networks. At the beginning, a brief description of the IEEE 802.11 standard is presented with a particular focus on channels supported. In the second section Wireless Mesh Networks are presented considering their characteristics and applications. Finally several channel assignment schemes are analyzed looking for advantages and disadvantages.

1.1 IEEE 802.11 Standard

IEEE 802.11 is a set of standards for wireless local area network (WLAN) computer communication, developed by the IEEE LAN/MAN Standards Committee (IEEE 802) in the 5 GHz and 2.4 GHz public spectrum bands. The 802.11 comes in several different versions, the most popular being \( a/b/g \). The chief difference between them is that \( b/g \) versions operate on the 2.4GHz spectrum and \( a \) operates on the 5.8GHz spectrum. The various versions 802.11 standard differ in the physical characteristics that determine a nodes operation in a wireless local area network or LAN. The 802.11 standard defines specifications such as the channel characteristics including the frequency of operation and the channel bandwidth, modulation scheme, the transmission power which determines the transmission range of a node, etc. An 802.11 LAN is based on a cellular architecture where the system is subdivided into cells, where each cell (called Basic Service Set or BSS, in the 802.11 nomenclature) is controlled by a Base Station (called Access Point, or in short AP). Even though that a wireless LAN may be formed by a single cell, with a single Access Point, most installations will be formed by several cells, where the Access Points are connected through some kind of backbone (called Distribution System or DS), typically Ethernet, and in some cases wireless itself. The whole interconnected Wireless LAN including the different cells, their respective Access Points and the Distribution System, is seen to the upper layers of the OSI model, as a single 802 network, and is called in the Standard as Extended Service Set (ESS).
The 802.11 family includes over-the-air modulation techniques that use the same basic protocol. The most popular are those defined by the 802.11b and 802.11g protocols, and are amendments to the original standard. 802.11a was the first wireless networking standard, but 802.11b was the first widely accepted one, followed by 802.11g and 802.11n. Security was originally purposefully weak due to export requirements of some governments, and was later enhanced via the 802.11i amendment after governmental and legislative changes. 802.11n is a new multi-streaming modulation technique that is still under draft development, but products based on its proprietary pre-draft versions are being sold. Other standards in the family (e-f, h, j) are service amendments and extensions or corrections to previous specifications.

802.11-1997 (802.11 legacy)

The original version of the standard IEEE 802.11, released in 1997 and clarified in 1999, specified two raw data rates of 1 and 2 megabits per second (Mbit/s) to be transmitted in Industrial Scientific Medical frequency band at 2.4 GHz.

Legacy 802.11 was rapidly supplemented (and popularized) by 802.11b.

802.11a

The 802.11a standard uses the same core protocol as the original standard, operates in 5 GHz band with a maximum raw data rate of 54 Mbit/s, which yields realistic net achievable throughput in the mid-20 Mbit/s.

<table>
<thead>
<tr>
<th>Release Date</th>
<th>Op. frequency</th>
<th>Data Rate(Typ)</th>
<th>Data Rate(Max)</th>
<th>Range(Indoor)</th>
</tr>
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<tbody>
<tr>
<td>October 1999</td>
<td>5 GHz</td>
<td>23 Mbit/s</td>
<td>54 Mbit/s</td>
<td>~35 m</td>
</tr>
</tbody>
</table>

Since the 2.4 GHz band is heavily used to the point of being crowded, using the relatively un-used 5 GHz band gives 802.11a a significant advantage. However, this high carrier frequency also brings a slight disadvantage: The effective overall range of 802.11a is slightly less than that of 802.11b/g; 802.11a signals cannot penetrate as far as those for 802.11b because they are absorbed more readily by walls and other solid objects in their path.
802.11 b

802.11b has a maximum raw data rate of 11 Mbit/s and uses the same media access method defined in the original standard. 802.11b products appeared on the market in early 2000, since 802.11b is a direct extension of the modulation technique defined in the original standard. The dramatic increase in throughput of 802.11b (compared to the original standard) along with simultaneous substantial price reductions led to the rapid acceptance of 802.11b as the definitive wireless LAN technology.

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<tr>
<th>Release Date</th>
<th>Op. frequency</th>
<th>Data Rate(Typ)</th>
<th>Data Rate(Max)</th>
<th>Range(Indoor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>October 1999</td>
<td>2.4 GHz</td>
<td>4.5 Mbit/s</td>
<td>11 Mbit/s</td>
<td>~35 m</td>
</tr>
</tbody>
</table>

802.11b devices suffer interference from other products operating in the 2.4 GHz band. Devices operating in the 2.4 GHz range include: microwave ovens, Bluetooth devices, baby monitors and cordless telephones.

802.11 g

In June 2003, a third modulation standard was ratified: 802.11g. This works in the 2.4 GHz band (like 802.11b) but operates at a maximum raw data rate of 54 Mbit/s, or about 19 Mbit/s net throughput. 802.11g hardware is fully backwards compatible with 802.11b hardware.

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<tr>
<th>Release Date</th>
<th>Op. frequency</th>
<th>Data Rate(Typ)</th>
<th>Data Rate(Max)</th>
<th>Range(Indoor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 2003</td>
<td>2.4 GHz</td>
<td>23 Mbit/s</td>
<td>54 Mbit/s</td>
<td>~35 m</td>
</tr>
</tbody>
</table>

The then-proposed 802.11g standard was rapidly adopted by consumers starting in January 2003, well before ratification, due to the desire for higher speeds, and reductions in manufacturing costs. By summer 2003, most dual-band 802.11 a/b products became dual-band/tri-mode, supporting a and b/g in a single mobile adapter card or access point. Details of making b and g work well together occupied much of the lingering technical process; in an 802.11g network, however, activity by a 802.11b participant will reduce the speed of the overall 802.11g network.

Like 802.11b, 802.11g devices suffer interference from other products operating in the 2.4 GHz band. Devices operating in the 2.4 GHz range include: microwave ovens, Bluetooth devices, baby monitors and cordless telephones.
802.11n

<table>
<thead>
<tr>
<th>Release Date</th>
<th>Op. frequency</th>
<th>Data Rate(Typ)</th>
<th>Data Rate(Max)</th>
<th>Range(Indoor)</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 2009 (est.)</td>
<td>5 and/or 2.4 GHz</td>
<td>74 Mbit/s</td>
<td>300 Mbit/s (2 stream)</td>
<td>~ 70 m</td>
</tr>
</tbody>
</table>

802.11n is a proposed amendment which improves upon the previous 802.11 standards by adding multiple-input multiple-output (MIMO) and many other newer features. Though there are already many products on the market based on Draft 2.0 of this proposal, the TGn workgroup is not expected to finalize the amendment until November 2008.

Channels and international compatibility

802.11 divides each of the above-described bands into channels, analogously to how radio and TV broadcast bands are carved up but with greater channel width and overlap. For example the 2.4000-2.4835 GHz band is divided into 13 channels each of width 22 MHz but spaced only 5 MHz apart, with channel 1 centered on 2412 MHz and 13 on 2472, to which Japan adds a 14th channel 12 MHz above channel 13.

Availability of channels is regulated by country, constrained in part by how each country allocates radio spectrum to various services. At one extreme Japan permits the use of all 14 channels (with the exclusion of 802.11 g/n from channel 14), while at the other Spain allowed only channels 10 and 11 (later all of the 14 channels have been allowed ), to which France adds 12 and 13. Most other European countries are almost as liberal as Japan, disallowing only channel 14, while North America and some Central and South American countries further disallow 12 and 13.

Channels Supported

802.11b/g (Frequency range 2.400 - 2.483GHz)

- US/Canada: 11 (1 - 11)
- Major European country: 13 (1 - 13)
- France: 4 (10 - 13)
- Japan: 11b: 14 (1-13 or 14th), 11g: 13 (1 - 13)
- China: 13 (1 - 13)

802.11a
- US/Canada: 12 non-overlapping channels (5.15 - 5.35GHz, 5.725 - 5.825GHz)
- Europe: 19 non-overlapping channel (5.15 - 5.35GHz, 5.47 - 5.725GHz)
- Japan: 4 non-overlapping channels (5.15 - 5.25GHz)
- China: 5 non-overlapping channels (5.725 - 5.85GHz)

**Modulation Technique**

- 802.11b/g: DSSS (DBPSK, DQPSK, CCK), OFDM (BPSK,QPSK, 16-QAM, 64-QAM)
- 802.11a: OFDM (BPSK,QPSK, 16-QAM, 64-QAM)

Besides specifying the center frequency of each channel, 802.11 also specifies (in Clause 17) a spectral mask defining the permitted distribution of power across each channel. The mask requires that the signal be attenuated by at least 30 dB from its peak energy at ±11 MHz from the center frequency, the sense in which channels are effectively 22 MHz wide. One consequence is that stations can only use every fourth or fifth channel without overlap, typically 1, 6 and 11 in the Americas, 1-13 in Europe.

Since the spectral mask only defines power output restrictions up to ±22 MHz from the center frequency to be attenuated by 50 dB, it is often assumed that the energy of the channel extends no further than these limits. It is more correct to say that, given the separation between channels 1, 6, and 11, the signal on any channel should be sufficiently attenuated to minimally interfere with a transmitter on any other channel. Due to the near-far problem a transmitter can impact a receiver on a "non-overlapping" channel, but only if it is close to the victim receiver (within a meter) or operating above allowed power levels.
1.2 Wireless Mesh Networks

Wireless Mesh Networks (WMNs) are built on a mix of fixed and mobile nodes interconnected via wireless links to form a multi-hop ad hoc network. Wireless mesh networks consist of mesh routers and mesh clients, where mesh routers have minimal mobility and form the backbone of WMNs. They provide network access for both mesh and conventional clients. The integration of WMNs with other networks such as the Internet, cellular, IEEE 802.11, IEEE 802.15, IEEE 802.16, sensor networks, etc., can be accomplished through the gateway and bridging functions in the mesh routers. Mesh clients can be either stationary or mobile, and can form a client mesh network among themselves and with mesh routers. WMNs are anticipated to resolve the limitations and to significantly improve the performance of ad hoc networks, wireless local area networks (WLANs), wireless personal area networks (WPANs), and wireless metropolitan area networks (WMANs). They are undergoing rapid progress and inspiring numerous deployments. WMNs will deliver wireless services for a large variety of applications in personal, local, campus, and metropolitan areas. Despite recent advances in wireless mesh networking, many research challenges remain in all protocol layers. This section presents a detailed study on recent advances and open research issues in WMNs. System architectures and applications of WMNs are described, followed by discussing the critical factors influencing protocol design. Theoretical network capacity and the state-of-the-art protocols for WMNs are explored with an objective to point out a number of open research issues. Finally, testbeds, industrial practice, and current standard activities related to WMNs are highlighted.

Network architecture

WMNs consist of two types of nodes: mesh routers and mesh clients. Other than the routing capability for gateway/repeater functions as in a conventional wireless router, a wireless mesh router contains additional routing functions to support mesh networking. To further improve the flexibility of mesh networking, a mesh router is usually equipped with multiple wireless interfaces built on either the same or different wireless access technologies. Compared with a conventional wireless router, a wireless mesh router can achieve the same coverage with much lower transmission power through multi-hop communications. Optionally, the medium access control (MAC) protocol in a mesh router is enhanced with better scalability in a multi-hop mesh environment. In spite of all these differences, mesh and conventional wireless routers are usually built based on a similar hardware platform. Mesh routers can
be built based on dedicated computer systems (e.g., embedded systems) and look compact. They can also be built based on general-purpose computer systems (e.g., laptop/desktop PC). Mesh clients also have necessary functions for mesh networking, and thus, can also work as a router. However, gateway or bridge functions do not exist in these nodes. In addition, mesh clients usually have only one wireless interface. As a consequence, the hardware platform and the software for mesh clients can be much simpler than those for mesh routers. Mesh clients have a higher variety of devices compared to mesh routers. They can be a laptop/desktop PC, pocket PC, PDA, IP phone, RFID reader, BACnet (building automation and control networks) controller, and many other devices.

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

- **Infrastructure/Backbone WMNs.** The architecture, where dash and solid lines indicate wireless and wired links, respectively. This type of WMNs includes mesh routers forming an infrastructure for clients that connect to them. The WMN infrastructure/backbone can be built using various types of radio technologies, in addition to the mostly used IEEE 802.11 technologies. The mesh routers form a mesh of self-configuring, self-healing links among themselves. With gateway functionality, mesh routers can be connected to the Internet. This approach, also referred to as infrastructure meshing, provides backbone for conventional clients and enables integration of WMNs with existing wireless networks, through gateway/bridge functionalities in mesh routers. Conventional clients with Ethernet interface can be connected to mesh routers via Ethernet links. For conventional clients with the same radio technologies as mesh routers, they can directly communicate with mesh routers. If different radio technologies are used, clients must communicate with the base stations that have Ethernet connections to mesh routers. Infrastructure/Backbone WMNs are the most commonly used type. For example, community and neighborhood networks can be built using infrastructure meshing. The mesh routers are placed on the roof of houses in a neighborhood, which serve as access points for users inside the homes and along the roads. Typically, two types of radios are used in the routers, i.e., for backbone communication and for user communication, respectively. The mesh backbone communication can be established using long-range communication techniques including directional antennas.
Client WMNs. Client meshing provides peer-to-peer networks among client devices. In this type of architecture, client nodes constitute the actual network to perform routing and configuration functionalities as well as providing end-user applications to customers. Hence, a mesh router is not required for these types of networks. In Client WMNs, a packet destined to a node in the network hops through multiple nodes to reach the destination. Client WMNs are usually formed using one type of radios on devices. Moreover, the requirements on end-user devices is increased when compared to infrastructure meshing, since, in Client WMNs, the end-users must perform additional functions such as routing and self-configuration.

Hybrid WMNs. This architecture is the combination of infrastructure and client meshing. Mesh clients can access the network through mesh routers as well as directly meshing with 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 provide improved connectivity and coverage inside the WMN. The hybrid architecture will be the most applicable case in our opinion.
Characteristics

The characteristics of WMNs are explained as follows:

- Multi-hop wireless network. An objective to develop WMNs is to extend the coverage range of current wireless networks without sacrificing the channel capacity. Another objective is to provide non-line-of-sight (NLOS) connectivity among the users without direct line-of-sight (LOS) links. To meet these requirements, the mesh-style multi-hopping is indispensable, which achieves higher throughput without sacrificing effective radio range via shorter link distances, less interference between the nodes, and more efficient frequency re-use.

- Support for ad hoc networking, and capability of self-forming, self-healing, and self-organization. WMNs enhance network performance, because of flexible network architecture, easy deployment and configuration, fault tolerance, and mesh connectivity, i.e., multi-point-to-multi-point communications. Due to these features, WMNs have low upfront investment requirement, and the network can grow gradually as needed.

- Mobility dependence on the type of mesh nodes. Mesh routers usually have minimal mobility, while mesh clients can be stationary or mobile nodes.

- Multiple types of network access. In WMNs, both backhaul access to the Internet and peer-to-peer (P2P) communications are supported. In addition, the integration of WMNs with other wireless networks and providing services to end-users of these networks can be accomplished through WMNs.

- Dependence of power-consumption constraints on the type of mesh nodes. Mesh routers usually do not have strict constraints on power consumption. However, mesh clients may require power efficient protocols. As an example, a mesh-capable sensor requires its communication protocols to be power efficient.
Thus, the MAC or routing protocols optimized for mesh routers may not be appropriate for mesh clients, such as sensors, because power efficiency is the primary concern for wireless sensor networks.

- Compatibility and interoperability with existing wireless networks. For example, WMNs built based on IEEE 802.11 technologies must be compatible with IEEE 802.11 standards in the sense of supporting both mesh-capable and conventional Wi-Fi clients. Such WMNs also need to be inter-operable with other wireless networks such as WiMAX, Zig-Bee, and cellular networks. Based on their characteristics, WMNs are generally considered as a type of ad-hoc networks due to the lack of wired infrastructure that exists in cellular or Wi-Fi networks through deployment of base stations or access points. While ad hoc networking techniques are required by WMNs, the additional capabilities necessitate more sophisticated algorithms and design principles for the realization of WMNs. More specifically, instead of being a type of ad-hoc networking, WMNs aim to diversify the capabilities of ad hoc networks. Consequently, ad hoc networks can actually be considered as a subset of WMNs. To illustrate this point, the differences between WMNs and ad hoc networks are outlined below. In this comparison, the hybrid architecture is considered, since it comprises all the advantages of WMNs.

- Wireless infrastructure/backbone. As discussed before, WMNs consist of a wireless backbone with mesh routers. The wireless backbone provides large coverage, connectivity, and robustness in the wireless domain. However, the connectivity in ad hoc networks depends on the individual contributions of end-users which may not be reliable.

- Integration. WMNs support conventional clients that use the same radio technologies as a mesh router. This is accomplished through a host-routing function available in mesh routers. WMNs also enable integration of various existing networks such as Wi-Fi, the Internet, cellular and sensor networks through gateway/bridge functionalities in the mesh routers. Consequently, users in one network are provided with services in other networks, through the use of the wireless infrastructure. The integrated wireless networks through WMNs resembles the Internet backbone, since the physical location of network nodes becomes less important than the capacity and network topology.

- Dedicated routing and configuration. In ad hoc networks, end-user devices also perform routing and configuration functionalities for all other nodes. However, WMNs contain mesh routers for these functionalities. Hence, the load
on end-user devices is significantly decreased, which provides lower energy consumption and high-end application capabilities to possibly mobile and energy constrained end-users. Moreover, the end-user requirements are limited which decreases the cost of devices that can be used in WMNs.

- **Multiple radios.** As discussed before, mesh routers can be equipped with multiple radios to perform routing and access functionalities. This enables separation of two main types of traffic in the wireless domain. While routing and configuration are performed between mesh routers, the access to the network by end users can be carried out on a different radio. This significantly improves the capacity of the network. On the other hand, in ad hoc networks, these functionalities are performed in the same channel, and as a result, the performance decreases.

- **Mobility.** Since ad hoc networks provide routing using the end-user devices, the network topology and connectivity depend on the movement of users. This imposes additional challenges on routing protocols as well as on network configuration and deployment.

### Application scenarios

Research and development of WMNs is motivated by several applications which clearly demonstrate the promising market while at the same time these applications cannot be supported directly by other wireless networks such as cellular networks, ad hoc networks, wireless sensor networks, standard IEEE 802.11, etc. In this section, we discuss these applications.

- **Broadband home networking.** Currently broadband home networking is realized through IEEE 802.11 WLANs. An obvious problem is the location of the access points. Without a site survey, a home (even a small one) usually has many dead zones without service coverage. Solutions based on site survey are expensive and not practical for home networking, while installation of multiple access points is also expensive and not convenient because of Ethernet wiring from access points to backhaul network access modem or hub. Moreover, communications between end nodes under two different access points have to go all the way back to the access hub. This is obviously not an efficient solution, especially for broadband networking. Mesh networking, can resolve all these issues in home networking. The access points must be replaced by wireless mesh routers with mesh connectivity established among them. Therefore, the
communication between these nodes becomes much more flexible and more robust to network faults and link failures. Dead zones can be eliminated by adding mesh routers, changing locations of mesh routers, or automatically adjusting power levels of mesh routers. Communication within home networks can be realized through mesh networking without going back to the access hub all the time. Thus, network congestion due to backhaul access can be avoided. In this application, wireless mesh routers have no constraints on power consumptions and mobility. Thus, protocols proposed for mobile ad hoc networks and wireless sensor networks are too cumbersome to achieve satisfactory performance in this application. On the other hand, Wi-Fis are not capable of supporting ad hoc multi-hop networking. As a consequence, WMNs are well suited for broadband home networking.

![WMNs for Broadband Home Networking](image)

**Figure 1.3:** WMNs for Broadband Home Networking [1]

- Community and neighborhood networking. In a community, the common architecture for network access is based on cable or DSL connected to the Internet, and the last-hop is wireless by connecting a wireless router to a cable or DSL modem. This type of network access has several drawbacks:
  - Even if the information must be shared within a community or neighborhood, all traffic must flow through Internet. This significantly reduces network resource utilization.
  - Large percentage of areas in between houses is not covered by wireless services.
  - An expensive but high bandwidth gateway between multiple homes or neighborhoods may not be shared and wireless services must be set up individually. As a result, network service costs may increase.
Only a single path may be available for one home to access the Internet or communicate with neighbors. WMNs mitigate the above disadvantages through flexible mesh connectivities between home. WMNs can also enable many applications such as distributed file storage, distributed file access, and video streaming.

- Enterprise networking. This can be a small network within an office or a medium-size network for all offices in an entire building, or a large scale network among offices in multiple buildings. Currently, standard IEEE 802.11 wireless networks are widely used in various offices. However, these wireless networks are still isolated islands. Connections among them have to be achieved through wired Ethernet connections, which is the key reason for the high cost of enterprise networks. In addition, adding more backhaul access modems only increases capacity locally, but does not improve robustness to link failures, network congestion and other problems of the entire enterprise network. 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 thus, improve the robustness and resource utilization of enterprise networks. WMNs can grow easily as the size of enterprise expands. WMNs for enterprise networking are much more complicated than at home because more nodes and more complicated network topologies are involved. The service model of enterprise networking can be applied to many other public and commercial service networking scenarios such as airports, hotels, shopping malls, convention centers, sport centers, etc.
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 in any cellular networks. For example, an IEEE 802.11g node can transmit at a rate of 54 Mbps. Moreover, the communication between nodes in WMNs does not rely on a wired backbone. Compared to wired networks, e.g., cable or optical networks, wireless mesh MAN is an economic alternative to broadband networking, especially in underdeveloped regions. Wireless mesh MAN covers a potentially much larger area than home, enterprise, building, or community networks. Thus, the requirement on the network scalability by wireless mesh MAN is much higher than that by other applications.

Transportation systems. Instead of limiting IEEE 802.11 or 802.16 access to stations and stops, mesh networking technology can extend access into buses, ferries, and trains. Thus, convenient passenger information services, remote monitoring of in-vehicle security video, and driver communications can be supported. 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.

Building automation. In a building, various electrical devices including power,
light, elevator, air conditioner, etc., need to be controlled and monitored. Currently this task is accomplished through standard wired networks, which is very expensive due to the complexity in deployment and maintenance of a wired network. Recently Wi-Fi based networks have been adopted to reduce the cost of such networks. However, this effort has not achieved satisfactory performance yet, because deployment of Wi-Fis for this application is still rather expensive due to wiring of Ethernet. If BACnet (building automation and control networks) access points are replaced by mesh routers, the deployment cost will be significantly reduced. The deployment process is also much simpler due to the mesh connectivity among wireless routers.

- Health and medical systems. In a hospital or medical center, monitoring and diagnosis data need to be processed and transmitted from one room to another for various purposes. Data transmission is usually broadband, since high resolution medical images and various periodical monitoring information can easily produce a constant and large volume of data. Traditional wired networks can only provide limited network access to certain fixed medical devices. Wi-Fi based networks must rely on the existence of Ethernet connections, which may cause high system cost and complexity but without the abilities to eliminate dead spots. However, these issues do not exist in WMNs.

- Security surveillance systems. As security is turning out to be a very high concern, security surveillance systems becomes a necessity for enterprise buildings, shopping malls, grocery stores, 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.
In addition to the above applications, WMNs can also be applied to Spontaneous (Emergency/Disaster) Networking and P2P Communications. For example, wireless networks for an emergency response team and firefighters do not have in-advance knowledge of where the network should be deployed. By simply placing wireless mesh routers in desired locations, a WMN can be quickly established. For a group of people holding devices with wireless networking capability, e.g., laptops and PDAs, P2P communication anytime anywhere is an efficient solution for information sharing. WMNs are able to meet this demand. These applications illustrate that WMNs are a superset of ad-hoc networks, and thus can accomplish all functions provided by ad hoc networking.
Chapter 2

Channel Assignment in WMNs

Channel Assignment (CA) in a multiradio WMN environment consists of assigning channels to the radio interfaces in order to achieve efficient channel utilization and minimize interference. In this chapter, we describe different schemes that can be used to assign channels in a wireless mesh network. These schemes are generally classified as: Static, Dynamic and Hybrid Channel Assignment.

2.1 Introduction

WMNs have emerged as a promising candidate for extending the coverage of WiFi islands and providing flexible high-bandwidth wireless backhaul for converged networks. The wireless backbone, consisting of wireless mesh routers equipped with one or more radio interfaces, highly affects the capacity of the mesh network. This has a significant impact on the overall performance of the system, thus generating extensive research in order to tackle the specific challenges of the WMN. Current state-of-the-art mesh networks, which use off-the-shelf 802.11-based network cards, are typically configured to operate on a single channel using a single radio. This configuration adversely affects the capacity of the mesh due to interference from adjacent nodes in the network. Various schemes have been proposed to address this capacity problem, such as modified medium access control (MAC) protocols adapted to WMNs, the use of channel switching on a single radio, and directional antennas. While directional antennas and modified MAC protocols make the practical deployment of such solutions infeasible on a wide scale, the main issue in using multiple channels with a single radio is that dynamic channel switching requires tight time synchronization between the nodes.
Equipping each node with multiple radios is emerging as a promising approach to improving the capacity of WMNs. First, the IEEE 802.11b/g and IEEE 802.11a standards provide 3 and 12 non-overlapping (frequency) channels, respectively, which can be used simultaneously within a neighborhood (by assigning non-overlapping channels to radios). This then leads to efficient spectrum utilization and increases the actual bandwidth available to the network. Second, the availability of cheap off-the-shelf commodity hardware also makes multiradio solutions economically attractive. Finally, the spatio-temporal diversity of radios operating on different frequencies with different sensing-to-hearing ranges, bandwidth, and fading characteristics can be leveraged to improve the capacity of the network. Although multiradio mesh nodes have the potential to significantly improve the performance of mesh networks, efficient channel assignment is a key issue in guaranteeing network connectivity while still mitigating the adverse effects of interference from the limited number of channels available to the network. A WMN node needs to share a common channel with each of its communication-range neighbors with which it wishes to set up a virtual link 1 or connectivity. However, to reduce interference, a node should minimize the number of neighbors with which it will share a common channel. There is thus a trade-off between maximizing connectivity and minimizing interference, as illustrated in Fig. 2.1. In this figure the maximum connectivity that can be achieved is shown in Fig. 2.1a. In both Fig. 2.1b and 2.1c, there are four channels available but only three can be assigned to the radios in Fig. 2.1b that maximize connectivity. On the other hand, all four can be exploited simultaneously if the only goal is to minimize interference, as shown in Fig. 2.1c. The above issues provided us with the motivation to undertake a systematic study of different channel assignment schemes for WMNs, and examine their relative strengths and weaknesses.

We compare different CA schemes.
2.2 Static Assignment

Fixed assignment schemes assign channels to interfaces either permanently or for long time intervals with respect to the interface switching time. Such schemes can be further subdivided into common channel assignment and varying channel assignment.

Common Channel Assignment is the simplest scheme. In this case the radio interfaces of each node are all assigned the same set of channels. 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 network interface cards (NICs) used per node. Thus, although this scheme presents a simple CA strategy, it fails to account for the various factors affecting channel assignment in a WMN. In this section we will not describe any scheme using this technique.

In the Varying Channel Assignment scheme, interfaces of different nodes may be assigned different sets of channels. However, the assignment of channels may lead to network partitions and topology changes that may increase the length of routes between the mesh nodes. Therefore, in this scheme, assignment needs to be carried out carefully. Below is presented the VCA approach through two existing algorithms, TiMesh, from paper [7], and MesTic, from paper [5].

2.3 Dynamic Assignment

Dynamic assignment strategies allow any interface to be assigned any channel, and interfaces can frequently switch from one channel to another. Therefore, when nodes need to communicate with each other, a coordination mechanism has to ensure they are on a common channel. For example, such mechanisms may require all nodes to periodically visit a predetermined rendezvous channel to negotiate channels for the next phase of transmission. In the Slotted Seeded Channel Hopping (SSCH) mechanism, each node switches channels synchronously in a pseudo-random sequence so that all neighbors meet periodically in the same channel. The benefit of dynamic assignment is the ability to switch an interface to any channel, thereby offering the potential to use many channels with few interfaces. However, the key challenges involve channel switching delays (typically on the order of milliseconds in commodity 802.11 wireless cards), and the need for coordination mechanisms for channel switching between nodes. For this category are presented three schemes: Hyacinth, from paper [9], MeshChop, from paper [4], Distributed Channel Assignment, from
2.4 Hybrid Assignment

Hybrid channel assignment strategies combine both static and dynamic assignment properties, for example, by applying a fixed assignment for some interfaces and a dynamic assignment for other interfaces. Hybrid strategies can be further classified based on whether the fixed interfaces use a common channel or varying channel approach. The fixed interfaces can be assigned a dedicated control channel or a data and control channel, while the other interfaces 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. For this category are presented two schemes, one using varying channel, HMCP, from paper [8], and one using common channel approach, BSF-CA, from paper [2].

2.5 Other Assignments

In this section are presented other channel assignment schemes that consider new approach for selecting channel. In particular, are introduced two algorithm, one for broadcast and one for unicast traffic, that use superimposed codes, from paper [6].
2.6 Static Channel Assignment Schemes

TiMesh

In this scheme, logical topology formation, interface assignment, channel allocation, and routing are formulated as a joint linear optimization problem. They call the proposed MC-WMN architecture TiMesh [7]. Its characteristics are:

- The model formulation takes into account the number of available NICs in each wireless mesh router, the number of available frequency channels, the communication range and the interference range of the wireless mesh routers, and the expected traffic load between different source and destination pairs.

- The model formulation allows having multiple logical links between the same pair of routers. This further increases the effective data transmission rate between the two routers.

- The proposed algorithm guarantees the network connectivity. It also supports both internal traffic among the wireless routers and external traffic to the Internet.

This scheme first models an MC-WMN by a physical topology graph \( G(N,E) \) where \( N \) denotes the set of all vertices and \( E \) denotes the set of all unidirectional edges. Each vertex represents a stationary wireless mesh router. Each wireless mesh router is equipped I network interface cards and there are \( C \) orthogonal frequency channels available.

For any two nodes \( m \) and \( n \) such that \( e_{mn} \) belongs to \( E \), and any frequency channel \( i \) belonging to \( \{1, \ldots, C\} \), we define a link channel allocation variable \( x^i_{mn} \). In the logical topology, if node \( m \) communicates with node \( n \) over the \( i \)th frequency channel, then \( x^i_{mn} \) is equal to 1; otherwise, it is equal to zero. To establish the logical links, nodes \( m \) and \( n \) should assign the same frequency channels to communicate with each other. This requires that,

\[
x^i_{mn} = x^i_{nm}, \quad \forall \ m, n \in N, \ e_{mn} \in E, \ \forall \ i = 1, \ldots, C. \quad (1)
\]

The link channel allocation variables implicitly provide the required information to create the logical topology. Due to traffic and interference constraints, it is possible that there is a link between nodes \( m \) and \( n \) in the physical topology graph (i.e., \( e_{mn} \) belongs to \( E \)), but there is no logical link between them in the logical topology. In that case, we have \( x^i_{mn} = 0 \) for all \( i = 1, \ldots, C \). Note that we allow multiple logical links between the same pair of nodes in the logical topology. We
operate independently over distinct frequency channels and can significantly increase the effective capacity between two neighboring nodes. For any node $m$ belongs to $N$ and any channel $i$ belonging to $\{1, \ldots, C\}$, we define $y_{m}^{i}$ to be as follows:

$$y_{m}^{i} = \begin{cases} 1, & \text{if } \exists n \in N \text{ and } e_{mn} \in E, \text{ such that } x_{mn}^{i} = 1 \\ 0, & \text{otherwise.} \end{cases}$$ (2)

Where $y_{m}^{i}$ corresponds to the node channel allocation variable corresponding to node $m$ and channel $i$. From (2), $i=1$ $y_{m}$ indicates the total number $i$ of channels that are being used by node $m$ to establish logical links with its neighboring nodes. Since each NIC operates on a distinct frequency channel:

$$\sum_{i=1}^{C} y_{m}^{i} \leq I, \quad \forall m \in N. \quad (3)$$

The link and node channel allocation variables implicitly provide the required information for interface assignment. The desired correspondence in (2) is obtained by having $y_{m}$ be a continuous real variable for all nodes $m$ belonging to $N$ and all channels $i$: $\{1, \ldots, C\}$ and also requiring that:

$$0 \leq y_{m}^{i} \leq \sum_{n \in N, e_{mn} \in E} x_{mn}^{i}, \quad (4a)$$

$$x_{mn}^{i} \leq y_{m}^{i} \leq 1, \quad \forall n \in N, \ e_{mn} \in E. \quad (4b)$$

Let $c^{0}$ denote the nominal link-layer data rate in the corresponding 802.11 standard (e.g., 54 Mbps in 802.11a). Also let $0 \leq c^{i} < c^{0}$ denote the effective capacity of the $mn$ logical link $(m, n)$ in the direction from node $m$ to node $n$ over frequency channel $i$. We have:

$$c_{mn}^{i} \leq \frac{x_{mn}^{i}}{c^{0}}, \quad \forall m, n \in N, \ e_{mn} \in E, \forall i = 1, \ldots, C. \quad (5)$$

For any two nodes $m$ and $n$ such that $emn$ belongs to $E$, is defined a set of potential interfering links $F_{mn}$ included to $E$. $F_{mn}$ includes all $e_{pq}$ belonging to $E$ such that nodes $p$ or $q$ (or both) are within the interference range of nodes $m$ or $n$ (or both). Note that always $e_{mn}$ belonging to $F_{mn}$.

$$\frac{c_{mn}^{i}}{c^{0}} + \sum_{p, q, e_{r} \in F_{mn}} \frac{c_{p}^{i}}{c^{0}} \leq 1, \quad \forall m, n \in N, \ e_{mn} \in E, \forall i = 1, \ldots, C. \quad (6)$$

Let $y_{sd}$ denote the expected traffic rate to be delivered between source and destination pair $(s, d)$, where $s, d$ belongs to $N$. The information $y_{sd}$ is assumed known
for all source and destination pairs is given. For any source and destination pair \((s, d)\), any nodes \(m, n\) belonging to \(N\) such that \(e_{mn}\) belongs to \(E\), and any channel \(i\) belonging to \(\{1, \ldots, C\}\), is defined a binary routing variable \(a_{sd}^{mn,i}\). The variable \(a_{sd}^{mn,i}\) is equal to 1 if the \(mn,i\) traffic from source \(s\) to destination \(d\) is being routed via link \((m, n)\) in the direction from node \(m\) to node \(n\) over channel \(i\), and is equal to 0 otherwise. Note that \(a_{sd}^{mn,i} = a_{sd}^{mn,i}\) in general. Multiple links between a pair of nodes can provide more than one path between them. Since each of the multiple links is operating over a distinct channel, packets that are forwarded on different links experience different latencies. Thus, if packets that belong to the same flow use parallel links between a pair of neighboring nodes, this can cause packets to arrive out of order. To avoid this issue, only one of the available logical links between each pair of neighboring nodes is used to route packets of each flow. That is,

\[
\sum_{i=1}^{C} a_{sd}^{mn,i} \leq 1, \quad \forall s, d, m, n \in N, \, e_{mn} \in E. \quad (7)
\]

Let \(a_{mn,i}^{sd}\) denote the aggregate traffic from all source and \(mn\) destination pairs that is routed over logical link \((m, n)\) in the direction from node \(m\) to node \(n\) over channel \(i\). We have,

\[
\lambda_{mn} = \sum_{s, d \in N} a_{mn,i}^{sd} r_{sd}, \quad \forall m, n \in N, \, e_{mn} \in E; \quad \forall i = 1, \ldots, C. \quad (8)
\]

The aggregate traffic cannot be more than the effective \(mn\) capacity \(c_{i}\) for all nodes \(m, n\) belonging to \(N\) such that \(e_{mn}\) belongs to \(E\), and \(mn\) all channels \(i\): \(\{1, \ldots, C\}\). Consider the following constraint:

\[
\lambda_{mn}^{i} \leq A c_{mn}^{i}, \quad \forall m, n \in N, \, e_{mn} \in E; \quad \forall i = 1, \ldots, C. \quad (9)
\]

Note that this is a positive parameter.

The flow conservation requires that for \(s, d, m\) belonging to \(N\),

\[
\sum_{n \in N, i=1}^{C} a_{mn,i}^{sd} r_{sd} - \sum_{n \in N, i=1}^{C} a_{mn,i}^{sd} r_{sd} = \begin{cases} a_{sd}, & \text{if } s = m, \\ 0, & \text{if } d = m, \\ \text{otherwise.} \end{cases}
\]

(10)

From constraint (9), the difference is always non-negative. The difference tends to 0 and the corresponding logical \(mn\) \(mn\) link becomes more prone to congestion. Let \(D_{\text{min}}\) denote the minimum difference across all channels and all \(mn\) \(mn\) links that exist in the logical topology. That is,
The desired correspondence in (11) can be obtained by requiring that:

$$
\delta_{\min} \leq (\Lambda \epsilon_{mn}^i - \lambda_{mn}^i) + \Lambda \epsilon^0(1 - x_{mn}^i), \quad \forall m, n \in N, e_{mn} \in E, \forall i = 1, \ldots, C. \tag{12}
$$

The hop count constraint is defined to be as follows:

$$
\sum_{m,n \in N, e_{mn} \in E} \sum_{i=1}^{C} a_{mn,i}^{sd} \leq \Gamma h_{G}^{sd}, \quad \forall s,d \in N. \tag{13}
$$

where \( T \geq 1 \) is a tunable parameter to set an upper bound on the routing stretch factor. Note that there is always a trade off between load balancing and shortest path routing. This trade off can be controlled by using the tunable parameter \( T \). By assigning \( T = 1 \), the routing part of the algorithm becomes the shortest path routing. By assigning \( T = \infty \), the hop-count constraint (13) is relaxed. In general, the greater the tunable parameter \( T \), the larger the feasible region.

The complete joint problem formulation is:

\[
\begin{align*}
\text{maximize} & \quad \delta_{\min} \\
\text{subject to} & \quad x_{mn}^i = x_{mn}^i, \\
& \quad x_{mn}^i \leq y_{mn}^i, \\
& \quad y_{mn}^i \leq \sum_{e_{mn} \in E} \lambda_{mn}^i, \\
& \quad \sum_{i=1}^{C} y_{mn}^i \leq 1, \\
& \quad \sum_{i=1}^{C} \epsilon_{mn}^i \leq \epsilon_{mn}^0, \\
& \quad \epsilon_{mn}^i + \sum_{p,q \in E, p < q} \sum_{i=1}^{C} a_{mn,i}^{sd} = \begin{cases} 1, & \text{if } s = m, \\ -1, & \text{if } d = m, \\ 0, & \text{otherwise}, \end{cases}, \\
& \quad \sum_{i=1}^{C} a_{mn,i}^{sd} \leq 1, \\
& \quad \lambda_{mn}^i \leq \Lambda \epsilon_{mn}^i, \\
& \quad \delta_{\min} \leq (\Lambda \epsilon_{mn}^i - \lambda_{mn}^i) + \Lambda \epsilon^0(1 - x_{mn}^i), \\
& \quad \sum_{i=1}^{C} \sum_{e_{mn} \in E} a_{mn,i}^{sd} \leq \Gamma h_{G}^{sd}, \\
\end{align*}
\]

where

- \( x_{mn}^i, a_{mn,i}^{sd} \in \{0, 1\}, \quad y_{mn}^i, \epsilon_{mn}^i, \lambda_{mn}^i, \delta_{\min} \geq 0, \)
- \( y_{mn}^i \leq 1, \quad \epsilon_{mn}^i \leq \epsilon_{mn}^0, \)
- \( x_{mn}^i, \epsilon_{mn}^i, \lambda_{mn}^i, \delta_{\min} \geq 0, \quad \forall m, n, i, \quad \epsilon_{mn}^i \leq \epsilon_{mn}^0, \quad \forall i = 1, \ldots, C. \)

(14)
There are efficient commercial software to solve linear mixed-integer programs. Most of them use the branch-and-cut algorithm. Problem (14) can easily be solved in practice for small-scale MC-WMNs. However, finding the optimal solutions are not trivial for large-scale networks. An alternative is to use some simple and efficient metaheuristic methods to find the sub-optimal solutions. In this scheme, they use the Iterated Local Search (ILS) which is a metaheuristic algorithm. The pseudo-code for the proposed ILS algorithm is provided in Algorithm 1 from [7]. Given the sub-optimal topology formation, interface assignment and channel allocation solutions, the routing path from source $s$ to destination $d$ is assigned by traversing the logical topology from source $s$ to destination $d$, and by choosing the next hop based on the maximum observed value for routing variable $a$. The intuitive justification is that if the relaxed asd is close to 1, it indicates that it is better to forward $mn,i$ the packets from source $s$ to destination $d$ on the logical link $(m, n)$ over channel $i$. On the other hand, if the relaxed asd $mn,i$ is close to 0, it implies that it is better to avoid forwarding packets on logical link $(m, n)$ over channel $i$.

Observations:

This algorithm is able to find the best solution for balancing traffic load. This scheme however cannot respond dynamically if the traffic changes over certain period of time. Moreover, because the logical topology is chosen to minimize interference (without a common channel), if a node fails communication, the network could be partitioned without possibilities to restore the system.
MesTic

The first scheme analyzed is called MesTic [5], which stands for mesh-based traffic and interference aware channel assignment. It has the following important features:

- MesTic 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.

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 this scheme has been designed for a mesh network with a single gateway node, but could easily be extended to multiple gateways with minor modifications to the basic scheme.

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, $\text{Rank}(\text{node})$, 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:

- The aggregate traffic at a node based on the offered load of the mesh network

- The distance of the node, measured as the minimum number of hops from the gateway node

- 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:

$$\text{Rank}(\text{node}) = \frac{\text{Aggregate Traffic}(\text{node})}{\min \text{ hops from the gateway (node)} \times \text{number of radios (node)}} \quad (1)$$

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 Eq. (1) increases the rank of a node with its traffic. In addition, due to the hierarchical nature of a mesh topology, the nodes nearest 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. They envisage that the traffic characterizations aggregated from a large number of network flows change over longer periods of time, whereas MesTiC can reassign 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 Fig. 2.1.
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, 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, the least used channel among those already assigned to its radios is assigned to the link (II.2.b).

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.

**Algorithm:**

Below we present the pseudo-codes of MesTiC which begins with a set of input parameters. The connectivity graph represents an undirected graph where a pair of nodes has a link between them if they are located within the transmission range of each other. In this algorithm is used an aggregate link traffic matrix between nodes within transmission range. The multi-radio conflict graph , which represents the potential interference between the multi-radio links in the connectivity graph based on the interference model of the network, is input in the algorithm. Based on these inputs, the rank \( R \) of each node is computed. While visiting a node and its radios, the algorithm assigns channels to its links in the order of decreasing aggregate link traffic, thus trying to minimize the potential interference as computed on the basis of the multi-radio conflict graph.

**Step 1:** Input:

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

**Step 2:** Ranking function: Equation (1)

**Step 3:** Assignment of channels to radios.

- MesTiC visits every node based on its rank, the higher the Rank, the earlier a node \( V \) is visited

- 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

- Now for every link not assigned a channel yet, MesTiC will pick the link estimated to carry higher traffic first

- 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
• 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

• 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

Observations:
The aggregate traffic must be know at the beginning of the channel allocation. Traffic load is not static, it changes over certain periods of time.
2.7 Dynamic Channel Assignment Schemes

Hyacinth

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

In particular, this scheme, from [9], 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

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.

**Routing Tree Construction:** The basic tree construction process uses the metric by each WMN node to determine a parent is dynamic to achieve better load balancing, and 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, i.e., wired gateways. Assume a node X has already discovered a path to the wired network. It periodically, every \(T_a\) time units, broadcasts this reach-ability 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 reach-ability tree. Fig 2.3 shows the message exchange sequence.

The cost metric in this case 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 in the previous subsection 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 without global coordination, as in the case of centralized algorithm.

- Neighbor-Interface Binding: the key problem in the design of a distributed channel assignment algorithm is channel dependency among the nodes. 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, we 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 Fig 2.4.
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. Because a gateway node does not have any parent, it uses all its NICs as DOWN-NICs. To increase the relay capability, each non-gateway node attempts to equally divide its NICs into UP-NICs and DOWN-NICs.

- Interface-Channel Assignment: 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, where k is the ratio of the interference range and the communication range. 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. 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 interface-to-channel mapping is adjusted periodically, every $T_c$ time units.

- Virtual Control Network: unlike in a single-channel mesh network, nodes in a multi-channel WMN may not share any common channel with some of their physical neighbors. One simple option is to add a CONTROL-NIC on each node, tune it to a common channel, and route all control traffic such as ADVERTISE messages over this control network. This additional hardware interface can be saved by forming a virtual control network over the same multi-channel mesh network to exchange control packets. With the use of virtual control network, a new node needs to scan all channels for broadcasting HELLO messages during the neighbor discovery phase.

- Failure Recovery: when a node fails, nodes in its sub-tree lose their connectivity to the wired network. Hyacinth reorganizes the network to bypass the failed node and restore the connectivity. To accommodate node failures, each WMN node remembers alternative advertisements it has received from all other potential parent nodes. Upon detection of a parent-node failure, each of its child nodes sends a JOIN message to a “backup” parent node, and re-establishes its connectivity with the wired network. This scheme allows fast recovery from a node failure without committing any additional physical radio resources.

![Figure 2.5: Failure Recovery](image)

(a) Failure message after node A fails  
(b) New connectivity after recovery
Observations:

Dividing the NICs into UP-NICs and DOWN-NICs, every node require an higher number of radio interfaces than other schemes.

The aggregate traffic must be known at the beginning of the channel allocation.
MeshChop

The proposed MeshChop scheme [4] uses a unique connected component based channel hopping approach to make local adaptations to external interference and still reaps the benefits of centralized assignment. In particular MeshChop has two important properties:

- No change to network topology - This simple localized scheme for channel re-assignment, for every router interface independently make the decision to switch to a new channel if the current channel on which it is on gets congested above a threshold limit. This scheme has disadvantages. If two neighboring router interfaces A and B, initially on the same channel, independently decide to switch to another channel, they might lose their existing connectivity. This will breakdown all flows between the link A-B. The flows will resume only after the routing algorithm running over the mesh network discovers new routes for these flows which is a slow process and can take a few seconds. Even worse, if a router interface loses connectivity with neighboring interfaces after switching to a new channel, it might not be able to find connectivity to any other neighboring interface on that channel. This will partition the mesh network and stop all flows passing through that router interface. MeshChop uses a neat connected component based channel adaptation approach to overcome this problem. In this approach, all interfaces that are on the same channel and act as a single-hop link to each other together switch to a new channel. This maintains connectivity between existing neighbors while still moving the interfaces on to a new non-congested channel.

- Minimum to zero overheads - A typical channel adaptation scheme, centralized or localized, that adapts to external interference will have some basic overheads. Firstly, to decide a new channel for a router interface that experiences congestion on the current channel, a channel adaptation scheme will need to probe the quality of other channels. This involves considerable overhead. Secondly, there will be communication overheads related to channel switching. If the channel adaptation is done independently by every router interface there will be communication overheads in discovering dead (broken) and new links formed due to channel switching. If the scheme is centralized, there will be communication overheads in frequently propagating channel quality information to the central server responsible for channel assignment decisions. MeshChop cuts down the overheads drastically by employing a simple randomized channel re-assignment technique using only one time information.
As a starting point we assume that a good centralized algorithm has already made a channel assignment and assigned routes to the mesh network. Time is divided into slots each slot being a few seconds long. At the beginning of each slot, every connected component, which consists of nodes on the same channel (explained later), switches to one of the available non-overlapping channels randomly. Different random channel hopping sequences for every connected component can be provided by assigning a unique seed to each connected component when the centralized algorithm is run. The centralized algorithm can then be run periodically (on the order of hours) to account for any long term capacity requirement or traffic pattern changes.

Algorithm:

MeshChop has the following key steps.

Step 1: Centralized channel assignment. In this step, a good centralized channel assignment algorithm assigned channel to all router interfaces based on capacity requirements.

Step 2: Connected component identification. This is the first and the most basic step of MeshChop. In this step, Mesh-Chop identifies the connected components in the mesh after the centralized channel assignment. This can be done by using simple graph theory techniques.

Step 3: Time synchronization. To avoid temporary link connectivity failures due to asynchrony in channel switching times of the router interfaces of a connected component, we run a time synchronization protocol over the mesh network.

Step 4: Channel hopping. Once the connected components are identified, Mesh-Chop assigns a randomized channel hopping sequence to the connected components which is isomorphic to the centralized channel assignment. This hopping sequence for a connected component is sent out to all the routers whose interfaces belong to that component. For distributing the hopping sequence to respective routers, MeshChop utilizes the underlying mesh network. All connected components follow their hopping sequence until the centralized algorithm builds a new logical channel assignment for the mesh network.

Observations:

This not-deterministic method in switching channel does not consider the possibility of spend more time on channels that offer less congestion. Random channel hopping allows the connected component to spend its time between channels which are congested and those which are not and gives an average case behavior which is far
better than the worst case where a connected component experiences continuous external interference.

This scheme needs time synchronization.
Distributed Channel Assignment

In this scheme from [3], it's presented a distributed channel assignment strategy that utilizes the entire 802.11 spectrum and routes flows to maximize the capacity of the network. Large size networks compel solution to be distributed. In this scheme the goal is to maximize the utilization of the wireless spectrum. Clearly, if one knows the positions and hardware configurations of all nodes in the mesh network and the traffic demands of these nodes, one could perform a centralized allocation of channels to nodes and routes within the mesh network to maximize the utilization. However, the class of mesh networks we wish to support are not amenable to such a method. In particular, this scheme is interested in mesh networks with the following properties:

- The network contains many nodes, such that implementing a centralized algorithm would prove difficult, if not impossible.
- The flow demands are not known a priory, or could change dramatically over short periods of time.
- The network topology is for all intensive purposes static. Nodes or links between nodes may fail or move slowly, and the assignment of channels to nodes and routes within the mesh network should adapt accordingly, but that such changes occur on a timescale much larger than the changes in flow demands. A well-designed distributed solution can handle these small changes gracefully that only affect small portions of the network at a time, with decisions to be made based on local information. Centralized solutions will likely have to reconsider the entire network to update their channel assignment.

Algorithm:

In this scheme, a node $i$ selects a channel that minimizes the sum of interference cost from the set of nodes, $S$, within its interference range as shown in Algorithm 1. When there are multiple channels that minimize the interference cost, the node can select one of them arbitrarily. If its prior choice minimized the sum of interference costs, then the node makes no change. Each node $i$'s choice of channel depends only on information that is available within its local domain, hence, the algorithm is truly distributed, using only information available within its local region.
Algorithm 1: ChannelSelection(node i)

Input
Si : Set of nodes in i’s interference range.
cj : The channel of each node j belonging to Si
ci : i’s current channel

begin procedure
for all channel k = 1, ..., K,
    F(k) = interference cost for channel k
if F(ci) > F(k) for any k = 1, ..., K, then
    ci ← kmin where kmin = k : F(k) < F(k’) for any k’ = 1, ..., K
end if
end procedure

It is not intuitively obvious that this distributed channel selection process is self-stabilizing, i.e., that nodes continually looking to improve on their local interference cost will eventually converge to a stable channel allocation; one node’s channel change can increase some other node’s interference level, and cause the other node to change its channel, and so forth. To prove stabilization, they make some simplifying assumptions about the network environment:

• Every node i has the correct channel information of all other nodes in its interference range, Si .

• No other node in Si changes its channel simultaneously with node i.

An additional distributed protocol is used to ensure that these two properties are held, as shown in figure 2.6.

Figure 2.6: Protocol message flow

This protocol is described in the reference paper, and uses a second algorithm, Is-RequestConflicting to check if the new channel that a node requests to change, conflicts with the channel used by the node that receive the request.
Algorithm 2: IsRequestConflicting(node j)

Input
i : node that sent the REQUEST.
ci : i's current channel number.
cinew : channel number i intends to change to.
cj : j's current channel number.
cjnew : channel number j intends to change.

begin procedure
if f(ci, cj) > 0 then return true
else if f(ci, cjnew) > 0 then return true
else if f(cinew, cj) > 0 then return true
else if f(ci, cjnew) > 0 then return true
else return false
end if
end procedure

This scheme models the interference between partially overlapping channels in 802.11g radio will affect how channels are allocated by the algorithm. It is used a relatively straightforward cost function with a tunable parameter:

\[ f(a, b) = \max(0, \delta - |a - b|) \]

where channel indices a and b also denote their center frequencies. There are two special cases: when \( \delta = 1 \), all channels are orthogonal from one another, such that interference only occurs between two competing transmissions on the same channel. When \( \delta = 0 \), no channel is assigned any weight, and F(k) will always equal 0. This case enables us to test randomly assigned channels: when \( \delta = 0 \) and nodes are initially assigned their channel at random, there is no incentive to change, so the allocation remains in its initial (random) state.

Observations:

This scheme could be not well suitable for network with limited number of nodes. A distributed system is necessary when we have large scale network but in the case of enterprise or local network a centralized system can be more performance.

Traffic information is not considered.
2.8 Hybrid Channel Assignment Schemes

HMCP

HMCP: Hybrid Multi-channel Protocol[8] is a link-layer protocol that assumes each node has at least two interfaces. Every node divides its available interfaces into two groups. The interfaces in the first group are designated as "fixed interfaces", and are fixed (for long intervals relative to packet transmission times) on specified channels, called "fixed channels". Different nodes are free to choose a possibly different set of fixed channels. The interfaces in the second group are called "switchable interfaces", and these interfaces can frequently switch among the remaining non-fixed channels. To simplify rest of the discussion, we assume each node has exactly two interfaces, one of which is fixed and the other is switchable. The fixed channels can be explicitly advertised to neighbors by broadcasting "Hello" messages. Whenever a sender needs to send packets to a receiver, it can switch its channel to the receiver's fixed channel and send packets. Thus, once the fixed channel of a node is discovered through the reception of a "Hello" message, explicit channel synchronization is not needed.

The selection of fixed channel among nodes can be done in a distributed fashion. Each node maintains a Neighbor Table containing the fixed channels being used by its neighbors. A node periodically checks the number of other nodes also using the same channel as itself, for the fixed channel. If the estimated number is significantly larger than average, then the node changes its fixed channel to a less used channel, and advertises this information using a "Hello" message. Figure 2.7 depicts a simple data transfer example using HMCP. Each node has two interfaces - one fixed and one switchable. Assume that node A has packets to send to node C via node B. Suppose nodes A, B, and C have their fixed interfaces on channels 1, 2, and 3 respectively. Assume that initially nodes A, B, and C have their switchable interfaces on channels 3, 1, and 2 respectively. In the first step, node A switches its switchable interface from channel 3 to channel 2, before transmitting the packet, because channel 2 is the fixed channel of node B. Node B can receive the packet since its fixed interface
is always listening to channel 2. In the next step, node B switches its switchable interface to channel 3 and forwards the packet, which is received by node C using its fixed interface. Once the switchable interfaces are correctly set up during a flow initiation, there is no need to switch the interfaces for subsequent packets of the flow (unless a switchable interface has to switch to another channel for sending packets of a different flow).

In the proposed protocol, nodes in a neighborhood may be listening to different channels, and therefore a single broadcast transmission does not reach all neighbors. Therefore, local broadcast is implemented by sending a copy of the broadcast packet on all channels. Consequently, the total overhead of local broadcast is larger than in a single channel network. However, if the overhead is measured in terms of packets sent per channel, then this approach continues to have the same overhead as in a single channel network.

The experiment assumes that our protocol uses two interfaces. Each channel is assumed to support a data rate of 54 Mbps, which is the highest data rate specified in IEEE 802.11a. As we can see from the figure 2.8, the FTP throughput in single channel networks rapidly degrades when the number of hops along a chain increases (this behavior is well-known). However, the FTP throughput degradation is less severe when multiple channels are used. When multiple channels are available, HMCP assigns the fixed channel of successive nodes along the chain to different channels. Also, when an intermediate node is receiving data using one interface, it can simultaneously forward data to the next node using the second interface. Consequently, HMCP offers higher throughput by using different channels on successive hops, and by using the two interfaces to receive and send data in parallel. The key observation from Figure 2.8 is that multiple channels can significantly improve throughput of a flow in multi-hop scenarios. Furthermore, even with only a few interfaces (2 in this example), having large number of channels (up to 12 channels in this example) is
beneficial.

The interface switching latency depends on the available hardware, and current hardware imposes switching latency in the range of a few milliseconds, while future hardware may be able to achieve delays of a few hundred microseconds. High switching delay affects performance by increasing the cost of a broadcast (since each broadcast requires switching channels), and by increasing the end-to-end delay of a flow if the best route for a flow requires switching at some node along the flow. When a route with frequent switching is used with TCP traffic, the path RTT increases. TCP throughput is inversely proportional to the RTT of the path, and therefore degrades with higher RTT. As long as the fraction of path RTT contributed by switching delay is small, switching delay has minimal impact on throughput (therefore, for 1 ms delay, there is little degradation in the throughput). When the switching delay starts contributing to a larger fraction of the path RTT, throughput degradation is more significant.

Observations:

Contemporary hardware does not permit to use this kind of channel assignment, but it can be consider in the future.
BSF-CA

This scheme presents a centralized, interference-aware channel assignment algorithm and a corresponding channel assignment protocol aimed at improving the capacity of wireless mesh networks by making use of all available non-overlapping channels. The algorithm selects channels for the mesh radios in order to minimize interference within the mesh network and between the mesh network and co-located wireless networks. Each mesh router utilizes an interference estimation technique to measure the level of interference in its neighborhood because of co-located wireless networks. The algorithm, called the Breadth First Search Channel Assignment (BFS-CA) algorithm[2], uses a breadth first search to assign channels to the mesh radios. The algorithm utilizes an extension to the conflict graph model, the Multi-radio Conflict Graph (MCG), to model interference between the multi-radio routers in the mesh. The MCG is used in conjunction with the interference estimates to assign channels to the radios. This scheme ensures that channel assignment does not alter the network topology by mandating that one radio on each mesh router operate on a default channel. While to prevent flow disruption, link redirection is implemented at each mesh router. This technique redirects flows over the default channel until the channel assignment succeeds.

The Channel Assignment Server (CAS), which can be co-located with the gateway, performs channel assignment to radios. In assigning channels, the CAS satisfies the following goals:

- Minimize interference between routers in the mesh: In satisfying this goal, first, the CAS should satisfy the constraint that for a link to exist between two routers, the two end-point radios on them must be assigned a common channel. Second, links in direct communication range of each other should be tuned to non-overlapping channels. Third, because of the tree-shaped traffic pattern expected in wireless mesh networks, channel assignment priority is given to links starting from the gateway and then to links fanning outwards towards the edge of the network.

- Minimize interference between the mesh network and wireless networks co-located with the mesh: In satisfying this goal, the CAS periodically determines the amount of interference in the mesh due to co-located wireless networks. The interference level is estimated by individual mesh routers. The CAS should then re-assign channels such that the radios operate on channels that experience the least interference from the external radios.

The goal of interference estimation is to periodically measure the interference level
in each mesh router’s environment. Accurate measurement, however, is challenging and requires that expensive hardware be used. Instead, as an approximation, we rely on the number of interfering radios on each channel supported by each router as an estimation of interference. An interfering radio is defined as a simultaneously operating radio that is visible to a router but external to the mesh. A visible radio is one whose packet(s) pass Frame Check Sequence (FCS) checks and are therefore correctly received. It is assumed that the CAS informs the router of radios internal to the mesh. The information could consist of an IP address range or an exhaustive list of all radio MAC addresses in the mesh.

Conflict graphs are used to model interference in cellular radio networks. A conflict graph for a mesh network is defined as follows: consider a graph, G, with nodes corresponding to routers in the mesh and edges between the nodes corresponding to the wireless links. The conflict graph does not correctly model routers equipped with multiple radios. Therefore, we extend the conflict graph to model multi-radio routers. In the extended model, called the Multi-radio Conflict Graph (MCG), are represented edges between the mesh radios as vertices instead of representing edges between the mesh routers as vertices as in the original conflict graph.

After constructing the MCG, the CAS uses the BFS-CA algorithm to select channels for the non-default radios. Once the channels are selected for the mesh radios, the CAS instructs the routers to configure their radios to the newly selected channels. The CAS periodically invokes the channel selection to cope with the varying nature of interference in the mesh.

This is the scheme we will use as background to build our channel assignment scheme, so we will describe later the details of the Multi-radio Conflict Graph and the default and non-default channel selection.
2.9 Other Channel Assignment Schemes

Superimposed Code Based Channel Assignment

In this section, are proposed two channel assignment algorithms based on s-disjunct superimposed codes [6]. The basic idea is sketched as follows. For each node, all available orthogonal channels are labeled as either primary or secondary via a binary channel code-word. This labeling is controlled by an s-disjunct superimposed $(s, 1, N )$-code. The codeword of the transmitting node, together with those of the interferes, determine the channel.

Note that primary channels are always preferred during channel assignment. Our analysis indicates that by exploring the s-disjunct property of the $(s, 1, N )$-code, it is possible to achieve interference-free channel assignment for both unicast and broadcast. Under certain conditions, interference-free broadcast and unicast can be achieved. Since these algorithms assign channels to transmitters for both unicast and broadcast, and because the channels are selected from a small subset of primary channels whenever possible, algorithms can effectively decrease the overall switching delay caused by the oscillation of switching back and forth due to the large difference between the numbers of radios and channels.

These algorithms support dynamic, static, and adaptive channel assignment without requesting any complex scheduling and/or channel coordination. These algorithms make no assumptions on the underlying network settings such as traffic patterns and MAC/routing protocols. Therefore they are applicable to a wide range of mesh networks.

Superimposed Codes:

Superimposed codes were introduced by Kautz and Singleton in 1964. Since then, they have been extensively studied and applied to various fields, such as multi-access communications, cryptography, pattern matching, circuit complexity, and many other areas of computer science. In this section, are introduced the basic definitions and properties of superimposed codes. Let $N$, $t$, $s$, and $L$ be integers such that $1 < s < t$, $1 \leq L \leq t - s$, and $N > 1$. Given a $N \times t$ binary matrix $X$, denote the $i$th column of $X$ by $X(i)$, where $X(i) = (x_1(i), x_2(i), \ldots, x_N(i))'$. Where $X(i)$ is a codeword $i$ of $X$ with a length $N$. In other words, $X$ is a binary code with each column corresponding to a codeword.
Figure 2.9: Example of a superimposed (3, 1, 13)-code of size 13

\[
\begin{pmatrix}
1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 1 \\
1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 1 \\
1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 1 & 0 \\
1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 1 & 1 & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1 & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 1 & 1
\end{pmatrix}
\]

Let \( w \) and \( l \) be defined as:

\[
w_s = \sum_{i=1}^{N} x_k(i)
\]

\[
\lambda_j = \sum_{i=1}^{t} x_j(k)
\]

Therefore \( w \) and \( l \) are called the column weight and row weight of \( X \), respectively.

**s-disjunct Code:** A binary matrix \( X \) is called an \( s \)-disjunct code if and only if it has the property that the Boolean sum of any \( s \) codewords in \( X \) does not cover any codeword not in that set of \( s \) codewords.

Based on the definitions, a superimposed \((s, 1, N)\)-code is a \( s \)-disjunct code. Taking the \((3, 1, 13)\)-code shown in figure 2.9 as an example, the Boolean sum of the first 3 codewords of \( X \) is \( X(1) \) and \( X(2) \) and \( X(3) = (1,1,1,1,0,0,0,0,1,1,1,0)' \), which doesn’t cover any other codeword of \( X \) but themselves. According to the \( s \)-disjunct characteristic of the superimposed \((s, 1, N)\)-code, we can derive the following important property:

- Given an \((s, 1, N)\) superimposed code \( X \), for any \( s \)-subset of the codewords of \( X \), there exists at least one row at which all codewords in the \( s \)-subset contains the value 0.

**Application:**

A MultiRadio-MultiChannel wireless mesh network can be modeled by a directed graph \( G(V,E,C) \), where \( C \) is the corresponding channel code. For any given node \( u \) belonging to \( V \), \( c_u \) belonging to \( C \) is a binary vector with each element corresponding to a channel and its 1/0 value representing this channel being a primary channel or a secondary channel of node \( u \). So, a direct mapping between a superimposed
s-disjunct code $X$ (represented by a $N \times t$ matrix), and the channel code $C$ of a network $G$ can be built, where: $N$ represents the number of available orthogonal channels, and each codeword of $X$ indicates a possible channel codeword to a node in $G$. Then the column weight $w_i$ of $X$ represents the number of primary channels a node $i$ has, and the row weight $l_j$ represents the number of nodes that take channel $k_j$ as a primary channel.

**Channel Assignment for Broadcast Traffic**

Let $G$ be an MR-MC wireless mesh network with $N$ available orthogonal channels, and $X$ be the superimposed $(s,1,N)$-code for its channel assignment. For any node $u$ in $G$, a unique code-word $X(u)$ belonging to $X$ is associated with $u$ indicating $u$’s primary and secondary channel sets. Denote by $N(u)$ the set of interferes of $u$. Algorithm 1 is a computes a set of channels for node $u$’s broadcast transmissions. Intuitively, $u$ should choose only those channels not being used by any of its interferes from its primary channel set. If none of these primary channels is available, $u$ should choose the secondary channels that are not primary to any of the nodes in $N(u)$, the set of interferes of $u$. Since all nodes intend to utilize their primary channels whenever possible, choosing a channel that is secondary to all interferes is a reasonable choice. If $u$ can not find out a channel that is secondary to all interferer, it picks up the primary channels that are primary to the least number of nodes in $N(u)$. The algorithm is:

Algorithm 1: Channel Assignment for Node $u$

**Input:** Codewords $X(u)$ and $X(N(u))$

**Output:** $CH(u)$, the set of channels assigned to $u$

```plaintext
function CH(u) = ChannelSelect(X(u), X(N(u)))
    CH1(u) ← Find the set of primary channels
    that are secondary to all nodes in $N(u)$
    if $CH1(u) = 0$ then
        CH(u) ← CH1(u)
    else
        CH2(u) ← Find the set of secondary channels that
        are secondary to all nodes in $N(u)$
        if $CH2(u) = 0$ then
            CH(u) ← CH2(u)
        else
            CH3(u) ← Select the primary channels with
            the least row weight in $N(u)$
            CH(u) ← CH3(u)
        end if
    end if
```

These channel assignment criterions reflect the design principle: a node always selects a channel that causes the least interference to its neighborhood.

**Conditions for Interference-Free Channel Assignment**

Note that Algorithm 1 does not require a node u to collect the codewords of all interferers. If u knows nothing about its neighborhood, one of its primary channels will be picked for transmission. However, if N(u) is the complete set of interferers of node u, interference-free channel assignment is possible.

- If CH1(u) = 0, node u does not interfere with any other node in N(u)

When CH1(u) = 0, node u picks up channels from CH1(u), a subset of u’s primary channel set, for transmission. CH1(u) contains channels that are primary to u but secondary to all nodes in N(u). For every node v belonging to N(u), v can’t use any channel from CH1(u) based on Algorithm 1 since v is assigned with either its own primary channels (from CH1(v) or CH3(v)), which can’t be in CH1(u), or channels that are secondary to all interferers in N(v) (CH2(v)), which are secondary to u too since u belongs to N(v). Note that based on this condition, if N(u) is the complete set of interferers of node u, u’s transmissions on the channels from CH1(u) do not cause any interference to other on-going traffic.

- If CH1(u) = 0 holds for every node u belonging to V, and N(u) is the complete set of interferers of u in the network G(V,E), the channel assignment based on Algorithm 1 guarantees interference free communications in the network.

This condition indicates that if each node can compute a primary channel that is secondary to all its interferers based on Algorithm 1, interference-free communications in the whole network can be achieved.

- Given a node u with CH1(u) = 0 and CH2(u) = 0, if CH1(vi) = 0 holds for all its interferers v1, v2, ..., v|N(u)|; node u’s transmissions do not interfere with any other node in N(u)

Therefore, u’s and its interferers’ transmission channels do not overlap, and thus u’s transmissions do not interfere with its interferers, and are not interfered by its interferers.

These conditions do not place any restrictions on the size of the interferer set for any node. Can be proved that:
If $s \geq |N(u)|$ and $N(u)$ is the complete set of interferers of $u$ for every node $u$ in $G$, the channel assignment based on Algorithm 1 guarantees interference-free communications in the network.

In other words, if $s$ upper-bounds the cardinality of the complete interferer set of each node in the network, interference-free communications can be achieved. This condition is very rigorous. However, for a stationary multi-radio multi-channel mesh network where the mesh routers can be carefully placed, the set of interferers could be small to provide sufficient coverage. In this scenario, channel assignment based on Algorithm 1 yields an interference-free network.

If this condition is too rigorous, in the paper there are further analysis to derive the probabilities for interference-free channel assignment when $|N(u)| > s$ based on Algorithm 1. Hence, is studied the probability that a node $u$ can find out a channel to achieve interference-free communication in its local neighborhood when $s' > s$, where $s' = |N(u)|$.

**Observations:**

If the wireless mesh network is built using 802.11-based hardware, to guarantee interference-free communication, considering the number of available non-overlapping channels, we must distribute routers in a way where the set of interference node is very small.

**Channel Assignment for Unicast Traffic**

In this section, is considered the channel assignment for the unicast traffic from node $u$ to node $v$, where $u$ and $v$ reside in each other’s transmission range.

It can be proved that the channel codewords from one-hop neighbors of both the sender and the receiver suffice for Algorithm 2 to achieve 100% throughput with a very simple scheduling algorithm.

**Algorithm 2 Channel Assignment for unicast from $u$ to $v$**

**Input:** Codewords $X(N(u))$, and $X(N(v))$

**Output:** $CH(u \rightarrow v)$, a channel to the link from $u$ to $v$

**function** $CH(u \rightarrow v) = \text{Unicast Channel Select}(X(N(u)), X(N(v)))$

$CH1(u) \leftarrow$ Find a primary channel that is secondary to all nodes in $N(v)$ and $\{v\} \setminus \{u\}$

if $CH1(u) = 0$ then

$CH(u \rightarrow v) \leftarrow CH1(u)$

else

$CH2(u) \leftarrow$ Find a secondary channel that is secondary
to all nodes in $N(u)$ and $\{u\}$ but primary
to at least one node in $N(v)$

if $CH2 = 0$ then
  \[ CH(u \rightarrow v) \leftarrow CH2(u) \]
else
  \[ CH3(u) \leftarrow \text{Select a channel that is primary to } u \]
  \[ \text{and secondary to } v \]
  \[ CH(u \rightarrow v) \leftarrow CH3(u) \]
end if
end if
end function

In this second algorithm a node should utilize its primary channels if possible; otherwise, it should choose a secondary channel that is secondary to all nodes in its closed neighborhood, but not secondary to all nodes in the receiver’s neighborhood, since otherwise, the receiver may choose the same channel for its own unicast, causing interference. Therefore Algorithm 2 is a localized transmitter-oriented channel assignment algorithm.

**Interference Analysis**

Note that there are two different kinds of interferences for the unicast traffic: the direct interference caused by immediate neighbors and the indirect interference caused by the neighbors of the receiver. The first one results in the exposed terminal problem while the second one results in the hidden terminal problem. The hidden and exposed terminal problems are well-known phenomena in wireless networks due to the broadcast nature of the wireless media.

![Figure 2.10: Hidden and Exposed terminal problem](image)

It can be proved that when the number of immediate neighbors of any node in the network is upper-bounded by $s$, the hidden/exposed problems can be solved and the network communication is free of interference.

**Observations:**

Note that for a superimposed $(s, 1, N)$-code, the upper bound of $s$ is limited by $N$. Therefore $s$ cannot be a large number if the number of available channels $N$ in
the network is small. However, this should not be a restriction on the application of superimposed codes in IEEE 802.16e based stationary MR-MC wireless mesh networks. The OFDMA technique in IEEE 802.16e allows bandwidth to be divided into many lower-speed sub-channels to increase resistance to multi-path interference. Typically a large number of non-overlapping orthogonal sub-channels are available for simultaneous transmissions. Therefore in this case, s can be large since N is large. However, the non-overlapping channels in 802.11 standards are limited (3 non-overlapping channels in IEEE 802.11b/g; 12 or 19 non-overlapping channels in IEEE 802.11a). Therefore s in 802.11-based wireless mesh networks is limited to some small number, which may affect the effectiveness of channel assignment.
2.10 Discussion

Given the explosive growth in "WiFi" deployments that operate in the same (unlicensed) spectrum as wireless mesh networks, any static assignment will likely result in the operation of the mesh on channels that are also used by co-located WiFi deployments. The resulting increase in interference can degrade the performance of the mesh network.

For this reason our Channel Assignment algorithm addresses the channel assignment problem and specifically investigates the dynamic assignment of channels in a wireless mesh network. We chose the hybrid and centralized, interference-aware channel assignment algorithm BSF-CA [2] as template for the thesis. This channel assignment protocol aimed at improving the capacity of wireless mesh networks by making use of all available non-overlapping channels and that intelligently selects channels for the mesh radios in order to minimize interference within the mesh network and between the mesh network and co-located wireless networks.

The main disadvantages of this scheme is that it does not consider the traffic load information during the assignment process. Hence, our first improvement will try to introduce this new information into the algorithm. Second, we will develop an algorithm that can be used in a wireless mesh network with more gateways available, this because the BSF-CA algorithm is designed to work on single-gateway WMNs. At last we will change the routing metric.
Bibliography


