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Interference-Aware Adaptive Spectrum Management for Wireless Networks using Unlicensed Frequency Bands

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Abstract

The growing demand for ubiquitous broadband network connectivity and continuously falling prices in hardware operating on the unlicensed bands have put Wi-Fi technology in a position to lead the way in rapid innovation towards high performance wireless for the future. The success story of Wi-Fi contributed to the development of widespread variety of options for unlicensed access (e.g., Bluetooth, Zigbee) and has even sparked regulatory bodies in several countries to permit access to unlicensed devices in portions of the spectrum initially licensed to TV services. In this thesis we present novel spectrum management algorithms for networks employing 802.11 and TV white spaces broadly aimed at efficient use of spectrum under consideration, lower contention (interference) and high performance.

One of the target scenarios of this thesis is neighbourhood or citywide wireless access. For this, we propose the use of IEEE 802.11-based multi-radio wireless mesh network using omnidirectional antennae. We develop a novel scalable protocol termed LCAP for efficient and adaptive distributed multi-radio channel allocation. In LCAP, nodes autonomously learn their channel allocation based on neighbourhood and channel usage information. This information is obtained via a novel neighbour discovery protocol, which is effective even when nodes do not share a common channel. Extensive simulation-based evaluation of LCAP relative to the state-of-the-art Asynchronous Distributed Colouring (ADC) protocol demonstrates that LCAP is able to achieve its stated objectives. These objectives include efficient channel utilisation across diverse traffic patterns, protocol scalability and adaptivity to factors such as external interference.

Motivated by the non-stationary nature of the network scenario and the resulting difficulty of establishing convergence of LCAP, we consider a deterministic alternative. This approach employs a novel distributed priority-based mechanism where nodes decide on their channel allocations based on only local information. Key enabler of this approach is our neighbour discovery mechanism. We show via simulations that this mechanism exhibits similar performance to LCAP.

Another application scenario considered in this thesis is broadband access to rural areas. For such scenarios, we consider the use of long-distance 802.11 mesh networks and present a novel mechanism to address the channel allocation problem in a traffic-aware manner. The proposed approach employs a multi-radio architecture using directional antennae. Under this architecture, we exploit the capability of the 802.11

hardware to use different channel widths and assign widths to links based on their relative traffic volume such that side-lobe interference is mitigated. We show that this problem is NP-complete and propose a polynomial time, greedy channel allocation algorithm that guarantees valid channel allocations for each node. Evaluation of the proposed algorithm via simulations of real network topologies shows that it consistently outperforms fixed width allocation due to its ability to adapt to spatio-temporal variations in traffic demands.

Finally, we consider the use of TV-white-spaces to increase throughput for in-home wireless networking and relieve the already congested unlicensed bands. To the best of our knowledge, our work is the first to develop a scalable micro auctioning mechanism for sharing of TV white space spectrum through a geolocation database. The goal of our approach is to minimise contention among secondary users, while not interfering with primary users of TV white space spectrum (TV receivers and microphone users). It enables interference-free and dynamic sharing of TVWS among home networks with heterogeneous spectrum demands, while resulting in revenue generation for database and broadband providers. Using white space availability maps from the UK, we validate our approach in real rural, urban and dense-urban residential scenarios. Our results show that our mechanism is able to achieve its stated objectives of attractiveness to both the database provider and spectrum requesters, scalability and efficiency for dynamic spectrum distribution in an interference-free manner.

Nothing endures but change.

Heraclitus

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Declaration

I declare that this thesis was composed by myself, that the work contained herein is my own except where explicitly stated otherwise in the text, and that this work has not been submitted for any other degree or professional qualification except as specified. Some of the material used in this thesis has been published in the following papers:

- "Coordinated TV White Space Spectrum Sharing for Home Networks via Micro Auctions."
  Sofia Pediaditaki, Maziar Nekovee and Mahesh Marina.
  Technical Report, 2012.
  http://homepages.inf.ed.ac.uk/mmarina/papers/jul12-tr.pdf

- "Traffic-Aware Channel Allocation in Long-Distance 802.11 Mesh Networks."
  Sofia Pediaditaki, Mahesh K. Marina and Daniel Tyrode.
  ACM International Conference on Modeling, Analysis and Simulation of Wireless and Mobile Systems (MSWIM), 2012.

- "A Learning-based Approach for Distributed Multi-Radio Channel Allocation in Wireless Mesh Networks."
  Sofia Pediaditaki, Philip Arrieta, and Mahesh K. Marina.
  IEEE International Conference on Network Protocols (ICNP), 2009.

- "A Learning-based Channel Allocation Protocol for Multi-Radio Wireless Mesh Networks."
  Sofia Pediaditaki and Mahesh K. Marina.
  IEEE International Conference on Computer Communications (INFOCOM) student workshop, 2009.

(Sofia Pediaditaki)

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Chapter 1

Introduction

1.1 Motivation

The development of wireless networking and communications standards, such as the IEEE 802.11 a/b/g (Wi-Fi) [6], and the continuously decreasing cost of wireless devices operating in unlicensed frequency bands have contributed immensely towards widespread use of wireless networks, especially for high-speed wireless Internet access. In fact, wireless access is expected to be the primary mode of Internet access in the years to come with Wi-Fi continuing to be the leading technology for general-purpose wireless networks. The success story of Wi-Fi has stimulated innovation in wireless communication technology and also contributed to the development of a widespread variety of wireless options (e.g., Bluetooth, Zigbee) operating on the unlicensed bands. Moreover, spectrum regulators across countries have already considered allocating unused portions of the spectrum residing in traditionally TV licensed frequency bands, called TV white spaces, for unlicensed use.

Motivated by these technology shifts, *the focus of this thesis is on efficiently managing the available spectrum in unlicensed spectrum based wireless networks, specifically 802.11 mesh networks and TV white space networks*. The aim is to keep interference under check and improve performance which may potentially stimulate innovative devices and services.

1.1.1 802.11-based Multi-Channel Mesh Networks and Spectrum Management Challenges

In wireless networks, each pair of nodes communicate over a shared medium rather than via a dedicate wire as in wired networks. As a result, communication between a pair of nodes can cause interference to neighbouring transmissions operating on the same channel. This limits the available network capacity (or achievable network throughput). In wireless local area networks (WLANs) for which IEEE 802.11 is the de facto standard, client devices associate with an infrastructure device called Access Point (AP). In such networks, the interference problem can be mitigated by having mutually interfering APs assigned different channels. However, wiring APs together is a significant component of costs involved in deploying WLANs. To keep the wiring costs low, AP density is usually much lower than it needs to be to serve the growing number of wireless devices. Moreover, the wiring requirement also makes it difficult to extend the WLAN coverage.

To overcome the above-mentioned problems with WLANs, *wireless mesh networking* has recently emerged as a promising technology [7]. The mesh network architecture in which APs are interconnected wirelessly enables low-cost, ubiquitous wireless Internet access with easily extendable coverage via reduced dependence on the wired infrastructure. Due to these advantages along with improved robustness, which stems from the mesh connectivity, mesh networks are considered as a promising solution for a wide variety of applications in densely populated urban areas (e.g., high-speed urban mobile access, public safety). In these scenarios, the main challenge is to offer the same level of sustained bandwidth as wired access in the presence of interference due to the high density. However, throughput degradation due to interference is more severe in wireless mesh networks than in WLANs because of multihop wireless relaying requirement induced by wireless interconnection of APs [8]. Since packets may need to traverse several hops to reach the destination, they are subjects to interference at each intermediate hop.

Multi-radio wireless mesh network architecture is commonly seen as a practical way for efficiently utilising the available spectrum and alleviating interference related performance degradation. In the multi-radio mesh architecture, architecture each router (doubling as an access point) is equipped with multiple radios (e.g., 802.11), which enables the utilisation of diverse channels to mitigate interference and increase capacity. In urban settings, in particular, mesh networks are most commonly deployed using omnidirectional antennae to provide blanket coverage and minimise cost. *Allocating channels to radios, however, is a non-trivial problem.* Two neighbouring nodes cannot communicate unless they share a common channel, while the number of radios in practice is unlikely to match the number of available channels. Channel allocation should not only ensure network connectivity but also seek to reduce interference on any given channel. *Moreover, it is desirable to perform channel allocation in a distributed manner to be able to adapt to spatio-temporal variations in the number of available channels and their usability − coping with external interference from other devices using same portion of the wireless spectrum [9].* These objectives, however, are challenging because of the channel dependency problem among nodes. Due to this problem, changing the channel of an interface may cause a ripple effect of further changes in the network necessary to maintain connectivity [10].

Besides urban areas, long-distance 802.11 mesh networks are currently seen as a practical solution in helping bringing low cost Internet access to rural areas and developing regions (e.g., [11, 4]). The primary objective in such scenarios is to provide broadband services to low density scattered communities outside the big cities, which can bridge the gap in the economic development between rural and urban areas. In such scenarios where wired infrastructure is limited or not present, wireless mesh networks offer an ideal broadband access solution which is critical for various aspects of peoples lives, such as education, healthcare and entertainment. Access points in such networks, however, could be separated potentially by distances in the order of several Kms, hence their interconnection into a network is achieved with the use of a pair of high-gain directional antennae per link. A directional mesh network can be seen as a specific type of multi-radio multi-channel mesh network, where each node has as many radio interfaces as the number of incident links. Each of these links is assigned a different channel to avoid side-lobe interference that occurs with commonly used high-gain directional antennae. More specifically, non-negligible side-lobe energy from directional transmission on a link appears as interference to reception on other co-incident links and as such, it needs to be avoided. Moreover, for long-distance communication, besides directional antennae, higher radio transmit power may also be needed. Therefore, such long-distance point-to-point wireless communication is restricted by spectrum regulatory bodies to a few specified frequency bands with relatively higher transmit limits. The 5.8GHz frequency band is a band that falls into this category and available in most regions in the world. Consequently, the total amount of spectrum available for long-distance networks is limited (e.g., 100MHz in the 5.8GHz band as opposed to more than 500MHz available for indoor wireless LAN use in the 5GHz unlicensed frequency bands). *Rigid and static allocation of these channels would be inefficient as such allocation cannot adapt to spatio-temporal variations in user traffic demands*.

1.1.2 TV White Space Networks

TV white spaces are portions of the spectrum that will become available in several countries after the process of replacing the analogue television broadcasting by digital transmissions is complete. These bands could be used by cognitive radios provided their operation does not cause harmful interference to primary users. To date, both in the UK [12] and US [13], access to these bands have already been decided to be license-exempted. Regulations are also underway in Europe and are being considered elsewhere [14]. This is currently seen as a tremendous opportunity to increase capacity in places where WiFi networks have become overcrowded. Moreover, due to the better propagation properties, networks utilising TV white spaces are envisioned as ideal solutions for providing increased coverage at lower cost. To ensure protection to primary users, regulators have considered different methods for cognitive access. Among these the most prominent one is the use of a database combined with geolocation via which unlicensed devices will be granted access to locally vacant channels based on their geographical position and transmission power. However, in urban areas where the spectrum scarcity is most apparent, the TVWS spectrum left for high-power communications by secondary users is very little [15].

Shorter range communications have more hope of exploiting this new spectrum due to the lower transmission power. In fact, short range wireless technologies operating in the unlicensed bands, as exemplified by WiFi, are most affected by overcrowded spectrum and interference problems. We therefore consider TVWS spectrum as an opportunity to offload traffic from short range wireless technologies (e.g., WiFi, Zigbee) that are increasingly subject to interference in unlicensed bands. Our focus in particular is on the home networking scenario in which in-home wireless networking among various devices in the household (e.g., home entertainment systems, game consoles, appliances, energy meters) is not only becoming more prevalent but also is currently done using WiFi or Zigbee operating in the congested unlicensed bands. We envision that such devices in future will be TVWS- capable and can opportunistically use TVWS spectrum to relieve congestion across various spectrum bands used by home wireless devices. The emerging TV white space standards such as IEEE802.11af [16] and ECMA-392 [17] support our view.

Cognitive access to TV white spaces is still evolving. Regulatory bodies have not provided rules for the coexistence of multiple secondary users, thus operation on these bands is expected to suffer uncontrolled interference. Moreover, the effectiveness of the databases, which will determine the quality of the TV reception, will depend on the reliability of the location services and the sufficiency of the coverage predictions to provide reliable reception. Providers of services such as Freeview (e.g., BBC), which are used by a large percentage of the population are skeptical [18]. To address these challenges, this thesis considers a business model based on micro-auctions for operating the databases which aligns with the objectives of both the TV and broadband providers as well as end-users. In this model, access to the TVWS is provided as a service from database providers, who own and maintain the database, to broadband providers who request access to the TVWS spectrum on behalf of their clients (i.e., home networks). The subscribers to this service can enjoy the additional capacity while reliably avoiding disruptions to TV services by *coordinated access to the TVWS spectrum*. Unlike the ISM bands where coordination is not practical, in this scenario coordination is feasible since the geolocation database has access to both location and transmit power of the subscribed devices.

1.1.3 Network Model

The aforementioned spectrum management problems, although different from each other, can be potentially seen together in the context of a single network architecture such as the one shown in Figure 1.1. This figure depicts a tiered mesh network model that encompasses the urban, rural and home wireless network scenarios described above. The figure shows three tiers: At the bottom tier (the "home" tier), devices within a household form a home network by connecting together wirelessly. This tier connects the devices within a household to the middle tier via the home hubs. At the middle tier (the "subnet tier"), each of the subnets is an omnidirectional network comprised of nodes representing rooftop mesh access points or hubs (in a village or urban neighbourhood). Each network at the subnet tier follows a multi-radio wireless mesh network architecture. This model, where each access point is equipped with multiple radios, is commonly seen as a practical way to use multiple channels and mitigating performance degradation due to interference. At the top tier (the "backhaul

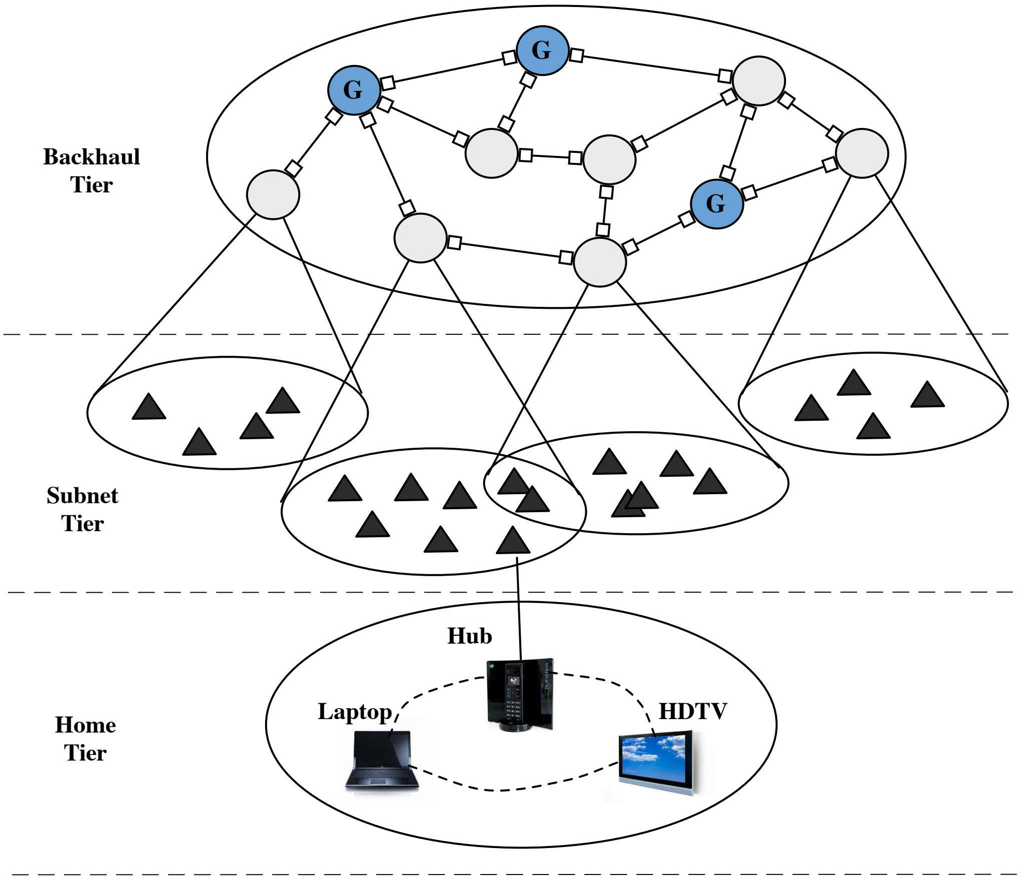


Figure 1.1: Multi-tier wireless mesh network model.

tier"), some nodes connect to the wired Internet infrastructure (nodes marked G for gateway). While some of the nodes at this tier only have the router role to forward data between other top tier nodes, several nodes additionally provide connectivity to the lower tier subnets using point-to-multi-point wireless links. Nodes at the top tier could be separated potentially by long distances in the order of several Kms, hence their interconnection into a network is achieved with the use of a pair of high-gain directional antennae per link. As such this tier can be seen as a point-to-point wireless network.

1.2 Thesis Contributions

In this thesis, we address the problem of adaptive spectrum management in the three specific application scenarios outlined above and propose novel solutions to address each of them.

1.2.1 Distributed Multi-Radio Channel Allocation for Multi-Channel 802.11 Wireless Mesh Networks

Channel allocation in multi-radio mesh networks is not trivial, because it needs to minimise interference, while ensuring that network connectivity is not compromised. The distributed case is even more challenging because of the channel dependency among the nodes, which can result in network instability. Nevertheless, distributed and adaptive channel allocation is necessary as explained in Section 1.1.1. Previous work in distributed channel assignment, however, places restrictions on the use of an interface,which limits the number of channels that can be utilised and, thus, the potential capacity gain. Other work predetermines the structure of the network and restricts the traffic patterns, which leads to inefficient channel utilisation for diverse traffic patterns (e.g., [10, 19, 20, 21, 22]). Other work relies on negotiation to perform channel assignment in a distributed manner, which induces substantial overhead (e.g., [23, 24, 25]).

This thesis proposes two novel distributed channel allocation mechanisms. The first scheme termed LCAP is a novel reinforcement learning-based approach where nodes independently and iteratively learn their channel allocation using a probabilistic adaptation algorithm [26, 27]. Extensive simulation-based evaluation of LCAP relative to the state-of-the-art ADC protocol [24] demonstrates that LCAP is able to achieve its stated objectives. These objectives include efficient channel utilisation across diverse traffic patterns, protocol scalability and adaptivity to factors such as external interference. Moreover, we empirically show that the probabilistic algorithm exhibits good convergence to low interference and connected network configuration when an explicit stopping condition is used. The worst case convergence time is hard to establish given the non-stationary nature of the network scenario. A loose upper bound can be obtained based on the constraint satisfaction problem problem formulation from [28], but such proof is unsatisfactory. Motivated by this, we develop a deterministic alternative, which employs a distributed priority-based mutual exclusion mechanism where nodes decide on their channel allocations based on only local information. We show that this alternative exhibits similar behaviour to our first approach. Key enabler of both approaches is a novel neighbour discovery mechanism that exploits the mesh network deployment model in practice, while being compliant to the 802.11 standard [26, 27].

1.2.2 Traffic-Aware Channel Width Adaptation for Long-Distance 802.11 Mesh Networks

Long distance wireless communication is associated with limited amount of spectrum due to higher transmit power requirements and also has to handle side lobe interference when using low cost directional antennae for rural/community wireless access. Efficient channel allocation in this scenario, therefore, necessitates allocation of incident links to different channels and adaptation to spatio-temporal variation in user traffic demands. We propose to accomplish the latter by leveraging the ability of commodity 802.11 hardware to vary the width of the channels [29] to adapt to the traffic load. Previous work on channel allocation in long-distance 802.11 mesh networks has not considered traffic-aware channel width adaptation. Instead it is motivated by either the impact of the high propagation delays on 802.11 performance for very long distance wireless links (e.g., [30]) or side-lobe interference (e.g., [31]). Other existing work on channel width adaptation for 802.11 networks does not consider directional antennae and focuses mainly on WLAN scenarios (e.g., [32, 33, 34]) in which the requirement to maintain network connectivity wirelessly is not an issue, thus they cannot be directly adapted to our multi-hop wireless network context. The limited work on channel width adaptation for mesh networks, either employs mathematical optimisation methods) making them unsuitable for large scale networks (e.g., [35, 36]), or makes unrealistic assumptions about network topology (e.g., single collision domain) or traffic patterns (e.g., single-hop sessions) [37].

Our work develops a channel width adaptation mechanism for long-distance directional mesh networks, which views channel width as a knob to enable traffic-aware channel allocation. Specifically, we propose a novel traffic-adaptive channel width adaptation mechanism, which assigns channel widths to links based on their relative traffic volume, while mitigating side-lobe interference. We show that the problem is NP-complete and propose a polynomial time, greedy channel allocation algorithm that guarantees valid channel allocations for each node. The algorithm facilitates adaptation to spatio-temporal variations in traffic demand through allocating wider channels to links with higher demand by taking spectrum away from links with less demand. Evaluation of the proposed algorithm via simulations of real network topologies shows that it consistently outperforms fixed width allocation due to its ability to adapt to spatio-temporal variations in traffic demands.

1.2.3 Coordinated TV White Space Spectrum Sharing for Home Networks using Micro Auctions

We consider the opportunistic secondary use of TVWS spectrum for home wireless networking applications as a way to relieve congestion in over-utilized WiFi frequency bands and at the same time exploit superior propagation properties of TVWS spectrum. In particular, we propose a micro auctioning[1] mechanism mediated by the geolocation database provider for *coordinated use of TVWS spectrum* by home networks in an interference-free manner. The unlicensed nature of TVWS spectrum implies that secondary users are given sufficient incentives to participate on a coordinated spectrum access method for interference-free access.

Previous work on spectrum auctions fails to capture this requirement. Specifically, it assumes that spectrum is licensed to some authority, thus it is largely oriented towards maximising revenue for the selling authority. (e.g., [38, 39, 40, 41, 42, 43, 44, 45, 46, 47, 48]). It is also important for a micro auctioning mechanism to support multi-channel auctions to meet the diverse and time-varying traffic (spectrum) requirements of secondary users. But some of the previous work only supports single-unit auctions (e.g., [42, 44]), thus adapting them to multi-channel auctions is not straight-forward. Other work while allowing multi-unit auctions, involves complex languages to express bidders' desires (e.g., [38, 39]) or allocates spectrum using a "best-effort" policy[2] (e.g., [38]). There exists other work that relies on linear programming [45, 46] for determin-

[1] auctioning for short time periods

[2] policy that allocates spectrum to users based on demand curves rather than strict demands

ing winners or complex critical neighbours searches for charging winners [41]. As an alternative to the aforementioned single-round auctions, the authors in [47, 48] have proposed multi-round solutions, which terminate if every channel is requested only by one bidder. However, this latter body of work assumes a single collision domain and tackles excess supply with linear programming, which makes it inefficient for larger scale scenarios like ours.

Our proposed auctioning mechanism enables efficient and adaptive sharing of TVWS spectrum in space and time among home networks (and their white space devices) with heterogeneous bandwidth requirements while offering incentives for providers and users alike. To the best of our knowledge, our work is the first to develop a scalable micro-auctioning mechanism for TVWS spectrum sharing through a geolocation database with home networking as the target use case. We evaluate our auctioning algorithm using realistic TV white space availability maps in the UK and actual distribution of homes in urban, sub-urban and rural environments. Our results show that our mechanism is able to achieve its stated objectives of attractiveness to both the database provider and spectrum requesters, scalability and efficiency for dynamic spectrum distribution in an interference-free manner.

1.3 Thesis Structure

Chapter 2 gives a background overview of the technologies and approaches used in this thesis and Chapter 3 discusses related work.

In Chapter 4, we present a protocol termed LCAP for efficient and adaptive distributed multi-radio channel allocation in 802.11 mesh networks. In LCAP, nodes autonomously learn their channel allocation based on neighbourhood and channel usage information. We also present a novel neighbour discovery protocol that allows nodes to obtain neighbourhood information even they do not share a common channel. LCAP is evaluated with respect to the state of the art ADC protocol using simulations.

Motivated by the non-stationary nature of the network scenario and the consequent difficulty of theoretically establishing LCAP's convergence time, we consider a deterministic alternative in Chapter 5. This approach employs a distributed priority-based mutual exclusion mechanism where nodes decide on their channel allocations based on only local information. We show via simulations that this mechanism exhibits similar performance to LCAP.

In Chapter 6, we address the channel allocation problem in long-distance 802.11

mesh networks in a traffic-aware manner. We consider a multi-radio mesh network architecture using directional antennae. We propose to exploit the capability of the 802.11 hardware to use different channel widths and assign different widths to links based on their relative traffic volume while ensuring that side-lobe interference is avoided. We show that the channel width assignment problem in question is NP-complete and propose a polynomial time, greedy channel allocation algorithm that guarantees valid channel allocations for each node. Evaluation of the proposed algorithm via simulations of real network topologies shows that it consistently outperforms fixed width allocation due to its ability to adapt to spatio-temporal variations in traffic demands.

In Chapter 7, we for the first time consider the use of TVWS spectrum for serving home wireless networking applications and thereby relieve already congested WiFi bands. We propose a novel approach for coordinated use of unused TVWS spectrum among home networks through a micro auctioning mechanism mediated by the geolocation database provider. The goal is to minimise contention among home networks, while avoiding disruption to primary users (TV receivers and microphone users). We evaluate our approach using real data from UK home distributions for dense urban, urban and rural residential environments. We examine the effect of uncoordinated access to these bands and argue that coordinated approach is more preferable. Our simulations show that our mechanism satisfies the design objectives for an interference-free, flexible and scalable mechanism which is considerate for both the seller and the buyers.

We provide concluding remarks in Chapter 8 and discuss future work in Chapter 9.

Chapter 2

Background

This chapter provides an overview of the technologies and approaches used in this thesis.

2.1 Wireless Communication Model

In wireless communications, two communication points (henceforth referred to as nodes) use “chunks” of radio frequencies (RF) to transfer information without the need of wires. These “chunks” are called *frequency channels*. A wireless channel is uniquely defined by the tuple $c =< f_c, w >$, where f_c represents the center frequency and w the width (or bandwidth) of the channel. The channel width determines the amount of information that can be carried by the particular channel.

Two nodes can communicate directly if they have a radio interface assigned to a common channel c and they lie within the transmission range of each other. The transmission range (also known as communication range) represents the range within which a packet can be successfully received if no unrelated transmission was causing interference. This range is determined by the received power at the receiver. The received power depends on the transmission power of the signal and the path loss over the distance between the transmitter and the receiver and the fading and shadowing effects, which determine signal attenuation. If R_T denotes the transmission range of a node A and d is the distance between node A and some other node B, then a packet can be successfully received by node B if $d \leq R_T$. A signal, however, is valid at the receiver if the signal-to-interference-plus-noise ratio (SINR) is above a certain threshold.This SINR is the ratio of the received power of the intended signal to the received power of noise (i.e., thermal noise at the receiver) and interference. The received interference

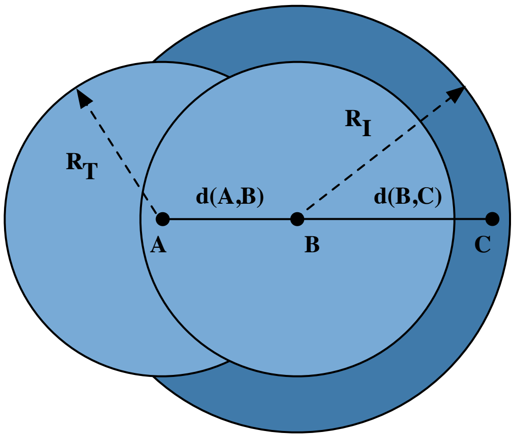


Figure 2.1: Radio Ranges.

power is the power of any signal transmitted by nodes within the interference range of the receiver at the same time communication from A to B is taking place on the shared channel. If R_I is the interference range of node B, a node C can corrupt packets sent from A to B if $d(B,C) \leq R_I$ and C operates on channel c. These radio ranges are described schematically in Figure 2.1.

2.2 Omnidirectional and Directional Antennae

A critical component of RF systems are the antennae, which are associated with the radio interfaces to produce radio waves. Broadly speaking, antennae can be categorised based on their directionality into two categories: Omnidirectional and Directional antennae [1]. This section gives an brief introduction to these antennae types with a focus on the basic concepts and advantages and disadvantages of each type.

Antennae are described by three properties: the gain, the direction and the polarisation. The antenna gain is the amount of energy that the antenna adds to a Radio Frequency (RF) signal, the direction is the transmission pattern and the polarisation of an antenna is the orientation of the electric field of the radio wave with respect to the Earth's surface and is determined by the physical structure of the antenna and by its orientation [1]. The direction of an antenna defines its coverage angle and is measured in degrees. The coverage angle of an antenna is called the beamwidth.

The coverage angle of an omnidirectional antenna is 360°, which allows the antenna to transmit and receive equally to all directions. Figure 2.2(a) shows the pattern

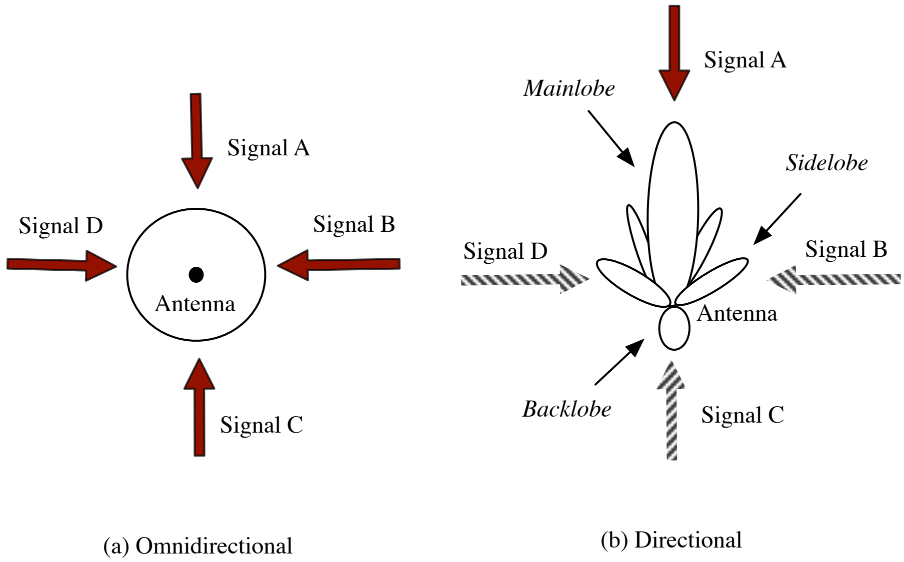


Figure 2.2: Antenna Patterns [1].

of an omnidirectional antenna with 4 incoming signals named A, B, C and D. Under this pattern, all depicted signals are received equally well. Figure 2.2(b) depicts a directional antenna. The mainlobe of the antenna is the direction with the maximum radiation or reception. The figure also shows sidelobes and a backlobe. These lobes represent energy leakage in unwanted directions. In this antenna type, signals B, C and D are suppressed because they are received outside the mainlobe of the antenna. The power of signal A, on the hand, is maximised. Note that the increase in power for a received signal depends on the antenna gain, which increases as the beamwidth decreases. This happens because the RF energy is distributed in a narrower area, which causes the signal to appears stronger.

Omnidirectional antennae do not require alignment in the direction of a specific destination, which makes makes them easier to deploy than directional antennae. They are also less costly and provide wider coverage than directional antennae. The latter is true because as the beamwidth of the directional antenna decreases, the number of required antennae to cover the desired directions increases. Furthermore, as the gain of the antenna is restricted towards a specific direction, directional antennae do not exploit the wireless broadcast advantage offered by the wireless medium. Wireless broadcast advantage allows every packet to be received by possibly any node within the sender's communication range. A message destined to several recipients, therefore, can be sent using a single packet. On the other hand, as explained before, directional antennae offer higher gain compared to omnidirectional antennae, due to the smaller beamwidth. This results in increased transmission range offered by directional antennae, which makes them suitable for long distances that omnidirectional antennae cannot cover. Moreover, the use of directional antennae provides spatial separation between contending links. More specifically, signals received outside the mainlobe can cause significantly less interference (i.e., signals in directions other than the mainlobe are rejected, unless they are received in the direction of sidelobes or backlobes, where interference is suppressed but not eliminated) than in the case of the omnidirectional pattern. This results in decreased interference and increased effective capacity.

Both antenna types have different advantages and disadvantages, thus the selection of an antenna must be strictly based on its application use. The main objective of our network model is to provide high speed connectivity at a low cost. To accomplish these two objectives, we propose a two-tier mesh architecture which exploits the advantages of both antenna types on top of the benefits of mesh connectivity. More specifically, at the bottom tier each subnet interconnects rooftop mesh access points in an urban neighbourhood or a village. The use of a pair of directional antennae per link is impractical in this scenario for several reasons. These networks need to be easy to deploy and maintain to be adaptive to network topology changes, such as new node joins and node failures. Moreover, they must be able to support arbitrary traffic patterns, including "intra-mesh" applications (e.g., surveillance). This necessitates denser deployments which are costly to achieve using directional antennae. The cost increases as the number of links increases, since a pair of directional antennae is required per link. Furthermore, this subnets are formed based on the population needs, thus they cannot be carefully planned. For this reason, they need to adapt quickly to temporal variations in link qualities, caused by interference and "bad" channels conditions. This requires fast and up-to-date dissemination of routing information in the network. Routing protocols, however, rely on broadcast transmissions, which, as explained above, are more efficiently supported in networks with omnidirectional antennae.

The main constraints at the top tier, on the other hand, is the need to connect nodes separated potentially by long distances in the order of several Kms. Long range transmissions necessitate high antenna gains for successful long range transmissions, which are not sustainable using omnidirectional antennae. This enforces the use of a pair of high-gain directional antennae per link to achieve interconnection of the backhaul nodes. The network at the top tier, however, can be carefully planned as opposed to the subnets at the bottom tier, thus the low cost objective can be still satisfied.

2.3 IEEE 802.11 Overview

The IEEE 802.11 [6], also known as Wi-Fi (Wireless Fidelity), is a set of standards for implementing wireless local area network (WLAN) communication in the frequency bands allocated for license-exempt use by regulatory bodies worldwide. More specifically, these standards specify the physical layer (PHY), including modulation and coding, packet formats and the medium access control (MAC) protocol for handling contention between multiple transmitters. The most popular versions are the 802.11a, 802.11b/g standards for communication in the 2.4 and 5 GHz frequency band respectively.

2.3.1 Physical Layer and 802.11 Channels

The 802.11b standard uses either Frequency Hopping Spread Spectrum (FHSS) or Direct Sequence Spread Spectrum (DSSS) for signal modulation allowing 1Mbps, 2Mbps, 5.5Mbps and 11Mbps data rate. The standard also divides the 2.4 GHz frequency band into a number of channels each 22 MHz wide. The number of available channels depends on the regulation of each country. There are 13 channels available in Europe, 11 channels in the US and 14 channels for Japan. The channels, however, are spaced only 5MHz apart and as such they significantly overlap with each other. Figure 2.3, shows that there are only 3 non-overlapping channels for Europe.

The 802.11a standard operates on frequencies in the 5GHz radio spectrum.This standard uses Orthogonal Frequency Division Multiplexing Modulation (OFDM) as a signalling method which allows higher data rates (i.e., up to 54 Mbps) compared to the 802.11b. The standard also provides channels 20 MHz wide with 20 MHz spacing between their centre frequencies, resulting in a larger number of non-overlapping channels. Figure 2.3 depicts the available channels in the 5GHz band for Europe. These channels reside in two different frequency blocks: from 5150 to 5350 MHz (for indoor use) and from 5470 to 5725MHz (for both indoor and outdoor use). Unfortunately, despite these advantages, 802.11a radios have shorter transmission range compared to 802.11b radios, caused by the higher operating frequency.

The 802.11g standard was developed as an attempt to combine the best of both 802.11a and 802.11b standards. 802.11g supports data rates up to 54 Mbps, similarly to 802.11a. The radios using the 802.11g standard, however, operate in the 2.4 GHz frequency band similarly to the 802.11b standard, thus enabling greater ranges and backward compatibility with 802.11b radios.

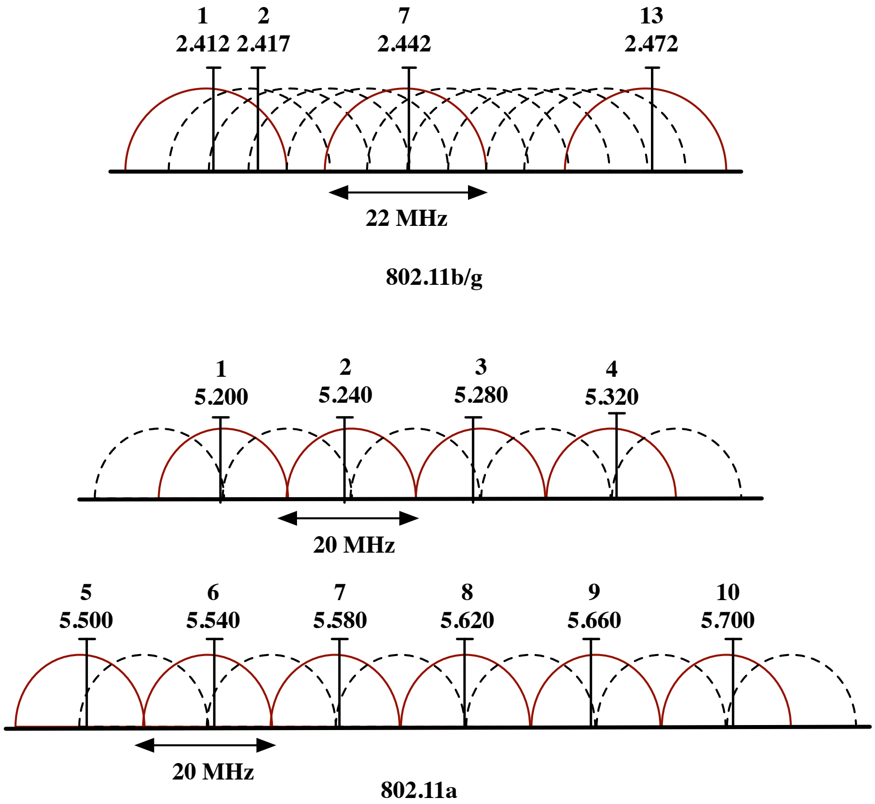


Figure 2.3: 802.11 Channels in the 2.4 GHz and 5 GHz licence-exempt bands in Europe [2].

2.3.2 Medium Access Control Layer

The IEEE 802.11 standard defines two different formats for data packets: broadcast and Unicast. Broadcast packets are destined to all nodes connected to the same network (i.e., broadcast domain) rather than an individual receiver. Every node can hear these packets, if it listens to the transmitting channel and resides within the transmission range of the sender node. Unicast packets, similarly to broadcast packets, require receiver nodes to listen to the same channel close to the transmitter, but differently from broadcast packets, they are destined to a specific node. When a node receives a unicast packet, it responds with an acknowledgement (ACK) packet after a Short Inter-Frame Space duration. If the sender node does not receive the ACK packet, the transmission is considered failed. For every failed unicast transmission, the sender resends the packet until the maximum number of permitted attempts is reached, in which scenario the packet is permanently discarded. Each node can identify whether the packet is destined for it by examining the destination address carried in the packet. Each node that receives a unicast packet and is not the intended destination, does not further processes the packet nor does it send an acknowledgement. They, however, update their Network Allocation Vector (NAV) with the duration of the ongoing communication. The NAV value works as a count down timer, which enforces neighbouring nodes to remain idle until the current communication has finished to avoid collisions.

The NAV value is a feature of the Medium Access Control (MAC) protocol used by the IEEE 802.11 standard to share the medium among contending transmitters. The defined MAC technique, called the Distributed Coordination Function (DCF) employs the Carrier Sensing Multiple Access/Collision Avoidance (CSMA/CA) protocol, according to which, a wireless station (whose NAV value is 0), must sense the medium for ongoing transmissions before attempting to send a packet. If the channel is sensed free, or after any ongoing transmission has finished, the station waits for a mandatory duration called Distributed Inter-Frame Space (DIFS). If the medium is found busy during that duration, the station defers its transmission. After that period elapses, each station chooses a random backoff period from the next CW (Contention Window) slots. CW is initially set to the minimum specified value (CW_{min}) and is doubled after every unsuccessful attempt to send the same packet until the maximum specified value (CW_{max}) is reached. This extra backoff period serves as a jitter to avoid collisions caused by multiple stations that simultaneously deferred their access (i.e., the channel was perceived busy) and then try to transmit after the channel is released.

The DCF mechanism also provides an optional virtual carrier sense mechanism to further reduce contention. This mechanism, when applied, uses a Request-To-Send/Clear-To- Send (RTS/CTS) packet exchange, when the size of the transmitted packet exceeds a predetermined threshold, prior to data transmission. More specifically, the transmitting station sends a very short RTS frame to the receiving station. if the receiver does not defer access, due to some ongoing communication, it responds with a CTS message. After receiving the CTS message, the sender starts sending the data packet. Other nodes overhearing the RTS/CTS messages, update their NAV value with the time needed for the actual data transmission as reported in these messages. The purpose of this mechanism is to tackle the hidden terminal problem [49] and to avoid interruptions in the transmission of long frames. The RTS/CTS handshake, however, has been shown to be ineffective in eliminating the hidden terminal problem [50], it adds considerable overhead in the network and, thus, it is rarely used in practice.

2.4 Wireless Mesh Networks

2.4.1 Overview

The main focus of the 802.11 standards is on WLANs operating in infrastructure Basic Service Set (BSS) modes. In this mode, stations[1] associate with a central device, called the Access Point (AP). The AP is connected to the wired Internet, providing this way Internet connectivity to the stations, while it is also used as a relay between them[2]. This mode, therefore, forms a single-hop network topology.

Unfortunately, as the demand for high speed ubiquitous network access is increasing, traditional networks become insufficient. Single-hop topologies rely on dense deployments to provide extended coverage, thus infrastructure cost is high. The need for low cost and decreased dependence on the wired infrastructure led to the development of the 802.11s standard, which is build on top of the current 802.11a/b/g standards. This standard describes the operation in networks composed of 802.11 devices, which are connected with each other wirelessly to increase coverage. In these networks, the devices establish and maintain connections between them automatically and provide connectivity over multiple hops. Such networks are called Wireless Mesh Networks (WMNs).

Several types of wireless mesh networks exist [7]. The most commonly used architecture, however, is in the infrastructure/backbone-based type, which is the focus of this work. Figure 2.4 shows an example infrastructure mesh network. An infrastructure mesh network is composed of mesh routers[3], mesh clients and gateways. Routers (statically positioned) are connected together to form the backhaul tier with the gateways connecting the backhaul to the Internet. End-user client devices are connected to the routers via the access tier for Internet access or to communicate with other clients. Typically, routers are equipped with two types of radio-one for backhaul communication and one for client communication. Typically, backhaul network interfaces/radios operate on 802.11a, since it is less crowded and provides more channels (Section 2.3). Client interfaces, on the other hand, typically use 802.11b/g, because most client devices have a 802.11b/g wireless card.

The mesh architecture offers several advantages. Mesh networks facilitate connectivity over multiple hop paths, which increases coverage range and decreases the cost

[1] In the IEEE802.11, any device that uses 802.11 standards is denoted as station.

[2] The IEEE802.11 also defines an independent BSS, where stations form a network without the need of an AP, but this type is less commonly used.

[3] Routers and access points are used interchangeably in this work when referring to mesh nodes.

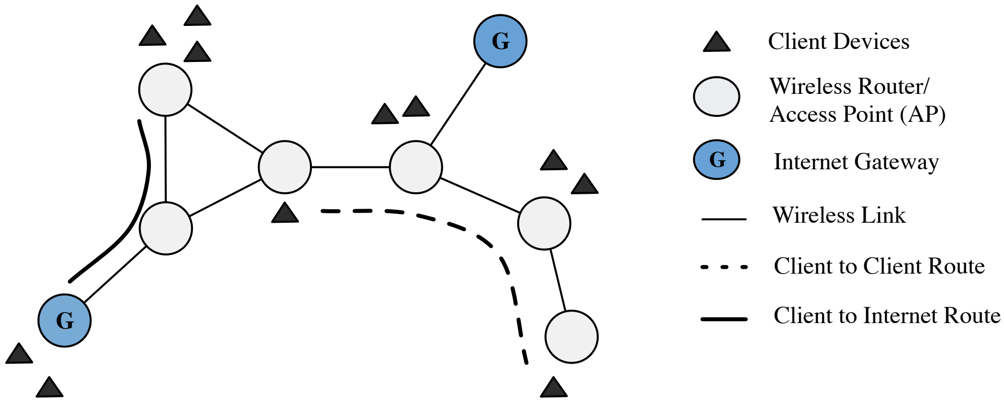


Figure 2.4: A Typical Wireless Mesh Network.

of deployment. A single mesh access point connected to the wired Internet can provide connectivity to clients at distances that do not allow direct association as required in traditional single hop WLANs. This reduces dependence in the wired infrastructure, which results in low deployment cost. Furthermore, mesh networks provide more than one alternative paths between two nodes. The existence of redundant paths ensures robustness in link failures, since it enables routing protocols to select a different path upon a link breakdown. Redundancy, therefore, suppresses network disruptions.

2.4.2 Application Scenarios

Application scenarios for wireless mesh networks are numerous [7]. In this section, we briefly describe few examples where the use of WMNs is beneficial:

- *Enterprise mesh networks*: These mesh networks are deployed within a building or among offices in multiple buildings. Although standard IEEE802.11 wireless networks are widely used in offices, these networks are interconnected through wired Ethernet connections, resulting in high cost. The purpose of the wireless mesh networks it to wirelessly interconnect the different networks to reduce the amount of required wired infrastructure and decrease enterprise expenses. The feasibility of such network is demonstrated in [51] where an all-wireless office mesh network is deployed and studied.

- *Community mesh networks*: These are mesh networks deployed for the purposes of a community: E.g., surveillance, distributed backup or news announcement. In the common architecture for network access uses cable or DSL connected to the Internet with only the last-hop being wireless (i.e., a wireless router is connected to a cable or DSL modem). This architecture, however, requires all traffic to flow through Internet even if traffic concerns only a single neighbourhood. Gateway nodes may not be shared among multiple houses or neighbourhoods, thus service costs may increase. Moreover, traditional deployments may provide only a small number of direct communication paths between houses. These disadvantages can be mitigating via flexible mesh connectivities provided by mesh networks. In these networks all participants within an area (e.g., a neighbourhood) own and maintain rooftop mesh nodes which are interconnected together to form the mesh. An famous deployed community mesh network is MIT Roofnet [52].

- *City mesh networks*: These networks extent the benefits of community mesh networks to cities. By installing public WiFi hotspots in different areas within a city and interconnecting these hotspots, mesh networks can inexpensively cover entire cities. These municipals mesh networks offer several advantages such as allowing commuters to check their emails in public transportations (e.g., bus, train), parks, or restaurants or facilitating public work officials in monitoring the city's power and water supplies. Example city mesh networks are the Heraklion MESH network [53, 54, 55] and Google WiFi [56]. The former is a small experimental network in the city of Heraklion in Crete, Greece. The latter, is a large network deployed by Google at Mountain View.

- *Rural mesh networks*: The goal of these networks is to provide low cost Internet access to underserved areas where broadband access technologies, which are prevalent in urban areas (fiber, DSL, cable, 3G/4G), will take years to fully penetrate. Broadband to rural communities, however, is particularly important for several reasons, such as to support the local economy by creating local business opportunities, to enable access to educational resources, or to facilitate health care via remote monitoring. Wireless mesh networks can provide inexpensive broadband wireless access to these areas via long distance communication links, thus depending significantly less in the wired infrastructure. Example rural mesh networks are the Connected Communities (ConCom) network [57] and the Tegola project [58, 59]. The ConCom is a relatively large broadband wireless access network covering the Western Isles of Scotland with a population around 26,000 spread across 11 islands and span of over 200Km. This network consists of 34 backhaul sites interconnected by point-to-point wireless links with widely different link lengths. It provides connectivity to public buildings (e.g., schools, community centers) as well as residential users. Tegola is a small network consisting of 5 backhaul wireless nodes deployed by the the University of Edinburgh (wireless and mobile group) in rural Scotland. Though originally intended as a research testbed, it currently also serves as a community wireless network connecting real users to the Internet.

2.5 Spectrum Management in Wireless Mesh Networks

Spectrum management is the process of managing the available spectrum such that available capacity is increased. This process, however, becomes more difficult as the number of devices continuously increases and the amount of useable spectrum is limited. This section provides an overview of the mechanisms for efficiently managing the available spectrum.

2.5.1 Channel Assignment

Unlike wired networks, in which each pair of nodes communicate via a dedicate wire, wireless networks involve transmissions over a shared medium - air. As a result, communication between a pair of nodes can cause interference to neighbouring transmissions operating on the same channel. To avoid packet losses due to simultaneous transmissions, the 802.11 MAC protocol uses the distributed coordination function mechanism with exponential backoff to control access to the medium in traditional omnidirectional WLANs (Section 2.3.2). Under this mechanism interfering stations compete for access to the channel, thus the number of allowed simultaneous transmissions and, hence, the obtained throughput depends on the density of the network. Furthermore, the DCF mechanism has been shown to be ineffective in eliminating collisions when a large number of stations compete for the channel [60] or interference in the presence of hidden terminals [50].

Throughput degradation is even more severe in wireless mesh networks, where packets may need to traverse several paths to reach the destination [8, 61]. Figure 2.5 shows a single-hop (a) versus a multi-hop network configuration (b). In both cases assume that only node A has traffic to send to the gateway node G. In this case, the

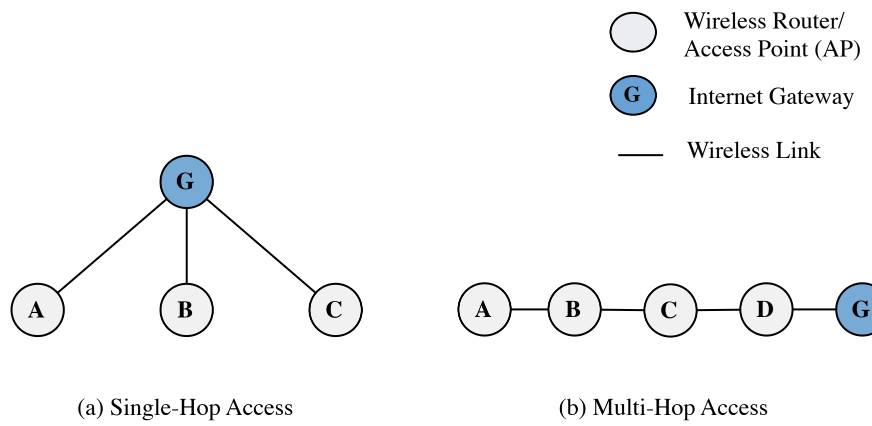


Figure 2.5: Internet Access via (a) single-hop (traditional WLAN) and (b) multi-hop (WMN) paths.

achievable theoretical throughput[4] for flow $A \rightarrow G$ equals the channel capacity. In the multi-hop setting, though, packets from node A to the gateway need to traverse intermediate nodes B, C and D forcing contention in the MAC protocol for a single flow. More specifically, while node A is transmitting, node B cannot transmit because it cannot transmit and receive at the same time. Additionally, node C cannot transmit because that would corrupt the packets from node A to node B. If we assume that only directly connected nodes interfere with each other, then the earliest node that can transmit in parallel with node A is node D. The achieved throughput therefore is one-third the channel capacity [61]. Intra-flow contention is even more restrictive when nodes which cannot communicate successfully, they can still interfere, thus they can corrupt each other's transmissions.

In such multi-hop settings, capacity can be enhanced by using the multiple channels available by the 802.11a/b/g standards. When interfering nodes operate on orthogonal channels, the number of concurrent transmissions is increased. Due to great reductions in hardware cost, multi-radio architectures, in which each node is equipped with multiple interface cards, are commonly considered as a practical way to utilise multiple channels. The problem that arises then is how to assign (map) channels to the available interfaces at each node such that (a) interference/contention is reduced, and (b) network connectivity is maintained.

[4]This is the maximum theoretical throughout in the absence of channel errors and without considering the MAC overhead (i.e., backoffs, inter-frame spacing, etc.)

One simple solution is to assign the same set of channels to the interfaces of every node in the network [62, 63, 64, 65]. Since the number of interfaces is very unlikely to match the number of available channels, though, this solution can only employ a small set of channels and thus provides limited gain. An alternative solution to exploit channel diversity more efficiently is to assign the interfaces of a node to the least used channels in the neighbourhood. Such approach balances channel usage and thus minimises interference by distributing channels across interfaces. Unfortunately, this method does not guarantee network connectivity. A pair of nodes needs to share a common channel to be able to communicate. A channel assignment mechanism, therefore, needs to balance between decreased channel usage and network connectivity.

2.5.2 Channel Width Adaptation

The IEEE802.11 standards partitions the unlicensed frequency spectrum into a preset number of channels of equal-width (i.e., 22MHz for 802.11b/g and 20MHz for 802.11a) (Section 2.3.1). The maximum capacity a link can offer, thus, is statically upper bounded by the width of the channel it is operating on. To illustrate how this static spectrum partitioning limits efficient spectrum utilisation, consider the scenario shown in Figure 2.6. This figure depicts a chain topology where each node is equipped with two interface cards and only adjacent nodes can communicate directly. We assume that the interference range of each node is twice its transmission range, thus nodes which are not directly connected can still interfere. For this reason, A should not communicate with B at the same time that B communicates with G when the corresponding links operate on the same channel to avoid interference. To enhance concurrent transmissions, thus increase the available capacity, links are allocated to non-overlapping channels each 20MHz wide as shown in Figure 2.6(a). As shown in figure, however, there are two ongoing sessions in this example network: One from node A to the gateway and one from node B to the gateway. The traffic demand of both sessions is 20Mbps, but because the traffic of both sessions traverses link (B,G), links are carrying different loads (i.e., link (A,B) carries 20Mbps traffic, but (B,G) carries 40Mbps). If 1MHz spectrum can deliver 1Mbps traffic, link (B,G) can only deliver 20Mbps, although its demand is 40MHz. It therefore becomes the bottleneck in the network. Assuming the available spectrum is 60MHz, a better allocation would be the one shown in Figure 2.6(b). The width of the channel assigned to link (B,G) is now 40MHz, thus the widths of both links match their loads and both sessions are satisfied simultaneously.

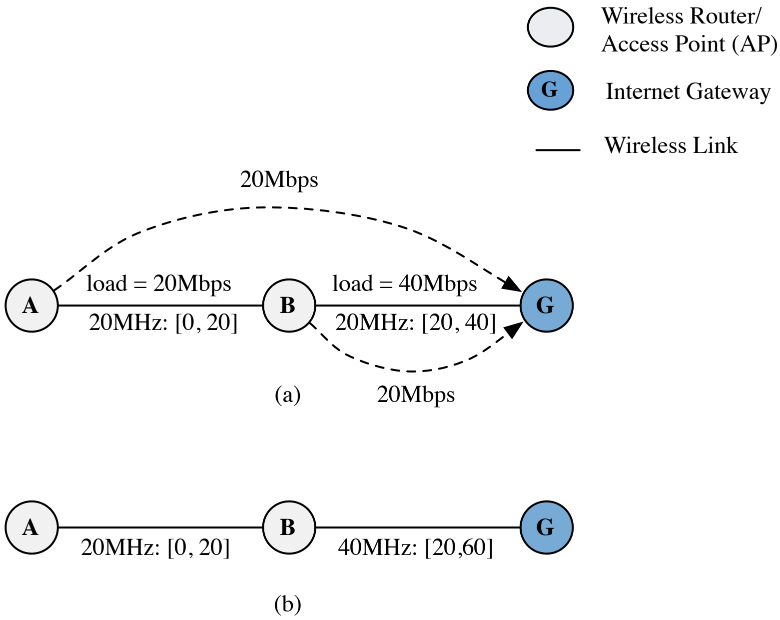


Figure 2.6: Scenario demonstrating (a) Inefficient spectrum allocation with fixed 20MHz width and (b) Traffic appropriate channel width allocation. Under each link, wMHz corresponds to the width of the channel assigned to it and [x,y] denotes the upper and lower frequency range of that channel.

The feasibility of a solution, which dynamically adjusts the widths of the channels to meet current needs has been demonstrated in recent work [29]. In this work, the authors showed that commodity network interface cards can be modified in software to permit communication at 5, 10, and 40 MHz channels in addition to the standard 20 MHz. Moreover, they illustrated the performance improvement by adjusting the width of the channel for a single link. A channel width adaptation mechanism for a network of nodes is highly challenging. More specifically, an effective channel allocation mechanism needs to allocate channels to links such that the widths match their loads. Since the usable spectrum, however, is finite, such non-uniform allocation can only be achieved through allocating "wider" channels to links with higher demand by taking spectrum away from links with less demand. This along with interference constraints, which dictate that interfering links should be assigned to non-overlapping channels, can result in links with no usable channel. An effective channel width adaptation mechanism, therefore, needs to ensure that the network topology remains intact. Moreover, since traffic demands also vary frequently during time, such approach should have low complexity to permit fast adaptation.

2.6 Spectrum utilisation of Under-utilised/Idle Bands via Secondary Access

The technologies and approaches we have described so far concern the operation in 802.11 frequency bands. Access to these bands is permitted to every wireless device subject to basic regulatory restrictions (e.g., limiting to indoor or outdoor use, staying within the EIRP limit) and etiquette rules such as vacating a channel on detecting a radar signal (e.g., 5GHz bands in Europe). The explosion in wireless devices, however has led to the over-utilisation of the 802.11 bands. This has motivated extensive research on ways to permit access to under-utilised or idle licensed frequencies (whose licensees are referred to as primary users), by unlicensed devices (referred to secondary users). The goal of this research is to facilitate more efficient spectrum utilisation without disrupting the primary users. This section focuses on spectrum management of idle or under-utilised bands with an emphasis on Cognitive Radio (CR) technology.

2.6.1 Cognitive Radios

Access to idle or under-utilised bands has been made practical by advances in microelectronics that enabled the development of radio transceivers, which can change radio characteristics, such as modulation and power, entirely in software. This capability enabled the use of the same hardware in different frequency bands and offered increased flexibility. This software reconfigurable hardware, referred to as Software Defined Radios (SDRs), combined with real-time sensing and decision-making capabilities resulted in the creation of Cognitive Radios (CRs). Different from SDRs which are only reconfigured on-demand, CRs are self-reconfigurable based on interaction with the environment in which it operates, thus they are capable of adaptively utilising the spectrum under consideration in a way that is transparent to the user [66].

Cognitive access to the idle or under-utilised licensed frequencies is being actively pursued by regulators as a mean for more efficient utilisation of the radio spectrum. Such access, however, needs to be controlled such that interference to the remaining TV broadcast stations as well as other licensed devices (e.g., wireless microphones) is prevented. To ensure that TV White Spaces are successfully detected and incumbents are protected from interference, both the UK and the US regulators have considered three access methods for cognitive devices: beacons, sensing and geolocation combined with a database [67]. However, although these approaches ensure that cognitive devices do not cause interference to primary users, they do not consider interference among secondary users in multiple cognitive radio systems. We refer to these approaches as “uncoordinated spectrum access”. Motivated by this, work in literature has studied interference-free distribution of under-utilised portions of licensed spectrum via micro-auctions[5]. In the section that follows, we briefly overview these two different forms of access.

2.6.2 Forms of Secondary Access

2.6.2.1 Uncoordinated Spectrum Access

As mentioned, before, spectrum regulators have considered three methods for uncoordinated access using cognitive devices: beacons, sensing and geolocation combined with a database [67].

In the beacon method, unlicensed devices are allowed to transmit if they receive a beacon signal indicating that the channel is vacant. One issue with a beacon mechanism it induces an additional beaconing overhead. Moreover, since beacon signals can be lost, it does not guarantee successful TVWS detection. Different from the beaconing method, sensing allows secondary users to independently detect the presence of TV signals by measuring the signal power on the channel. There are situations, however, where the signal path to a cognitive device from a TV transmitter is blocked preventing the CR to detect the TV signal. In this cases, the secondary user may cause severe disruption to TV receivers (hidden terminal problem).

Finally, secondary users can access the vacant licensed spectrum by means of geolocation combined with a database. In this method, a device determines its location and accesses a database, which informs it on the available vacant channels at that location. This method requires an administrative authority to develop and maintain the database and communication between the devices and the database. The latter issue, however, can be addressed through the use of a master-slave architecture. In this model, an access point or a base station (master) is connected to the database. The master node queries the database on the channel availability and instructs the secondary users (slaves) on the channels they can use. This method ensures that secondary

[5] We use the term micro-auctions to distinguish periodic auctions which performed in the order of hours from long-term auctions which are traditionally used by spectrum regulators to lease spectrum (e.g., to mobile wireless operators).

users do not access occupied channels, thus interference to incumbents is avoided. For this reason, FCC (Federal Communications Commission) and Ofcom (Office of Communications) - the regulatory bodies in the US and UK respectively - have decided to use the geolocation database as the primary TVWS spectrum access method.

2.6.2.2 Spectrum Access via Micro-Auctions

An alternative approach exploits auctioning mechanisms to facilitate coordinated spectrum access. An auction is a process via which a seller (or auctioneer) offers an item to a set of buyers (or bidders), collects the bids and allocates the item based on competition. This process involves a set of trading rules for resource allocation and pricing. When a single item is offered, four basic types of auctions are mainly defined [68, 69]: (1) the English auction; (2) the Dutch auctioN; (3) the first-price sealed-bid auction; and (4) the second-price sealed-bid auction.

The *English auction* (also known as *open*, *oral*, or *ascending-bid auction*) is the most widely used type of auction. In this type, each bid is higher than the previous one and the current highest bid is always known to the bidders. The price of the item is either announced by the auctioneer or the bidders themselves. The auction ends when no bidder wishes to bid further. The item is then sold to the buyer with the highest bid. In a variation of this auction type, the seller can define a minimum selling price for the item (called the *reserve price*), which if not reached, the item remains unsold. Additionally, the seller can specify the minimum amount by which two successive bids differ. The *Dutch auction* (also known as *descending-bid auction*) is the reverse of the English auction. Specifically, the auctioneer announces an initial high price and lowers the price until one bidder accepts. The winner pays the last announced price.

In the *first-price sealed-bid auction* potential buyers submit sealed bids and no buyer knows the bid of its opponent. The item is sold to the buyer who places the highest bid. The winner then pays the amount she bid. Different from the English auction, in this type, buyers can only bid once, thus they cannot observe their opponents' bids and accordingly change their decisions. Similarly to the first-price sealed-bid auction, in the *second-price sealed-bid auction* (also known as *Vickrey auction*), each buyer places a sealed bid independently of its rivals and the winner is the buyer with the highest bid. The amount the winner pays, however, is the bid of the second highest bidder (i.e., the bidder who would win the item if the current winner had not placed a bid).

In a more complicated version, more than one item is sold simultaneously. These auctions, called *combinatorial auctions*, enable buyers to bid on bundles of items rather than individual items [70, 71]. In these type of auctions, however, due to the large number of possible combinations, bidding and winner determination becomes a challenge. Buyers need a way to express their bids for every possible set of items, while winner determination becomes difficult for the sellers.

2.7 TV White Spaces

TV bands are the most extensively studied portions of the spectrum for opportunist secondary access using cognitive radios. TV bands concern channels at the VHF and UHF portion of the spectrum, which, at every country, are allocated to analogue television services. This spectrum is protected by spectrum regulatory bodies, which prohibit the operation of unlicensed devices on the channels within the TV band, with the exception of wireless microphones, remote controls and medical telemetry devices. These devices along with the TV transmitter stations are referred to as the primary users. Currently, however, several countries are in the process of replacing the analogue television signal by digital transmissions. This process, called the Digital SwitchOver (DSO), was completed in the US in June 2009 and is expected to be completed in the UK in 2012. After DSO, some of the analogue TV channels become vacant, because digital TV is more spectrally efficient and requires less bandwidth. These channels are known as cleared channels. Regulators plan to license the cleared spectrum through auctions (e.g., to mobile telecom operators for providing 4G services).

Moreover, after DSO is complete, a number of channels within a geographic area are excluded from TV transmissions. This happens because operation on these channels would create interference to nearby TV stations operating on the same channels or on channels adjacent to them. Unlike high power digital TV stations low power devices are being allowed to operate on such restricted channels without risking corruption of TV signals. The locally vacant TV channels, therefore, can still be utilised for low power transmissions. These channels are known as TV White Spaces (TVWS) (or Interleaved Spectrum in the language of Ofcom, the UK regulator).

Figure 2.7 shows the allocation of TV channels in the UK after the DSO is complete. The spectrum marked in grey is the cleared spectrum which will be licensed via long term auctions to other services. The channel marked in pink is regulated for exclusive use for wireless microphones and so forth (PMSE). Finally, the spectrum marked in blue is the TVWS that is permitted for secondary access. The figure shows

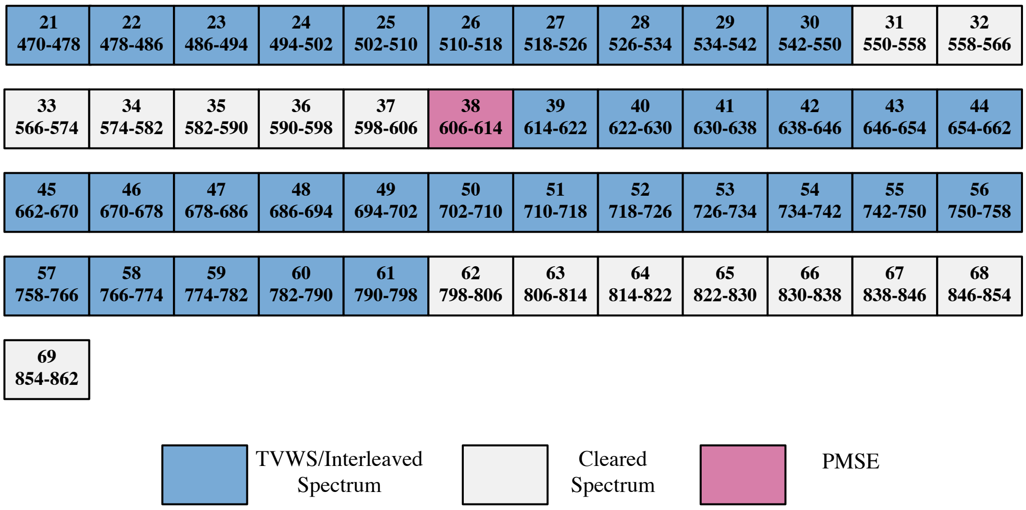


Figure 2.7: TV licensed spectrum allocation after DSO is complete [3].

for each channel its channel Number and frequency range (MHz).

2.7.1 Spectrum Characterisation

The channel map at Figure 2.7 shows the channels that will become available after DSO is complete in the UK. As explained in Section 2.7, however, the availability of these channels varies between different locations and as a function of transmit power from cognitive devices. Efficient use of white spaces, therefore, depends greatly on the ability to quantify the availability of channels for cognitive access. Motivated by this, in [72] the authors have developed a tool for modelling the spectrum availability in the UK using the DTV coverage maps of the UK [73]. These maps have been created using the location, antenna height, transmit power and frequency of the UKs DTV transmitters and have a resolution of 800x1600 pixels. Each pixel covers approximately an area of one square kilometer. A different coverage map is generated for each TV channel. Each pixel in these maps is either coloured indicating that the channel is occupied at the location associated with the pixel, or colourless otherwise. These maps are overlaid on top of a map of the UK which uses the UK national grid and features the signal propagation at different locations (we call the final maps, the overlaid coverage maps). A list of the vacant TV frequencies that can be used by a low-power cognitive devices for an input location can be obtained by parsing each of these maps.

2.7.2 TV White Space Spectrum Availability

The acquirement of the vacant channels for a given location, however, requires processing of 49 overlaid coverage maps (total 49 TV channels), which is computationally inefficient. Instead, the information provided by the overlaid coverage maps is stored in a relational database [74]. More specifically, the database holds a table which stores for each pixel of the UK map the following information: the horizontal and vertical reference of the pixel in the map (hereafter referred to as X and Y) and one entry for each of the 49 channels in the TV band. Each channel entry stores a flag indicating the usage of the channel within the area associated with the pixel. If a flag is not set, the corresponding channel at that location is free. This table is populated once by parsing each of 49 channel maps pixel by pixel. If the pixel in a channel map is coloured, the flag of the corresponding channel entry is set.

The list of TVWS channels is retrieved by simply querying the database using the X and Y of the pixel identifying the given UK location. This requires a simple transformation of a users' GPS location into national grid Easting and Northing, which are then converted into X and Y suitable for querying the database.

Chapter 3

Related Work

In this chapter, we discuss previous work related to this thesis. We first consider related work on channel assignment. We then discuss previous work on long distance mesh networks and present previously proposed approaches on channel channel width adaptation. Finally we discuss micro auction mechanisms for spectrum sharing.

3.1 Channel Assignment in Wireless Mesh Networks

Channel assignment is not a new problem, thus there is a wide body of related work. Unfortunately, this problem has been proven to be NP-hard in previous work by mapping it to the Graph-colouring problem [75, 76]. As a result, heuristic techniques are usually employed to assign channels to the nodes in the network.

Broadly speaking, this work can be classified into two main categories: One category includes channel allocation schemes that assume radios, which can achieve channel switching on a packet-by-packet basis with negligible delay [77, 78, 79, 80, 81, 82, 19], while the other category consists of mechanisms that assign channels for longer periods of time, such as hours or days [24, 21, 25, 22, 9, 76, 10, 83, 84, 85]. Additional related work proposes joint channel assignment and routing/scheduling solutions [86, 87], while other work introduces routing mechanisms assuming predetermined channel assignment. In what follows, we discuss each of these different approaches separately.

3.1.1 Assignment with On Demand Channel Switching

The goal of the mechanisms in this body of research is to find a channel for a single packet transmission or for a short a small number of transmissions such that multiple parallel transmissions are enabled and interference is minimised.

Bahl et al. [77] proposed a Slotted Seeded Channel Hopping (SSCH) channel assignment mechanism for single radio networks. SSCH assumes time is slotted and at each slot, each node uses a channel generated using a pseudo-random sequence (channel schedule). Two neighbouring nodes can communicate within a slot time, if their radios are swithed to a common channel. For this to happen, however, time synchronisation is required to implement the slotting and frequent schedule adaptation is needed for nodes to overlap on their channels frequently.

Shacham et al. [78] presented two different channel assignment mechanisms. In the first mechanism each node is equipped with a single radio tuned to a channel, which listens when it does not transmit (the quiescent channel). When a packet needs to be transmitted, the interface is switched to the quiescent channel of the intended receiver. This method is called receiver-directed scheme. In the second architecture each node is required to remain on its designated channel, but some nodes are equipped with more than one radios. When a node wishes to send a packet to a node on a different channel, it sends it via a multi-radio node, which serves as a bridge between channels. Different from the SSCH approach, in these solutions the selection of the quiescent channels and the distribution of this information is assumed to be performed by a separate mechanism and is already given.

Wu et al. [80] introduced a negotiation-based approach, where each node is equipped with two wireless interface cards. One interface is statically assigned to a common channel, the control channel, while the other can switch to channels other than the default one, called the data channel. Nodes use the control radio to transmit control messages and to negotiate the channels for data transmissions on the data radio. Nodes wishing to communicate need to negotiate via a three-way handshake mechanism (RTS/CTS/RES) on the control channel (distributed mutual exclusion [88]). If the nodes successfully settle on a channel, the data packet is then transmitted via the data interface on the agreed channel. The two drawbacks of this approach is the dedicated common channel, which is the bottleneck in the network and the required negotiation among the nodes, which induces extra overhead.

So et al. [79] proposed the Multi-Channel MAC (MMAC) protocol in which nodes also negotiate their communication channel. Different from the work in [80], though, each node uses a single transceiver. Specifically, periodic beacon transmissions are used to synchronise every node in the network into time intervals. Each of these intervals is further divided into two time periods. The first period at the beginning of the interval is a small window within which nodes are using a default channel and negotiate the channel to use for data transmission. Actual communication takes place during the second time window where radios are tuned to the chosen channel.

Maheshwari et al. [81] proposed two modifications for the receiver directed scheme presented in [78]. An additional channel busy tone at the receiver to prevent collisions just after switching and a notification of ongoing communication completion to wakeup potential transmitters. The modified, protocol, however, requires an additional interface. The authors also propose a single radio mechanism where communication follows transmission schedules, each composed of a control time window and the data window. During the control window all nodes listen to a default channel on which they negotiate the channel for the data window by exchanging RTS/CTS and RES messages. After a successful negotiation, the sender will transmit packets on the agreed channel. Collisions are avoided through a modified version of the Network Allocation Vector (NAV), with maintains one element per channel.

Kyasanur and Vaidya [19, 82, 89] presented a solution in which interfaces at a node are designated as either fixed or switchable. Different nodes use different channels for fixed interfaces; this channel assignment is not load-based and infrequently changed. Fixed interfaces can be seen as interfaces used for receiving data from neighbouring nodes a node uses its switchable interface tuned "on-demand" to the channel used by the fixed interface of a neighbour to communicate with that neighbour. Clearly, this protocol requires that each node has at least two interfaces. However, the case where nodes may have more than two interfaces is left unspecified by the authors. Besides, as elaborated in [20], this protocol cannot be readily implemented in current systems and requires special kernel support because it does not conform to the usual practice of associating each network interface with exactly one channel. The need for channel switching along with receive (fixed) channel contention lead to inefficiencies and limited performance improvements (in terms of throughput and delay), especially for traffic patterns where multiple flows are routed via a node.

The previous discussion suggests that on-demand channel allocation approaches require either time synchronisation or negotiation through a separate channel. This is necessary to ensure that the transmitter and the receiver operate on the same channel at a specific time to allow communication between them. This, however, introduces extra complexity and overhead in the network. Moreover, multi channel solutions with a single transceiver do not allow single packet broadcasting of messages. Since nodes use different channels, multiple copies of the same message are required to all reach neighbouring nodes. This has a major effect to routing protocols, which rely on broadcast messages to obtain topology information, while it consumes bandwidth. Furthermore, these mechanisms require modifications of the existing 802.11 MAC protocol, thus cannot be implemented using commodity hardware.

3.1.2 Centralised and Distributed Channel Assignment Algorithms

The schemes in this category assign channels to the interfaces of the nodes for long time periods, such as hours or days. Channel switching in these solutions is driven by changes in the network topology or the traffic load of the links. The overall goal is to improve upon previously static channel allocation approaches [62, 63, 64, 65] by balancing between channel usage and network connectivity.

Subramanian et al. [25] presented a centralised tabu-based and a distributed greedy algorithm (DGA) for assigning channels to communication links in the network with the objective of minimising total network interference. The centralised approach operates in two-steps: At the first step, the algorithm searches iteratively for good solutions without worrying about the interface constraints. At the second step, for each node with a number of assigned channels exceeding the number of available interfaces, the algorithm reuses the incident channels to eliminate violations. In the distributed approach, the responsibility for assigning channel to a link is given to the end point of that link with higher node ID; the owner of each link does the channel assignment via a negotiation and notification protocol. However, the DGA protocol is simplistic and can in fact cause network partitions. This can be easily seen by considering a simple tandem network with nodes in the middle having only one interface and lower IDs compared to those towards the ends.

Dhananjay et al. [84] introduced a channel assignment scheme for dual-radio mesh networks, where channels are assigned to the interfaces of the nodes based on channel sequences chosen by the gateways. The goal of each gateway is to assign non-overlapping channels to the links of the same path to mitigate intra-path interference. Nodes with the same distance from the gateway, however, are assigned the same channels, thus they interfering with each other. Moreover, when multiple gateways exist, the scheme targets at minimising interference only for transmissions at the first hop links from the different gateways. This solution therefore is unable to deal with inter-path interference. Finally, this approach is restricted to Internet traffic patterns.

Shin et al. [90] proposed a distributed channel assignment scheme where channels are assigned to the available interfaces (K) of each nodes with two different strategies depending on the number of available channels (N): the random assignment and skeleton assisted assignment strategy. The random assignment strategy is applied when $N < 2K$ and every node chooses randomly K channels. Based on the pigeonhole principle when $N < 2K$, any pair of nodes will share at least one common channel. Otherwise, ($N \geq 2K$), the network uses skeleton assisted assignment where the algorithm first finds a spanning subgraph of the network to maintain connectivity. The links at this subgraph are allocated to a default channel. Then, nodes, as before, choose a random set of channels and exchange their choices. If a pair of nodes does not share a common channel, the default channel is used for that link. The latter algorithm, however, requires an additional mechanism to find the spanning tree and does not easily adapt to network changes.

Xing et al. [21] proposed an alternative approach for localised channel assignment based on s-disjunct superimposed codes to support both unicast and local broadcast. In this approach, channels are divided into primary and secondary and each node chooses a channel codeword indicating its primary and secondary channels before joining the network. While this approach like the previous one also divides the interfaces into transmit and receive categories, it does transmitter oriented channel assignment unlike [19, 82]. As authors themselves note, their approach may not be effective for 802.11-based mesh networks with few tens of channels because the code strength is limited by the number of available orthogonal channels. Furthermore, this approach also limits the network size, which makes its practicality questionable.

Gao and Wang [22] introduced a game-theoretic approach which attempts to solve the channel assignment problem for multi-radio channel allocation in mesh networks as a static non- cooperative game. The authors again assume different sets of interfaces for transmission and reception like [19, 82, 21]. They, however, make a number of unrealistic assumptions, including: (i) each node participates in only one communication session; (ii) the whole network is a single collision domain (i.e., a node can hear transmissions by any other node in the network using the same channel); and (iii) Available bandwidth on a channel is equally shared by all radios using that channel. Thus, this work is mainly of theoretical interest.

Ramachandran et al. [9] proposed a centralised channel assignment algorithm, where one radio of each node in the network is tuned to a common channel. In this solution, a central server periodically collects measurements on external interference of every channel in the network, which defines their quality. Channels are then assigned to the communication links with the objective that links closer to the gateway are assigned higher quality channels and no two interfering links are assigned the same channel. This approach mandates that one radio at each node is tuned to a common channel. Although this preserves connectivity, it does not utilise channels efficiently. Furthermore, the prioritisation of links based on the distance from the gateway, does not facilitate arbitrary traffic patterns.

Ko et al. [24] proposed a distributed channel assignment protocol to assign channels to multi-radio nodes. The protocol requires one interface of each node to be dedicated to a common channel to all nodes in the network to ensure 100% connectivity. The remaining interfaces are then greedily assigned to channels that minimise the potential interference within the interference range of the node using a negotiation-based protocol. This solution, therefore, has the same drawbacks as the protocol proposed by Wu et al. [80]. The dedicated interface leads to inefficient utilisation of available channels and interfaces, while the channel negotiation incurs substantial overhead. Nevertheless, among the protocols discussed thus far, the ADC protocol is the most easily implementable distributed solution that can also support diverse traffic patterns.

Marina et al. [75] presented a formulation of the channel assignment problem as a topology control problem to provide low interference connected topologies. In this approach, each link is associated with a conflict weight, which reflects interference on that link and the goal is to minimise the maximum link conflict weight, while preserving connectivity. This is done via a polynomial time greedy heuristic, which computes the priorities for the mesh nodes and assigns channels based on the connectivity and conflict graph in the order of these priorities. In case of disconnection, the algorithm can alter node priorities to provide more flexibility.

Dionysiou et al. [91] also proposed a joint channel assignment and topology control solution, which contrary to [75] does not opt for full connectivity between nodes that are within range. Specifically, the authors presented a centralised algorithm which assigns channels to nodes and defines node pairs such that an objective is maximised. This objective is defined as a utility function of the MAC layer throughput. Key enabler of this approach is the throughput estimation module, which captures adjacent channel interference and pathloss. The authors propose different utility functions (i.e., aggregate throughput, fairness and link redundancy) and study how the different target objectives affects the channel assignment and network topology.

Das et al. [92] also considered the channel assignment problem for multi-radio multi-channel networks. They presented two integer linear programming optimisation models with the goal of maximising the number of links that can be active simultaneously. This work, however, does not discuss any practical channel assignment algorithms.

In Chapter 4 we present a new scalable protocol termed LCAP for efficient and adaptive distributed multi-radio channel allocation. LCAP address the limitations of previous work by not placing any restrictions on the interface use, the network structure or the traffic patterns. In this protocol nodes independently and iteratively decide their channel allocation based on neighbourhood and channel usage without the need for negotiation. This information is obtained via a novel neighbour discovery protocol which is effective without the need of common channels. Motivated by the non-stationary nature of the network scenario and the ensuing complex convergence study of LCAP, in Chapter 5 we consider a deterministic alternative. The latter approach employs a distributed priority-based mutual exclusion mechanism where nodes decide on their channel allocations based on only local information provided by the same neighbour discovery mechanism. Both mechanism have the same objectives: efficient channel utilisation across diverse traffic patterns, protocol scalability and adaptivity to factors such as external interference.

3.1.3 Joint Channel Assignment and Routing/Scheduling

In this section we describe the approaches that consider traffic demands and/or flow conflicts in channel assignment decisions. The schemes that fall under this category attempt to improve network performance by jointly tackling channel assignment and routing and/or scheduling. Joint optimisations, however, are more complex than decoupled solution, thus the majority of these solutions use integer linear programming.

Raniwala et al. [76] proposed a centralised greedy algorithm for assigning channels to the links in the network based on the carried traffic load. The traffic load information is given to the channel allocation algorithm, which assigns channels to the links such that the bandwidth that is made available is no less than their expected traffic load. Flows are routed with the new channel assignment and the expected loads are input again to the channel allocation algorithm. This iterative process process continues until there is no link whose load exceeds its available capacity. The drawback of this approach is that it requires the traffic load information for each node pair and the paths traversed by flows to be known before the channel allocation algorithm is initially applied.

A distributed version of the algorithm in [76] is proposed by Raniwala and Chiueh [10]. The authors were the first to highlight the channel dependency problem in the context of distributed multi-radio channel assignment. Due to this problem, changing the channel of an interface may cause a ripple effect of further changes in the network necessary to maintain connectivity. To bound the scope of a channel change, the authors impose a tree structure and partition the interfaces at a node into two disjoint sets (UP-NICs and DOWN-NICs) a node only determines the channels for its DOWN-NICs, whereas the channels for its UP-NICs are determined by the parent node. Even though their routing and channel assignment solution is load-aware, the aforementioned role assignment to interfaces leads to inefficient channel utilisation for traffic patterns other than the gateway-oriented traffic pattern. Das. e. al. [85] proposed channel assignment algorithms along the lines of [10]. Their approach, however, focuses on a wireless mesh network architecture based on directional antennae. The goal is to exploit spatial reuse benefit of directional communication to go along with the benefit of using multiple channels.

Alicherry et al. [93] developed an LP formulation for the joint channel assignment, routing and scheduling problem. The proposed algorithm requires several adjustment steps assuming the traffic demands and network topology are known. First, the algorithm attempt to find the paths that maximise throughput, while satisfy channel interference and flow constraints. The solution at this step, however, may not be feasible, since the number of channels assigned to a node may exceed the number of available interfaces. To find a feasible channel allocation, the algorithm modifies the solution based on available radios and number of assigned channels. Since such modifications may increase interference, the algorithm re-adjusts flows to minimise the maximum interference of all channels. Finally, an interference-free link schedule is developed such that flow conflicts are avoided.

Lin and Rasool [94] also proposed a solution for solving jointly the channel assignment, routing and scheduling problem. This approach, different from [93], does not require a priori information on the traffic load and, thus, it can operate in a distributed manner. Moreover, because it uses only local information, it is applicable to scenarios with dynamic traffic patterns. This solution, however, similarly to [19] assumes radios with fast-switching capability. Furthermore, the authors have not evaluated the convergence speed and messaging, which are crucial properties of the proposed scheme, under realistic traffic conditions. A variant of this algorithm for heterogeneous interfaces was studied by Bhandari and Vaidya [95].

Yu et al. [86, 87] presented joint channel assignment and link scheduling solutions for enhancing the capacity of multi-channel multi-radio wireless mesh networks. This work considered two-types of applications: ftp-type applications, where the goal is to find the minimum number of time slots to transmit all data, and video-type applications, where the objective is to satisfy the bandwidth requirement as much as possible. The authors consider solutions for radios with both fast- and non-fast-switching capabilities to increase capacity under the different traffic types. All solutions use integer linear programming to obtain feasible link schedules such that no two interfering links are assigned on the same slot.

Wu et al. [23] proposed a scheme which attempts to optimise network by selecting the best combination of channel assignment and routing (called a pattern in this work. Each node periodically evaluates the performance of the current solution and initiates a new pattern selection if the channel utilisation in the current pattern exceeds a predetermined threshold. In this case, a set of candidate patterns are identified and a better pattern is eligible for selection only if network connectivity is maintained. To ensure this, all neighbours of the current node and its neighbour on a link agree. This process involves negotiation among the nodes which induces substantial overhead in the network.

Tang et al. [96] approached the channel assignment problem as a topology control problem, similarly to [75]. The proposed heuristic assigns channels to the interfaces of the nodes ensuring that the formed network topology preserves k- connectivity and has the minimum co- channel interference among all K-connected topologies. Then, the authors propose a linear programming algorithm and a heuristic, which find paths to route requests such that their bandwidth requirement is satisfied given the bandwidth availability determined by the channel assignment in the previous step. Different from [76],the objective of the channel assignment is to choose the least used channels in the interference range, without considering the traffic load of the interfering links.

Gong et al. [97] also considered channel assignment and routing as a joint problem. For this, the authors combine channel assignment with the OLSR (Optimised Link State Routing) protocol [98]. The combined protocol performs channel re-allocation only when there is a channel conflict after a topology change. The goal of the protocol is to minimise channel usage in the two-hop neighbourhood to avoid collisions. This approach, however, is tight to the routing protocol, while one interface at each node is assumed to be assigned to a common channel through which nodes identify active neighbours.

3.1.4 Routing Decoupled from Channel Assignment

The approaches in this section decouple the channel assignment and routing problems in multi-interface multi-channel wireless networks and focus on optimising routing assuming predetermined channel assignment. Naively utilising the hop-count as the routing metric, however, has been shown to be inefficient [99]. De Couto [99] showed that a path with a higher number of short links (thus larger number of hops) can outperform a path with a lower number of long distance links (thus lower number of hops) because the links in the latter path exhibit lower quality. Motivated by this, the approaches in this section propose more sophisticated methods for identifying high-throughout routing paths by considering the dynamic characteristics of the wireless medium, such the link quality and interference.

Kodialam et al. [100] proposed a joint routing and scheduling scheme for multi-channel wireless networks to achieve a given rate vector. The authors formulate the problem using linear programming and introduce primal-dual algorithms to solve it. Scheduling is solved as a edge-colouring problem. This scheme assumes that each node is equipped with a single interface, while there is an adequate number of orthogonal channels to permit non-interfering transmissions. The authors study routing and scheduling, but channel allocation is not addressed, since interference is non-existent. The work is extended to accommodate multiple interfaces in [101].

Jain et al. [102] studied the problem of finding the optimal paths to maximise throughput in the presence of interference for a given network topology and workload. The proposed approach is a centralised solution, which utilises linear programming. Although the model is presented as applicable to multi-radio multi-radio cases (as opposed to previously proposed similar studies (e.g., Kodialam et al. [103])), the authors describe a method where the number of interfaces is constrained to be equal to the number of available channels. Moreover, contention is considered to be controlled perfectly by a central entity. Thus, the model does not consider the impact of interference when using 802.11 MAC. These assumptions are unrealistic and as such the work is of theoretical interest. It, however, motivates the need for interference-aware routing metrics.

Draves et al. [104] proposed a routing metric, called WCETT (Weighted Cumulative Expected Transmission Time), for routing in multi-radio, multi-hop wireless mesh networks. This metric is an extension of the ETX (Expected Transmission Count) metric proposed in [105], which measures the expected number of transmissions, including retransmissions that are needed to send a unicast packet across a link. WCETT improves over ETX by considering link bandwidth and channel diversity besides the loss ratio of a path. The WCETT metric, however, suffers from two drawbacks: First, it only captures intra-flow interference, since it only links belonging on the same path. Second, the metric is proven to be non-isotonic [106]. The isotonicity property determines whether routing protocols based on Dijkstra or Bellman-Ford can be used to find minimum weight paths cost paths and whether loop-free routing is ensured when hop-by-hop routing protocols are utilised [107]. For this reason, WCETT cannot be used with link-state routing protocols (e.g., Optimized Link State Routing Protocol (OLSR) [98]), which converge faster that distance-vector protocols when link quality changes and breaks occur often and induces much less overhead than on-demand routing and source routing protocols (e.g., Link Quality Source Routing defined in [104]).

Kyasanur and Vaidya [19, 89] proposed a routing metric, called MCR (Multi-Channel Routing) to work with a a channel assignment solution with on-demand channel switching, such the one presented in [19, 82]. This metric modifies the WCETT metric to capture the channel switching delay for links which are active on different channels. The motivation for this is that often channel changes induce switching delays that can decrease the benefits of a hybrid channel assignment, such the one proposed by Kyasanur and Vaidya. Similarly to WCETT, however, this metric is incorporated into a source routing protocol, thus exhibits the disadvantages of source routing.

Yang et al. [108] presented a routing metric, which considers channel switching for routing path decisions and captures inter-flow interference. This metric, called the Metric of Interference and Channel-switching (MIC), is composed of two components: Interference-aware Resource Usage (IRU) and Channel Switching Cost (CSC). The first component captures the inter-flow interference by considering the time a link waits for neighbouring transmissions to finish. The second component captures the impact of intra- flow interference. The second component, however, considers intra-flow interference only between two consecutive hops in a path. Moreover, the metric is not isotonic when applied directly. Isotonicity is achieved with complex transformations, which do not permit its incorporation into arbitrary link-state protocols.

Subramanian et al. [109] proposed a routing metric, which modifies WCETT to consider both inter-flow and intra-flow interference. This metric, called interference aware routing metric (iWARE), uses the same formula as WCETT, but additionally it incorporates the interfering power on a link in terms of measured SINR from interfering nodes. If there is no interference on a link, the metric is equivalent to WCETT. Similarly to WCETT, however, the metric is not isotonic, thus it cannot be used with a link-state routing protocol.

Genetzakis and Siris [110] proposed a routing metric, called Contention-Aware Transmission Time (CATT), which identifies high-throughput paths by capturing the time to transmit a packet across a link. The metric is motivated by the fact that the time to transmit a packet over a link l is influenced by the interference caused by transmissions from flows on different paths (inter-flow interference) than l and by transmissions on links other than l on the same path (intra-flow interference). The authors represent the interference from a link k as the ratio of packet length to transmission rate. Based on this, the CATT metric is given by the sum of the interference among the set of links whose transmission can interfere with the transmission on link l, including link l itself. The metric, therefore, considers both intra-flow and inter-flow interference. Moreover, the presented metric is isotonic and can be easily implemented in a link state protocol. In fact the authors propose a simple incorporation of the metric in the OLSR routing protocol [98]. Driven by these advantages, we have also used CATT along with OLSR for the evaluation of our channel allocation protocol [27]. The authors also propose two extensions to the basic CATT metric to include link packet loss and load.

3.2 Channel Allocation and MAC Design for Long-Distance Mesh Networks

Most of the work in this space focuses on TDMA-based MAC protocols as an alternative to 802.11. While part of the motivation behind these protocols is the detrimental impact of high propagation delays on 802.11 performance for *very* long distance wireless links in the order of 100Kms, the rest has to do with the so-called "side-lobe interference" issue [31]. The latter refers to the interference among incident (directional) links at a node using the *same* channel, especially when one or more of them are transmitting and other links are receiving. This type of interference occurs with commonly used high gain directional antennae having non-negligible side lobes in their radiation pattern.

The 2P protocol proposed by Raman and Chebrolu [31] is the first alternative design in the literature to address the above problems using a TDMA based approach that requires each node to alternate between transmitting (on all incident links) and receiving (again, on all incident links). Several subsequently proposed channel allocation protocols assume 2P as the underlying MAC protocol (e.g., [111, 112]). However, the 2P protocol works only if the network topology is a bipartite graph. This limitation has been addressed in a later proposal called JazzyMAC [113]. By their very nature, both 2P and JazzyMAC need inter-nodal time synchronisation, an additional requirement.

Our work on channel width adaptation in Chapter 6 instead assumes standard 802.11 MAC, based on the following two observations: (1) Real world long-distance wireless links are typically in the order of several Kms to few tens of Kms for which 802.11 MAC gives acceptable performance through suitable adjustment of the built-in ACK timeout. This is experimentally shown in [30] and is also confirmed by our experience deploying and monitoring the Tegola network in rural Scotland [59] for the past three years with links in the range of 2-20Km. (2) The use of multiple channels alleviates the side-lobe interference problem as different links at a node can be assigned to different non-interfering channels.

The recent channel assignment work of Dutta et al. [114] is similar in spirit to ours in that it also assumes standard 802.11 MAC, thereby leveraging readily available commodity 802.11 hardware. However, that work focuses on *directed* edge colouring, requiring a channel for each *directed* link, potentially resulting in inefficient spectrum utilisation with limited spectrum; it also increases the cost and deployment complexity — to support directed edge colouring, each node requires two directional antennae (and radios) per link and those antennae need to be carefully separated to manage side lobe interference.

More recent channel assignment work of Dutta et al. [114] is similar in spirit to our work (Chapter 6) in that it also assumes standard 802.11 MAC, thereby leveraging readily available commodity 802.11 hardware. However, that work focuses on *directed* edge colouring, requiring a channel for each *directed* link, potentially resulting in inefficient spectrum utilisation with limited spectrum; it also increases the cost and deployment complexity — to support directed edge colouring, each node requires two directional antennae (and radios) per link and those antennae need to be carefully separated to manage side lobe interference. For the evaluation of our work in Chapter 6, we compare with the more common and practical undirected edge colouring for which we consider several alternatives, each based on a different fixed size channel width.

3.3 Channel Width Adaptation

Channel width allocation is a relatively recent problem, thus the related work is limited compared to the wide collection of channel allocation schemes. Chandra et al. [29] were the first show the practicality of a channel width adaptation mechanism. The authors introduce a simple software modification using commodity wireless cards, which allows communication at 5, 10 and 40MHz in addition to the standard 20 MHz. Moreover, the authors examined the impact of channel width adaptation on throughput, range and power consumption and obtained experimental evidence of the potential benefits of adjusting the width of a channel in 802.11 networks. Their focus, however, is on the simplest case, i.e., single link, for which they propose a channel width adaptation algorithm called SampleWidth.

The study of Chandra et al. motivated other work in varying the width of channels to increase offered capacity. We categorise these schemes based on their application scenarios which broadly concern wireless Local Area Networks (WLANs), and multi-hop (mesh or ad-hoc[1]) networks.

3.3.1 Channel Width Adaptation for Wireless Local Area Networks

Gummadi et al. [32] proposed a variable-width frequency allocation scheme, called VWID (Variable WIDith channels), for improving the throughput of interfering nodes in WLANs. The authors show that splitting the spectrum into variable width channels among mutually interfering transmitters and keeping them active simultaneously is more effective than having them share a larger, fixed-width channel. Different from our work, VWID focuses on WLANs and concentrates on controlling interference by assigning variable channels to links only within a single 20MHz channel. Our work focuses on varying channel width to increase capacity to match traffic demands and utilises up to 40MHz channels.

Moscibroda et al. [33] considered channel width adaptation for achieving load balancing in multi-AP WLANs as an alternative approach to transmit power and client association controls. More specifically, the proposed heuristic processes access points (APs) in a particular ordering (e.g., from heaviest to lightest load). Following that

[1] Mesh networks can be seen as ad-hoc networks with a more planned configuration.

ordering the algorithm greedily attempts to assign the highest possible width which is closer to the APs demand. The algorithm terminates when all APs are assigned widths within the available spectrum. This work focuses on the problem of how to efficiently distribute spectrum among the different access points and does not tackle the allocation of spectrum to serve the associated clients, as opposed to [32].

More recently, Yuan et al. [34] employed a game-theoretic approach to address the same problem and proposed a decentralised learning-based algorithm for achieving optimal allocation. In this work, the APs in the WLAN are considered as players with a predefined set of strategies based in a discrete set of channel-widths and center-frequencies. The goal of the algorithm is to converge to an allocation among the access points where no two interfering APs share common spectrum. Evaluation results, however, show that the algorithm needs a high number of iterations to converge (e.g., 500 iterations for 10 APs).

Note that adapting these wireless LAN channel width adaptation proposals to our multihop wireless network context is not straightforward because of the fundamental differences between the two contexts. For instance, we have the requirement to maintain network connectivity *wirelessly*, whereas access points (APs) in a wireless LAN are interconnected via a wired backhaul network.

3.3.2 Channel Width Adaptation for Wireless Mesh Networks

Recently a few papers consider adapting channel width in the context of mesh networks. (e.g., [35, 36]), focusing on the omnidirectional mesh network scenario and mainly employing mathematical optimisation methods (e.g., mixed integer linear programming), which makes them unsuitable for large scale networks with frequent channel width adaptations.

Uddin et al. [35] addressed the problem of joint routing, scheduling and variable-width channel allocation for single-radio wireless mesh networks. The authors presented a integer linear programming solution for determining the set of links, along with their channel allocations, which can be active concurrently without violating the signal-to-interference and noise requirement that would cause corruptions at the intended receivers. Specifically, the authors assume a TDMA access scheme where time is partitioned into equal-size slots. Traffic can be routed into multiple different paths and links can be active in more than one slots to satisfy the traffic demands. The objective of the system is to find the minimum time that links are active without violating the

SINR requirements. Traffic demand for each session, however, is considered known.

Li et al. [36] proposed a joint on-demand spectrum assignment and routing protocol for QoS admission in multi-radio multi-channel multi-hop ad-hoc networks, where channel width adaptation solution works alongside with a an on-demand routing protocol (specifically, AODV). More specifically, each node is assumed to have a control interface for control messages and two categories for the remaining interfaces: the connectivity interfaces and the diversity interfaces. The former connects nodes to some neighbours to ensure basic connectivity, while the later can be adjusted based on traffic requirements, thus creating temporary links. This approach, however, is not suitable for our network model where the directional backhaul tier needs to be always available to the underlying tiers.

More recently, Wu et al. [37] considered the adaptive width channel allocation in multi-radio wireless mesh networks from a game theoretic perspective. Their solution uses combined channels to increase throughput in multi-radio networks. This work, however, is associated with unrealistic assumptions. Each node is assumed to participate in only one communication session over a single hop and all nodes lie within a single collision domain. Also, traffic is assumed backlogged for every node pair. Different from [37], our work, presented in Chapter 6, considers all possible widths to adapt to spatio-temporal variations in traffic demands and assign spectrum to links based on their relative volume. Furthermore, we make no assumptions about the traffic demand, pattern or the network topology.

3.4 Spectrum Sharing via Micro-Auctions

The work in this category focuses on management of portions of radio bands that is eligible for dynamic access. This spectrum is assumed to be un-utilised or negligibly utilised (such as bands allocated for military, government and public safety) and belongs to some authority. This authority makes the spectrum available to secondary users through real-time auctions. The goal of these mechanisms is truthfulness, maximum social welfare, maximum revenue and/or fairness.

Buddhikot et al. [115] introduced a centralised model for cellular networks coordinated spectrum access via a spectrum broker. The model assumes a portion of spectrum which is eligible for dynamic access, called the Coordinated Access Band (CAB) and a broker, which permanently owns the spectrum. The broker manages this spectrum within a region and grants time bound leases to wireless network operators, which predict the end user demands, and/or individual end-users. This work is later extended by Buddhikot and Ryan [116], who focused on spectrum pricing and spectrum allocation. However, although pricing is discussed, no practical algorithm is presented. Moreover, the authors formulate spectrum allocation using a linear programming solution, which, unfortunately, under a high number of requesters is unrealistic. Ryan et al. [45] further extended the work in [116] by proposing a hybrid pricing solution. Specifically, their solution employs single-round multi-unit auctions for on-peak periods and uniform pricing for all buyers during off-peak periods in order to decrease the frequency of auctions. The authors, however, propose, the use of a complex winner determination mechanism (i.e., linear programming [117] or search trees[118]) making the solution only applicable to small-scale networks.

Gandhi et al. [38] proposed a framework for single-round multi-unit auctions, where the eligible spectrum is partitioned into a number of equally bandwidth homogeneous channels. In this framework, a seller initiates an auction periodically and bidders express their preferences using a continuous concave piecewise linear price demand (PLPD) curve. After collecting the bids, the seller computes the optimal price and winning channels for each bidder such that the total revenue is maximised with respect to interference constraints. The proposed framework. however, assumes bidders compute their optimal PLPD curves and the amount of spectrum allocated to them depends on the seller. Moreover, the authors assume that bidders are willing to purchase any subset of channels they receive. Strict demands would require different curves which would make the bidding process more complex. In our approach, the demand of each bidder is adjusted solely by the bidder herself simply by allowing bidders to bid at will (i.e., demands cannot be partially satisfied).

Subramanian [39] also presented an auctioning mechanism for the model in [115]. In this model, different from [38], where the spectrum is divided into equal pieces, the available spectrum is partitioned into a finite number of channels for each different radio networks (e.g., GSM, TDMA) based on the channel bandwidth requirement of each network. Buyers can bid on channels of different type and a greedy graph-colouring based algorithm is used to allocate spectrum while maximising revenue under the interference constraints. However, bidders are assumed to have a separate function for each channel type, which specifies the price a bidder is willing to pay for a number of channels of that type. Similarly to [38], such functions make the bidding process complex. Moreover, none of these mechanisms protects buyers from strategic behaviours.

Ileri et al. [40] described a demand responsive framework where multiple network operators compete for providing their services to potential customers. The model assumes a spectrum provider, which leases portions of spectrum to network operators and acts as the mediator between a user the network operators. For each user, the network operators iteratively make offers with the overall goal of both maximising their profit and exceed the opponents demand as long as their expected profit is greater than zero. The winning operator is the standing operator, which is announced to the user. The user then can dismiss the offer if the offered price exceeds its own utility. This work, however, is only applicable to small-scale networks.

Wu et al. [42] presented a Vickrey-Clarke-Groves (VCG) mechanism for leasing of idle spectrum to secondary users. The mechanism addresses the vulnerability of the VGC mechanisms to buyers' collusions, which results in low revenue to the sellers. For this, the authors propose a solution which uses the conflict graph to classify bidders into virtual groups of non-interfering bidders that can share the same channel with negligible interference. The bid of each virtual group is then the sum of the individual bids in the group. The solution computes the set of winning virtual groups that maximises revenue and each virtual group is charged with the bid of the seconds highest group. Due to the computational complexity, however, this solution is only applicable to small-scale scenarios. Moreover, each buyer is assumed to be interested in obtaining only a single channel.

Zhou et al.[41] also proposed a VCG auctioning mechanism for leasing of idle spectrum to secondary users. The goal of the mechanism, called Veritas, is to enforce truthful bidding[2], which makes strategic bidding unnecessary and prevents market manipulation. More specifically, Veritas applies a greedy algorithm where bidders are associated with an available channel list and bids are sorted in descending order. In that order, bidders are allocated the requested channel if enough channels exist in its list. The allocated channels are then removed from the list of every interfering node. The winning bidders are charged the price of the loosing interfering neighbour with the highest bid. Sealed mechanisms, however, do not consider the valuation of the seller, thus channels can be sold in a price which is much lower than the seller's desired selling price. This problem was addressed by Wu and Vaidya [119], who proposed an algorithm where channels are not sold until the seller's valuation is met. Both mechanisms, however, assume that the bidder can effectively value its spectrum.

Jia et al. [43] also presented a VCG approach, but, different from [41], buyers are interested in obtaining channels in one or more different geographical areas (cells).

[2] In truthful auctions, bidders are enforced to bid their true valuations of the spectrum.

The goal this approach is to distribute the available spectrum such that revenue is maximised while truthful bidding is enforced. Moreover, this work assumes that although each buyer's valuation is private and only known to the buyer, the seller knows the distributions from which each valuation is drawn. Based on this assumption, then the authors devise two mechanisms: an optimal auction mechanism that maximises the expected revenue, which, however, is computationally expensive, and a suboptimal auction mechanism, which uses an approximation algorithm for the winner determination. Unfortunately, this mechanism does not allow partial fulfilment of buyer's spectrum requirements and, since each buyer has a single shot in bidding, bidders need to carefully compute their requirements and express their desires.

Gopinathan et al. [44] tackled the problem of bidder's starvation and proposed two mechanisms for increasing the diversity of the winning bidders, thus fairness. The goal of the first mechanism is to reach local fairness by increasing the minimum probability of some nodes in obtaining spectrum. This is achieved through the use of random variables and prioritisation of nodes with respect to their opponents. The second mechanism computes the fractional share of channels that each node receives such that social welfare is maximised for achieving global fairness. The latter algorithm, however, employs linear programming, thus is applicable to a limited number of bidders. Moreover, both mechanisms assume that each buyer wishes to obtain at most one channel.

More recently, Parzy and Bogucka [46] proposed an sealed auctioning mechanism for leasing the unused spectrum to big telecommunication mobile operators and small networks. The spectrum is assumed to be sold in segments each supporting different transmit powers. The broker informs the bidders about the available segments and each bidder responds with a bid consisting of a segment of interest and the offered price. To allocate the spectrum, the broker utilises a computationally expensive "branch-and-cut" optimisation method for spectrum allocation; as a result, this mechanism is unsuitable for coordinating access for a large number of users and for frequent (re-)allocations.

The auctioning mechanisms described so far used sealed single-shot auctions with the objective of increasing the revenue of the authority the spectrum is licensed to. This type of auctions, however, is burdensome to both sellers and bidders. One one hand, sellers use computationally complex methods to determine winners. These mechanisms are not only subject to scaling-up concerns, but also restricts them to infrequent uses. Moreover, the proposed algorithms cannot be easily extended to varying leasing periods for the channels, while they can be unfair to the spectrum providers, since the spectrum can be sold in a much lower price than the seller's valuation. On the other hand, buyers are assumed to have a method for intelligently valuing the channels and determine their bids. Moreover, due to high complexity in expressing bidder's preference in a bundles of channels, some mechanisms assume buyers are interested in single channels or maintain complex channel demand functions, or they allocate spectrum under inflexible ”all or nothing” policies.

Because of the complexity of previous auctioning methods along with the objective of achieving task simplicity for the bidders, Porter et al. [47] introduced the combinatorial clock (CC) auction. This mechanism is a simple algorithm which associates each channel with a low price. At each new round, bidders are allowed to bid within a given amount of time. When this time elapses. the algorithm counts up the demand for each item. For items with more than one buyer bidding on them, the price is raised. A new round starts with the new prices for the items and this process continues until no excess demand is found for any of the offered items. When the auction ends, all winning bidders purchase the items at the current clock price.

The effectiveness of the combinatorial clock auction was demonstrated experimentally and inspired the work of Forde and Doyle [48]. The latter employed this mechanism to facilitate spectrum trading in the context of an OFDMA (Orthogonal Frequency-Division Multiplexing)-based cognitive radio networks. More specifically, in their work the base station groups the free TV-licensed spectrum into uplink and downlink subcarriers and controls access to them among the subscribing cognitive devices by means of iterative auctions. Similarly to Porter et al. [47], these auctions associate each channel of the two groups with an initial price and allow buyers to choose specific channels in each group within a specified time. When the time elapses, if there are channels with more than one interested bidders, the price associated with items in excess demand is increased and a new bidding round is initiated. Otherwise, the items are allocated to the winning bidders.

The work in Chapter 7 focuses on controlling access to TV-white spaces among wireless home networks by means of auctions. Given the spectrum of interest is unlicensed in our scenario, an iterative mechanism following the concept of the work proposed by Porter et al. [47] is more appealing than a sealed-single shot auction. First, an iterative mechanism is considerate to both the seller and the buyer, secondly it has low complexity and thirdly it allows bidding in bundles of channels without the need of complex languages to express buyers' desires. This gives the incentive to the spectrum requesters to participate in the auction. Our scenario, however, is more challenging than those in [47, 48] due to two reasons: First, our work manages access to TV-white spaces with multiple interference relationships rather than assuming that competitive buyers lie within a single collision domain like in these two works. Secondly, due to the potentially large number of home networks, excess supply cannot be addressed with complex linear programming mechanisms similar to those utilised in Porter et al. [47].

Chapter 4

A Learning-based Approach for Distributed Multi-Radio Channel Allocation in Wireless Mesh Networks

4.1 Introduction

Wireless mesh networking is emerging as a promising technology for enabling low-cost, ubiquitous broadband Internet access via reduced dependence on the wired infrastructure. Multi-radio wireless mesh network architecture, in which each router (doubling as an access point) is equipped with multiple radios (e.g., 802.11), is commonly seen as a practical way for efficient utilisation of the available spectrum and alleviate the well-known performance degradation in multihop wireless networks with increasing network size, arising from the need to share the wireless medium among neighbouring transmissions and the ensuing multiple access interference.

We consider the distributed channel allocation problem in multi-radio mesh networks. Channel allocation involves assigning (mapping) channels to radio interfaces to achieve efficient channel utilisation and interference reduction while ensuring network connectivity. This problem is non-trivial in the typical case where the number of radio interfaces per node is smaller relative to the number of available channels. The distributed case is even more challenging because of the channel dependency among the nodes [10]. Nevertheless, efficient and adaptive distributed channel allocation is crucial for the following reasons:

- Enable emerging large-scale deployment scenarios (e.g., city-wide mesh network deployments such as in Taipei [120]). Larger scale scenarios also make it important to flexibly support a wide range of traffic patterns, including "intra-mesh" applications (e.g., surveillance and other neighbourhood/community applications [121]).

- Adapt to spatio-temporal variations in the number of available channels and their usability — coping with external interference from other devices using same portion of the wireless spectrum [9]; compliance with regulatory requirements such as dynamic frequency selection (DFS) [122, 123]; and exploiting spectrum "white" spaces [124].

In addressing this problem, we set ourselves the following design goals:

- *Efficient Channel Utilisation*: The rationale behind having this as an objective is clear and it directly benefits network performance (in terms of throughput and delay). This can be realised by reducing contention (interference) on any given channel by distributing it across as many channels as possible while not compromising network connectivity.

- *Protocol Scalability*: Our solution should have low communication overhead, thereby scale well to larger network scenarios.

- *Adaptivity*: We want our solution to not only adapt to network topology changes (e.g., node joins and failures), but also adapt to spatio-temporal variations in the number of usable channels, caused by factors such as external interference.

- *Flexibility*: We aim to support arbitrary traffic patterns and the use of any routing protocol (and metric) on top of our solution. Flexibility also means not placing any restriction on the use of an interface.

- Topology Preservation: Our approach should be preserve network topology to avoid network partitioning and decreased network performance (in terms of throughput and delay) due to decreased alternative paths. To ensure this we mandate that all links which are present in a single channel network should also exist in a multi-channel network.

We propose a novel approach for distributed multi-radio channel allocation that is based on learning and a protocol following this approach called Learning-based Channel Allocation Protocol (LCAP). Each node in LCAP independently and iteratively learns the channel allocation using a probabilistic adaptation algorithm for efficient channel utilisation while ensuring connectivity. Key enabler of the proposed approach is a novel neighbour discovery mechanism that exploits the mesh network deployment model in practice while being compliant to the 802.11 standard. This neighbour discovery mechanism enables neighbours to discover each other even when they do not share a common channel; it leverages a technique similar to channel quieting in DFS mechanism that is part of 802.11h standard [122]. A prototype implementation of the LCAP neighbour discovery module that is key to implementing the proposed approach is presented in [27, 125]. We conduct an extensive simulation-based evaluation to evaluate the effectiveness of LCAP with respect to channel utilisation, network performance with diverse traffic patterns, protocol scalability and adaptivity to factors such as external interference. Our results convincingly demonstrate that LCAP delivers superior performance on these dimensions compared to the state-of-the-art.

LCAP addresses the limitations of prior work [10, 19, 20, 23, 24, 21, 25, 22] by not placing any restrictions on the use of an interface, network structure or traffic patterns, while at the same time is localised and negotiation-free for scalable operation. Another factor contributing to LCAP's ability to achieve efficient channel utilisation is the fact that it does not require a common channel like some of the existing approaches (e.g., [24]). It also has an inherent adaptive quality that is key to coping with factors such as external interference and benefiting from dynamic spectrum access opportunities.

The remainder of this chapter is structured as follows. Next section presents the network model under consideration and provides a brief tutorial on learning automata upon which LCAP probabilistic channel allocation mechanism is based. In Section 4.3, we give an overview of LCAP approach following the aforementioned design goals and its conceptual architecture. Section 4.4 describes the LCAP neighbour discovery module, whereas probabilistic channel adaption in LCAP is explained in Section 4.5. Section 4.6 evaluates LCAP using a wide range of simulation experiments. We finally conclude in Section 4.7.

4.2 Model and Preliminaries

We consider a two-tier mesh network architecture, as in [126, 127], comprising of an access tier and a backhaul tier. The access tier connects end-user client devices to mesh nodes (i.e., each mesh node has WLAN AP functionality). Mesh nodes form the backhaul tier with a subset of the mesh nodes serving as gateways to the wider Internet.

The multihop mesh backhaul connects clients with the Internet and other client devices. This is a fairly common model in practice as is the separation of access and backhaul tiers on different radios and frequency bands [127], and the use of multiple radios for the mesh backhaul [128, 120]. Henceforth, we refer to the radio interfaces used for backhaul communication as *mesh interfaces* and interface used for client access as the *access interface*. We assume that all radio interfaces use omnidirectional antennae.

A few observations from a real-world perspective are in order to make the aforementioned model concrete. Using multiple backhaul radios operating in the 5GHz band is particularly attractive for improved capacity scaling given the availability of more number of channels (11 channels worldwide for indoor and outdoor use in 5.470-5.725 sub band and up to 24 channels in the US [123]) and the fact that 5GHz spectrum is less crowded. On the other hand, 2.4GHz band is typically used for the access interface as most client devices have a 802.11b/g interface. Regarding the typical number of radio interfaces, multi-radio platforms in the market provide up to 4 mini-PCI slots (e.g., RouterBOARD, Gateworks, WILIGEAR, Pronghorfn). With 4 interface slots and assuming one slot is used for the access interface, up to 3 interfaces can be used for the mesh backhaul with current hardware. Also, multi-band interfaces are preferred as they are widely available and provide greater flexibility than single band interfaces while having similar cost. We now introduce the notion of a *channel set*, which is the main tuning parameter in our proposed protocol. A channel set is 'a subset of channels' of size equal to the number of radio interfaces at a node. With S denoting the set of all channel sets, c channels and m interfaces, the number of channel sets, $|S| = \binom{c}{m}$. For example, for $c = 3$ and $m = 2$, there are $\binom{3}{2} = 3$ possible channel sets: $\{(1, 2), (1, 3), (2, 3)\}$.

Before providing more details about the proposed channel allocation mechanism we study the impact of channel allocation in the topology of multi-radio multi-channel wireless mesh networks and the argue for importance of preserving topology.

4.2.1 Topology Preservation

Channel assignment in multi-radio multi-channel mesh networks can alter network topology by removing links that would otherwise exist in single channel networks. For ease of understanding, consider the simple network shown in Figure 4.1. In this scenario, Node B is equipped with two interfaces, while nodes A and C have only one radio. The number next to each link indicates the channel the link operates on. Figure

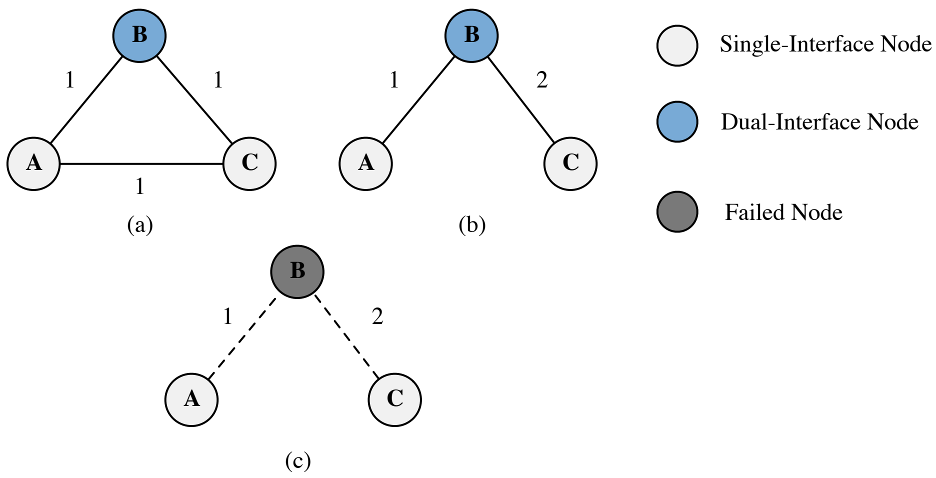


Figure 4.1: Network topology in (a) a single-channel network, (b) a multi-channel network and (c) the multi-channel network upon node failure.

4.1 shows the network topology in the single channel case where all radios are assigned to channel 1. Figure 4.1(b) illustrates the topology after channel assignment has been applied. As this figure shows, node A can communicate with node C only over a two-hop path via node B, while the single-channel case allowed direct communication between these nodes. In cases where links exhibit similar quality, longer paths are not preferable for two reasons: First, increasing the number of hops increases end-to-end delay and, second, a smaller number of longer paths increases network congestion thus decreases throughput. Figure 4.1(c) depicts an additional drawback when altering network topology. The figure shows that when node B fails, the network is partitioned into two different network islands. Nodes A and C are unreachable from each other causing disruption of flows. This scenario highlights the higher probability of network partitioning and the impact on routing when the number of alternative paths is decreased. To avoid such situations, we opt for a mechanism that ensures that all links which are present in a single channel network should also exist in a multi-channel network.

4.2.2 Learning Automata

Here we give a brief overview of learning automata [129] concepts to serve as a background for the LCAP probabilistic channel set adaptation component described in Section 4.5. Our discussion focuses on a specific type of learning automata called variable structure stochastic automata. A learning automaton is a mechanism intended for adapting to changes in environments with unknown characteristics via a learning process. An environment is represented by a triple $\{a, c, \beta\}$,where a represents the action set, c represents the set of penalty probabilities (each c_i corresponds to an action a_i in set a) and β represents the response set. The goal of an automaton is to choose the optimal action among the set of actions such that the average penalty is minimised (or equivalently, the average reward is maximised) after a sequence of rounds. Specifically, the automaton maintains a probability vector $p(t) = < p_1(t), p_2(t), ..., p_r(t) >$ associated with a predetermined set of actions a provided by the environment, where r corresponds to the number of actions in the action set and $\sum_{i=1}^{r} p_i(t) = 1$. In each round t, an action a_i is selected with probability p_i and the environment provides a penalty (or reward) c_i, which is used by the automaton to update the probabilities in $p(t)$. Specifically, the probability vector is updated as indicated by the used reinforcement scheme, which controls the learning behaviour of the automaton.

A general form of this scheme follows the rules shown in equations (4.1) and (4.2). At time t, the automaton has chosen action $a(t)$ and receives the environmental response $\beta(t)$. All probabilities corresponding to actions other than the used one are updated according to equation (4.1), while the probability of the current action is updated according to equation (4.2). Functions g_i and h_i are linear or non-linear functions of the probability of some action a_i.

$$p_i(t+1) = p_i(t) - (1-\beta(t)).g_i(p(t)) + \beta(t).h_i(p(t)),\ if\ a(t) \neq a_i \tag{4.1}$$

$$p_i(t+1) = p_i(t) + (1-\beta(t)).\sum_{j\neq i} g_j(p(t)) - \beta(t).\sum_{j\neq i} h_j(p(t)),\ if\ a(t) = a_i \tag{4.2}$$

Different value sets from which the environmental response can take values define different models for the automaton. In a P-model automaton, the response is binary — 0 or 1 corresponding to favuorable and unfavourable response, respectively. Q and S models differ from P-model in the sense that they neither totally reward nor totally penalise an action. Specifically, the environmental response in Q-model takes values from a finite set in [0, 1], while the response set is continuous in [0, 1] with S-model.

Moreover, depending on the functions g_i and h_i, several linear and non-linear reinforcement (updating) schemes can be obtained. Linear schemes are simplest and commonly used. They include the linear reward-penalty (L_{R-P}), linear reward-∈penalty

($L_{R-\in P}$) and linear reward-inaction (L_{R-I}). For r actions and binary environmental response, the general L_{R-P} scheme is shown in equations (4.3)–(4.6).

If $\beta(t)$=0

$$p_i(t+1) = (1-a).p_i(t)), \text{if} \quad a(t) \neq a_i \tag{4.3}$$

$$p_i(t+1) = p_i(t) + a.(1-p_i(t)), \text{if} \quad a(t) = a_i \tag{4.4}$$

If $\beta(t)$=1

$$p_i(t+1) = \frac{b}{r-1} + (1-b).p_i(t)), \text{if} \quad a(t) \neq a_i \tag{4.5}$$

$$p_i(t+1) = (1-b).p_i(t), \text{if} \quad a(t) = a_i \tag{4.6}$$

These equations are obtained by substituting $g_i(p(t)) = a.p_i(t)$ and $h_i(p(t)) = \frac{b}{r-1} - b.p_i(t)$ in equations (4.1) and (4.2), and noting that $\sum_{i=1}^{r} p_i(t) = 1$. In these equations, $0 < a, b < 1$ are learning parameters associated with reward and penalty response, respectively. The scheme is symmetric if $a = b$. In the case of L_{R-I}, $b = 0$, which means that this scheme ignores penalty responses from the environment. For $L_{R-\in P}$, $0 < b \leq a < 1$.

The suitability of the learning automaton approach for distributed adaptive decision making in highly uncertain stochastic environments combined with its theoretical basis has led to its application for various wireless networking problems (e.g., [130, 131]). In this work, we present a novel application for learning automata, i.e., distributed multi-radio channel assignment problem in mesh networks.

4.3 Overview

To address the design goals outlined in Section 4.1, we propose a novel learning-based approach that is fundamentally different from existing approaches. Specifically, with our proposed protocol termed LCAP, nodes autonomously learn their channel allocation, i.e., selection of a channel set (see Section 4.2), based on the well developed theory of learning automata [129], reviewed in Section 4.2.2. This learning is only based on information about local neighbourhood and channel utilisation within that neighbourhood. Each node acquires this information via a novel and lightweight neighbour discovery mechanism in LCAP that can help discover even those neighbours with

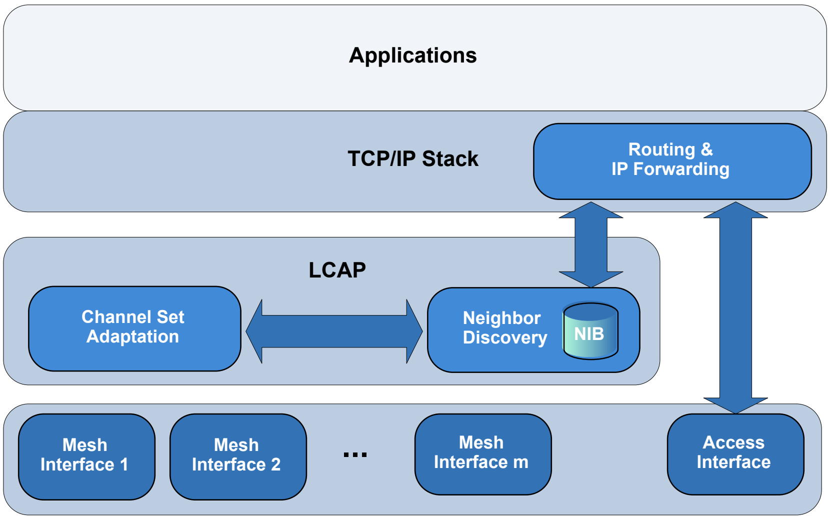


Figure 4.2: LCAP conceptual node architecture.

whom the node does not share a common channel. This is achieved by exploiting mesh network deployment model in practice and using channel quieting and switching in a way that still ensures compliance with the 802.11 standard.

The conceptual node architecture with LCAP is shown in Figure 4.2. Note that the channel set adaptation module at each node interacts only with the local neighbour discovery module. Also note that the configuration of interfaces with new channels determined by the channel set adaptation module is not explicitly shown in the figure. Routing and IP forwarding at the network layer relies on LCAP neighbour discovery module for two purposes: (1) routing related broadcast transmissions (e.g., TC messages in OLSR), which need to be sent over all M mesh interfaces; (2) to obtain the interface channel assignment information to update the IP forwarding table. Moreover, LCAP neighbour discovery module obviates the need for routing protocol neighbour discovery messages (e.g., OLSR HELLO messages). Specifically, LCAP HELLO messages can easily meet this need with the inclusion of additional information required by the routing protocol neighbour discovery component.

The fact that LCAP does not use a default channel like some other approaches (e.g., [24]) together with the selection of diverse channels for interface assignment at each node (elaborated in Section 4.5) helps in achieving efficient channel utilization. LCAP's negotiation-free property lowers the protocol overhead and contributes to its scalability. In fact, the only source of overhead in LCAP are the periodic HELLO messages used for neighbour discovery as evident from Figure 4.2. Therefore, LCAP's implementability rests largely on the neighbour discovery module. A detailed description of this module is given in Section 4.4, while a prototype implementation is presented in [27, 125]. Probabilistic channel set adaptation (described in Section 4.5) helps achieve the adaptivity and flexibility goals.

4.4 Neighbour Discovery

In this section, we describe the neighbour discovery component of the LCAP protocol. At a high level, discovering neighbouring mesh routers in a multi-radio wireless mesh network seems straightforward. This can be done by having each node periodically "broadcast" HELLO messages locally to announce its presence[1], thereby allowing neighbouring nodes to discover it.

Looking further into the details reveals that neighbour discovery is a more involved problem. We make the following observation to make this clear. Doing a local broadcast in a multi-radio mesh network may require sending the message to be broadcasted on *all* available channels if the sending node does not share a common channel with each of its neighbouring nodes. This is more so the case when the assignment of channels to radio interfaces is *being* determined. Since the number of mesh interfaces is typically smaller than the available channels, the channels they might be tuned to at a given point in time will not cover all channels. Therefore, it is necessary to somehow send each local broadcast message (e.g., a HELLO message) on every channel (even those that are not currently used by the mesh interfaces), especially when the channel assignment is being computed. This could be done naively by having each mesh interface send the message on its currently assigned channel and additionally designating one of the mesh interfaces to cycle through the rest of the "unused" channels to broadcast the message on those channels. However, this solution not only seems complicated but can also be disruptive to the distributed channel assignment process.

We propose a less disruptive solution that exploits the common two-tier mesh network deployment model described in Section 4.2 and makes use of channel quieting and switching as in the Dynamic Frequency Selection (DFS) mechanism that is part of the 802.11h standard [122]. The idea is to continue sending each HELLO message on mesh interfaces over their assigned mesh channels as in the naive solution above, but *use the access interface to send the HELLO message over unused mesh channels*.

[1] HELLO messages can additionally carry the channel utilisation map in the local neighbourhood as seen by the sending node to assist in finding a diverse channel assignment for interfaces.

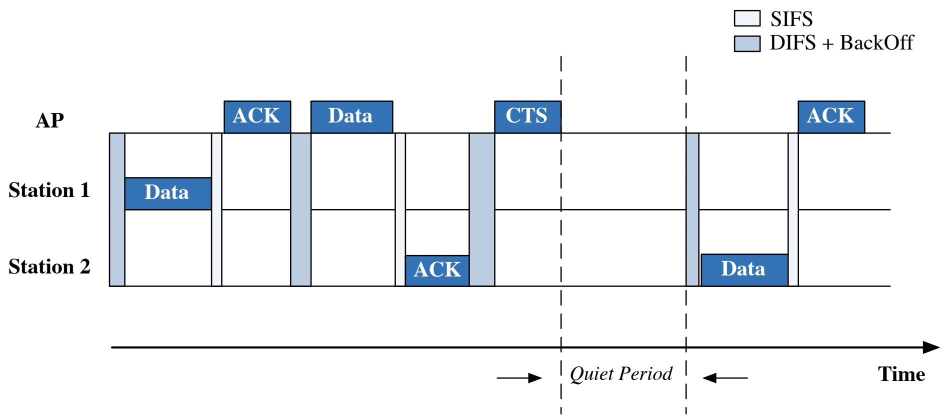


Figure 4.3: NAV-based channel quieting mechanism in LCAP neighbour discovery.

Specifically, client activity on the access interface of a mesh node is temporarily suspended for a short period every so often to "hop" through the unused channels, sending the HELLO message over each of them in the process. If the access interface is also operating over the 5GHz band like mesh interfaces, then this can be achieved by just using the channel quieting feature in the existing DFS mechanism, which is mandatory for 5GHz operation to avoid interference with radar systems.

But it is common for the access tier to use the 2.4GHz band, for which DFS functionality does not exist. For this typical case, we propose a *Network Allocation Vector (NAV) based channel quieting* mechanism to realize the channel quieting feature on 2.4GHz band with the very reasonable assumption that access interface can support multiple bands (both 2.4GHz and 5GHz bands). The idea is as follows. Whenever a mesh node needs to broadcast a HELLO message over its unused mesh channels in 5GHz band, the access interface configured as an AP generates a gratuitous CTS frame (more generally, a 802.11 MAC control frame) over the currently used channel in 2.4GHz band (say, channel 6) with the duration field in the frame set to the required *channel quieting period*. This causes clients associated with that AP to go into waiting mode until the specified NAV period elapses. This is illustrated in Figure 4.3. Immediately after effecting channel quieting, the access interface switches its band to 5GHz and hops through the specified set of unused mesh channels (say, channels 100, 120 and 140) sending HELLO message over each of those channels before finally switching back to the initial channel in the 2.4GHz band (i.e., channel 6 in this example).

Note that the NAV-based solution just described is compliant with the 802.11 standard and does not require any client-side modifications. In fact, several mechanisms in the 802.11 standard exploit the NAV feature, including inter-operation of contention-free channel access with contention-based access and 802.11g protection. We would also like to point out that our approach does not require time synchronization among nodes because nodes receive HELLO messages on channels currently assigned to their mesh interfaces. We present a method for estimating the channel quiet period in Section 4.4.2 given the current channel used by the access interface and the set of mesh channels to be visited. In the event a single channel quieting period is insufficient to visit all channels, the same process can be repeated a few times to complete the process of sending the HELLO message over all unused channels. Even then, the disruption to client traffic is going to be minimal — wait for channel access will likely be below hundred milliseconds as the channel quieting period with this mechanism is upper bounded by the maximum possible NAV value (approx. 33ms). Since reliable forwarding of client traffic is anyway dependent on having a stable backhaul mesh channel assignment and neighbour discovery is a crucial part of the channel assignment, this small overhead is justified. Note that this overhead is incurred only part of the time by using our optimization to reduce the frequency of HELLO messages when the backhaul mesh is sufficiently connected (see Section 4.5).

4.4.1 Neighbourhood Information Base and Hello Messages

Each node maintains information about neighbours and channel utilisation around the node. We collectively refer to this information as the Neighbourhood Information Base (NIB). It consists of NeighbourTable and ChannelUsageList. NeighbourTable at node I contains an entry for each 2-hop neighbour node J along with channels used by node J's interfaces. Each entry also includes additional information such as the latest sequence number received for node J, expiry time of that entry and a quality field. The quality field is used to implement a hysteresis feature (similar to OLSR) for robustness against bursty HELLO message losses and to filter out transient neighbours.

Each node I uses the channels usage information in its NeighbourTable to maintain an up-to-date ChannelUsageList; this list contains an entry for each channel with the corresponding value indicating the count of the number of interfaces in the node's 2-hop neighbourhood using that channel.

Each HELLO message broadcasted by a node I contains: channels used by I and its direct (1-hop) neighbours; a fresh sequence number generated by I; and I's ChannelUsageList.

4.4.2 Estimating Channel Quieting Period

Suppose that the access interface currently uses channel c_{init} in 2.4GHz band and also suppose that it has to visit channels $< c_1, c_2, ..., c_k >$ in 5GHz band in that order for neighbour discovery. It can be easily shown that the channel quieting period for this operation can be estimated as:

$$\begin{aligned} ChanQuietPeriod &= Switch_{2.4\rightarrow 5}(c_{init} \rightarrow c_1) \\ &+ \sum_{i=1}^{k} ChanDwellTime(c_i) \\ &+ \sum_{i=1}^{k-1} Switch_5(c_i \rightarrow c_{i+1}) \\ &+ Switch_{5\rightarrow 2.4}(c_k \rightarrow c_{init}), \end{aligned} \tag{4.7}$$

where $Switch_{2.4\rightarrow 5}(Switch_{5\rightarrow 2.4})$ represent the delay for switching from a channel in 2.4GHz (5GHz) band to a channel in 5GHz (2.4GHz) band and $Switch_5$ represents the delay for switching between two channels within 5GHz band. And $ChanDwellTime(c)$ is the time spent in a channel c while trying to broadcast a HELLO message. It can be estimated as:

$$\begin{aligned} ChanDwellTime(c) &= DIFS \\ &+ Backoff(c) * slotTime \\ &+ FrameSize/TransmitRate \\ &+ PropagationDelay, \end{aligned} \tag{4.8}$$

where $FrameSize$ is the size of the HELLO message size, $TransmitRate$ is typically the lowest for broadcast transmissions (6Mbps) and $Backoff(c)$ in slots can be estimated based on the work in [132] and the number of contending nodes on channel c obtained using the ChannelUsageList. Typical dwell time values are in the order of a few milliseconds. Even in the worst case when using 802.11 maximum frame size and having ten other contending nodes on the same channel (resulting in backing off for around 120 slots [132]), the dwell time is around 5.5ms.

Our work in [27] presents a prototype implementation of the LCAP neighbour discovery module on Gateworks multi-radio platform with 4 multi-band atheros based mini-pci cards. and demonstrates the effectiveness of our quieting approach.

4.5 Channel Set Adaptation

In this section, we describe the probabilistic channel set adaptation algorithm used at each node in LCAP that is rooted in learning automata [129]. Utility of learning automata approach for decentralised control problems was nicely articulated by Pasquale [133]. Our distributed multi-radio channel assignment problem shares the two fundamental characteristics of decentralised control problems outlined by Pasquale [133]: state-information uncertainty and mutually conflicting decisions. The former is obvious because in a distributed system, each node only has a partial and possibly outdated view of the whole system state information. Latter is also true due to the likelihood of channel dependencies, as discussed in Section 3. The application of learning automata approach to our distributed channel assignment can then be seen as a proactive and probabilistic search for good collective decisions via a series of "experiments" [133].

4.5.1 Channel Set Quality Metric

Before looking at the details of channel set adaptation algorithm, let us consider the question of evaluating the quality of a channel set as our problem is essentially that of enabling each node to autonomously converge on a good channel set by learning through feedback from the environment.

We use a simple and intuitive cost function for relative assessment of channel set qualities that "loosely" reflects the delay experienced for communication with neighbouring nodes when using a channel set.

Define $\delta_i^c(j)$ for a pair of direct (1-hop) neighbours node i and node j, and channel c such that $\delta_i^c(j) = 1$, if nodes i and j share channel c, ∞ otherwise.

Now define the cost of communicating from node i to a direct neighbour j over channel c as:

$$\begin{aligned} NC_i^c(j) \quad = \quad & \delta_i^c(j).\max(ChannelUsageList_i(c), \\ & ChannelUsageList_j(c)), \end{aligned} \tag{4.9}$$

where ChannelUsageList is part of the NIB maintained at each node (see Section 4.4) and $ChannelUsageList_i(c)$ is the number of interfaces in the 2-hop neighbourhood of node i assigned to channel c, as known by node i. Note that $\delta_i^c(j)$ in equation 4.9 can be seen as a connectivity check — only those neighbours sharing a common channel with node i have finite NC values at node i on common channels. The second term (i.e., the *max* operation) in equation 4.9 estimates the number of potential interfering (contending) nodes for node i when it tries to communicate with its direct neighbour j over channel c; this is obviously meaningful when $\delta_i^c(j) = 1$. Also note that nodes up to 3 hops away from node i are considered as potential interfering nodes.

Given the above, the quality of a channel set, s, at node i is defined as follows:

$$\begin{aligned} CSQ_i^s &= \sum_j NC_i^s(j), \\ &\quad \text{where} \quad NC_i^s(j) = \min(NC_i^c(j)), c \in s. \end{aligned} \tag{4.10}$$

4.5.2 Probabilistic Channel Set Adaptation

Each backhaul mesh node has a learning automaton (see Section 4.2.2) to help determine the channel assignment for mesh interfaces at that node. The action set for each automaton is the set of all possible channel sets denoted by S (see Section 4.2). Initially, all probabilities in the probability vector are set to $1/|S|$, meaning every channel set is equally likely. Afterwards, every *adaptation_interval*[2] (referred to as an adaptation round) at node i, it first computes the quality of all channel sets using equation (4.10) based on equation (4.9) and the information obtained via the LCAP neighbour discovery module (see Figure 4.2 and Section 4.4). The automaton at i then adjusts the probabilities in the probability vector based on the following linear update scheme, where s is the currently used channel set.

If $CSQ_i^s = \min(CSQ_i^u), u \in S$

$$p_k(t+1) = (1-a).p_k(t)), \text{if} \quad s \neq k \tag{4.11}$$

$$p_k(t+1) = p_k(t) + a.(1-p_k(t)), \text{if} \quad s = k \tag{4.12}$$

If $CSQ_i^s \neq \min(CSQ_i^u), u \in S$

$$p_k(t+1) = \frac{b}{|S|-1} + (1-b).p_k(t)), \text{if} \quad s \neq k \tag{4.13}$$

$$p_k(t+1) = (1-b).p_k(t), \text{if} \quad s = k \tag{4.14}$$

Note that these equations are essentially similar to equations (4.3)–(4.6) — equations (4.11) and (4.12) correspond to (4.3) and (4.4), whereas (4.13) and (4.14) correspond to (4.5) and (4.6). The goal of the above update scheme is to reduce the delay to communicate with neighbours by progressively and eventually moving towards a

[2] The adaptation interval is a variable parameter in LCAP.

channel set that is sufficiently diverse from channel sets used by other nodes in the neighbourhood. If the channel set quality value of the currently used set is the minimum among all possible sets, the environmental response is perceived as a reward and the probability of the current set is increased (Eq. 4.12). The probabilities of other channel sets are uniformly decreased (Eq. 4.11). On the contrary, if the channel set quality value for the current set is not the minimum, then the probability of the current set is decreased (Eq. 4.14), while the probabilities of the remaining sets are increased (Eq. 4.13). The learning parameters a and b for the aforementioned scheme were empirically determined to be 0.3 and 0.08, respectively.

Note that adaptation rounds at different nodes are independent and asynchronous, determined by the adaptation interval randomly chosen from a specified range depending on the state of the channel assignment (more on this later). An attractive feature of this update scheme is that it gradually increases the probability of the best action instead of totally committing to the action inferred to be the best in one-go. This gradual approach is more suitable for non-stationary environments where the penalty probabilities change over time — when a network of automata operates on the same environment, the action chosen by one automaton can change the quality of an action previously inferred to be the best by another automaton.

We have developed several optimisations to aid in faster convergence and further reduce protocol overhead. First, we allow exploration (i.e., continuation of the above probability vector updating scheme) until a channel set that provides connectivity to all neighbours[3]. In the event of any disruption (e.g., node join, node failure, external interference), the exploration is resumed again (somewhat akin to the way backoff counters are handled in the 802.11 MAC protocol). Second, we vary mean adaptation intervals and frequency of HELLO broadcasts in neighbour discovery based on the achieved connectivity to further improve convergence times and reduce neighbour discovery overhead. Specifically, each node evaluates its current channel set choice in terms of the connectivity. If a node is connected to more than x% of its neighbours (50% in our implementation), it increases the mean adaptation interval (from 3.5s to 16.5s in our evaluations[4]). By default, the neighbour discovery process at each node runs every HELLO interval (mean value set to 7.5 seconds in our implementation with interval values drawn uniformly from the range (0, 15s]). If, however, every neighbour of a

[3]We avoid useless channels that are not utilised by any neighbour.

[4]To be precise, the adaptation interval is randomly chosen from the interval [2, 5] seconds when neighbour connectivity is under 50% and it is chosen from [15, 18] seconds above that threshold.

node is connected to all its direct neighbours (kept track using a *connectivity_status* variable in the neighbour discovery NIB), the HELLO message frequency at the node is halved to reduce the overhead.

In the next section, we demonstrate good convergence behaviour of LCAP experimentally. Analytically characterising LCAP convergence properties is challenging in part because of the non-stationary nature of the environment in our setting. We observe that the size of the action set also plays a crucial role in the speed of convergence. Motivated by this, in Chapter 5 we propose an deterministic alternative.

We conclude this section by noting that our probabilistic channel adaptation framework is fairly general. For instance, it can be extended to account for adjacent channel interference [134] and partially overlapping channels [135] by using a modified channel set quality metric.

4.6 Evaluation

In this section, we study the performance of LCAP and evaluate its effectiveness in terms of the goals stated in Section 4.3, viz. efficient channel utilisation, protocol scalability, adaptivity and flexible support of different traffic patterns. Our evaluation is via simulation. We use the QualNet [136] simulator version 4.0 for our evaluations. We choose ADC protocol [24] for comparative evaluation as it is the most practical solution in the literature that can also support diverse traffic patterns (see discussion in Section 3). We also include the single channel case as a baseline. We have implemented both LCAP and ADC on QualNet. ADC implementation is based on the ADC paper, consultation with the authors and a longer technical report version provided by them. Our LCAP QualNet implementation includes the neighbour discovery module as described in Section 4.4 that uses the access interface for short periods periodically via channel quieting.

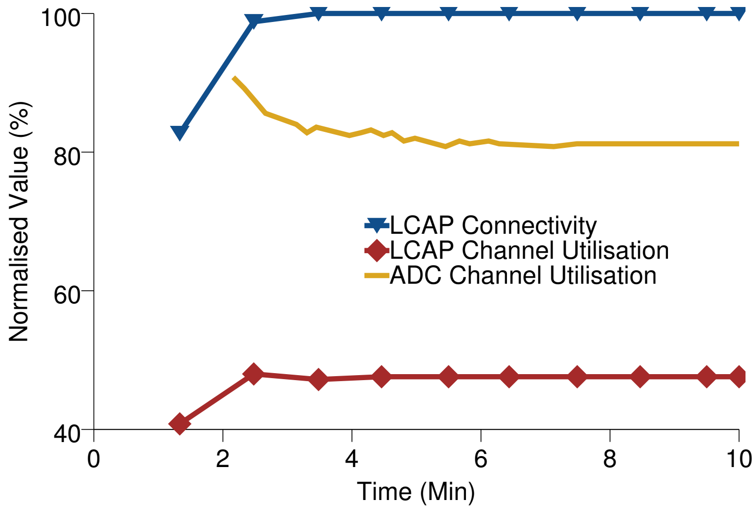
We set the channel and physical layer parameters to reflect an urban mesh network scenario based on the earlier measurement work in [126]. Specifically, we use two-ray propagation model with pathloss exponent $\alpha = 3.3$, shadowing with standard deviation $\sigma_\varepsilon = 5.9$, omnidirectional antennae with 15dBi gain and placed at 10m height [126]. Transmission power and receive sensitivity values for different transmission rates are set referring to default values for commodity hardware (specifically, Atheros-based Compex WLM54AG mini-PCI cards used in our multi-radio mesh network testbed). For routing, we use the OLSR routing protocol [98] with the CATT metric [110].

CATT metric has been shown to outperform other routing metrics for multi-radio mesh networks, and additionally has certain attractive features such as isotonicity and a unified way of accounting both inter-flow and intra-flow interference. Experimental results have been averaged over several runs with different random seeds.

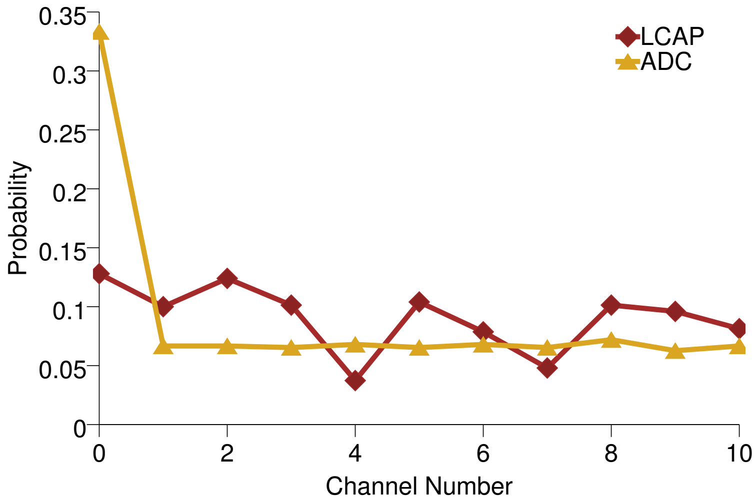
4.6.1 Channel Utilisation and Network Performance

As described in Section 4.3, efficient channel utilisation without hurting network connectivity is one of our goals. Before examining LCAP's ability to achieve this goal, let us first consider the metrics to quantify channel utilisation and connectivity. For channel utilisation, we use a simple metric that is protocol independent yet captures the extent to which contention (interference) is evenly distributed across all channels. Specifically, we use the difference between maximum and minimum number of mesh interfaces assigned to any channel, over all channels, as a measure of channel utilisation — a lower value of this measure implies a better channel utilisation. Note that the maximum number of interfaces assigned to a channel is upper bounded by the network size (as would be the case in a single-interface, single-channel network, for example). We use this upper bound to normalise channel utilisation measure and show it as a percentage value (see Figure 4.4(a)). We measure network connectivity as the percentage of links in a single channel network that are preserved by the multi-radio channel assignment protocol. As opposed to the standard graph-theoretic connectivity measures such as k-connectivity, this measure allows a fair comparison with ADC as it also achieves connectivity like in a single channel network (via the common channel).

Figure 4.4 (a) shows the key result, demonstrating that LCAP offers significantly better channel utilisation than ADC while ensuring connectivity. These results correspond to a 25-node 802.11-based multi-radio mesh network with nodes randomly distributed in a 1000m x 1000m field, 11 backhaul mesh channels in the 5.470-5.725GHz band and 3 mesh interfaces per node. We have also experimented with different number of channels and interfaces. Our results also show qualitatively similar impact from varying number of channels and interfaces as observed by other researchers in the past (e.g., [10]). Figure 4.4(a) shows that LCAP provides up to 40% improvement in channel utilisation over ADC. This is because LCAP does not require a common default channel (which has all nodes assigned to it in ADC) and due to its ability to select diverse channel sets for interfering set of nodes. This is also confirmed by the channel utilisation distribution plot in Figure 4.4(b), which shows that available channels



(a) Channel Utilisation and Connectivity



(b) Channel Utilisation Distribution

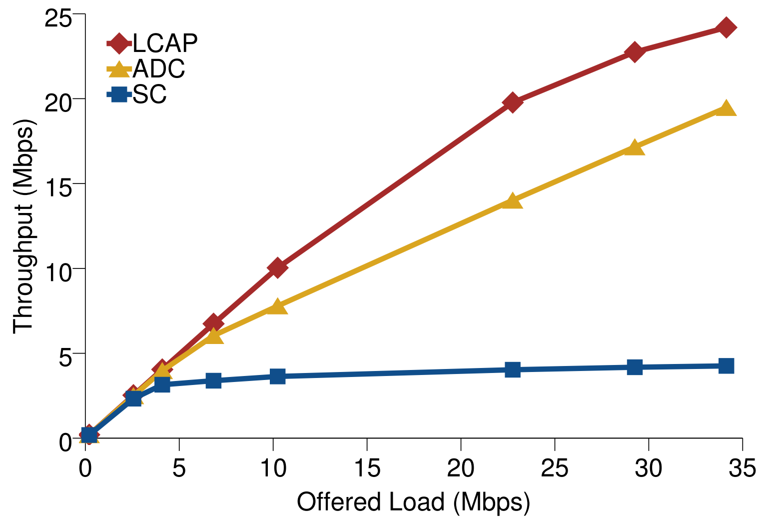
Figure 4.4: Channel utilisation, connectivity and protocol convergence with LCAP and ADC protocols in a 802.11-based multi-radio mesh network.

are more evenly used with LCAP. Note, the achievable channel utilisation is inherently limited by the number of interfaces and the need to maintain network connectivity; this means some degree of channel reuse is inevitable, which partly explains why LCAP channel utilisation stabilises around 48%. The result in Figure 4.4(a) also shows the convergence times for LCAP and ADC. Note, the connectivity curve is not shown for ADC as it is always connected due to the common channel. Observe that LCAP channel assignment converges much faster than ADC because the channel assignment in the latter is via negotiations with 3-hop neighbours of a node over the common channel.

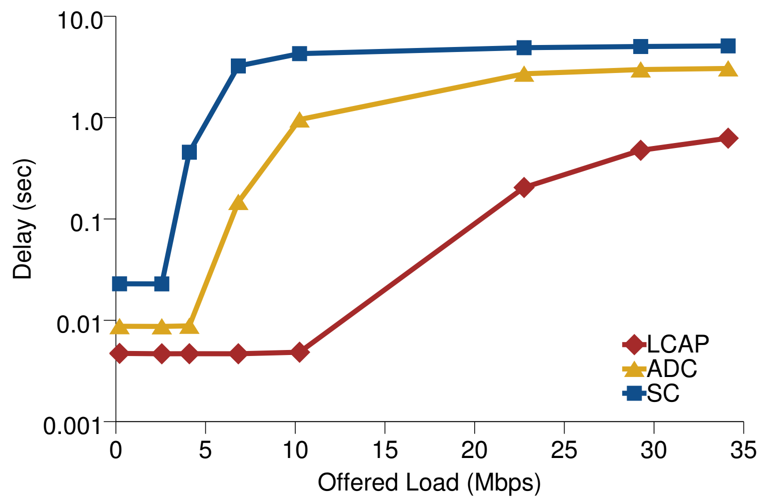
The improved channel utilisation in LCAP leads to its significantly better link layer throughput and delay performance compared to ADC and the single channel case (see Figure 4.5(a, b)) for the same network scenario as before. Note the log-scale in the delay plot. These results are obtained by increasing packet generation rate on each link for fixed size (1KB) packets. Figure 4.6(a, b) shows the relative performance of LCAP and ADC in the case of multihop traffic with two different traffic patterns. Random traffic pattern involves 10 CBR/UDP flows with 1KB packets and varying packet rate between 10 randomly chosen source-destination pairs. On the other hand, the traffic is from an Internet gateway node to 10 randomly chosen non-gateway nodes with all else being same as the random pattern. LCAP exhibits superior performance in both traffic patterns with up to 40% throughput improvement and similar or better delays, demonstrating its ability to support diverse traffic patterns. The performance differentials drop in the case of gateway pattern because the gateway node becomes the bottleneck limited by its number of interfaces (3, in this case).

4.6.2 Protocol Scalability

We now look at communication overhead of the protocols in terms of their control messages. We consider the same 25-node random network scenario as before and show the overhead for each of the protocols in Table 4.1. The overhead for the single channel case serves as a baseline as it represents the routing protocol (OLSR) overhead in a single-interface, single channel network. LCAP overhead is marginally higher than the single channel. This is because of two reasons: (1) although in our implementation HELLO messages in LCAP neighbour discovery also serve OLSR, we can see it differently as LCAP piggybacking on OLSR messages (specifically, HELLO messages), thus there is no additional overhead with LCAP; (2) in a multi-radio network, HELLO messages need to be sent multiple times on different interfaces, which explains the

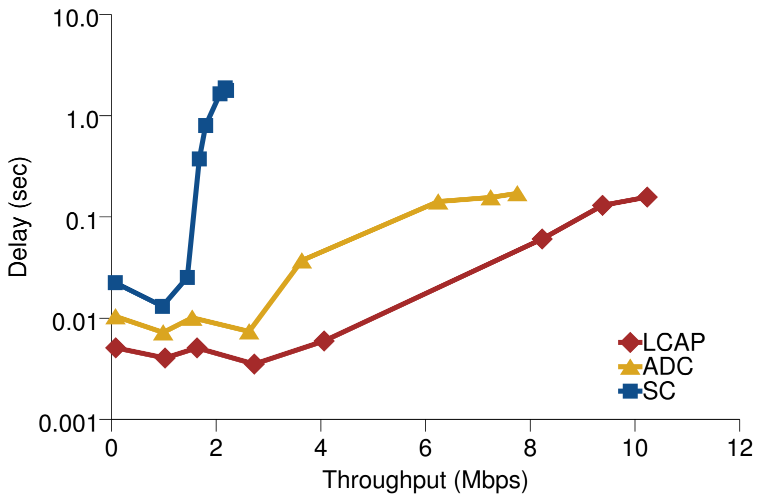


(a) Aggregate Link Layer Throughput

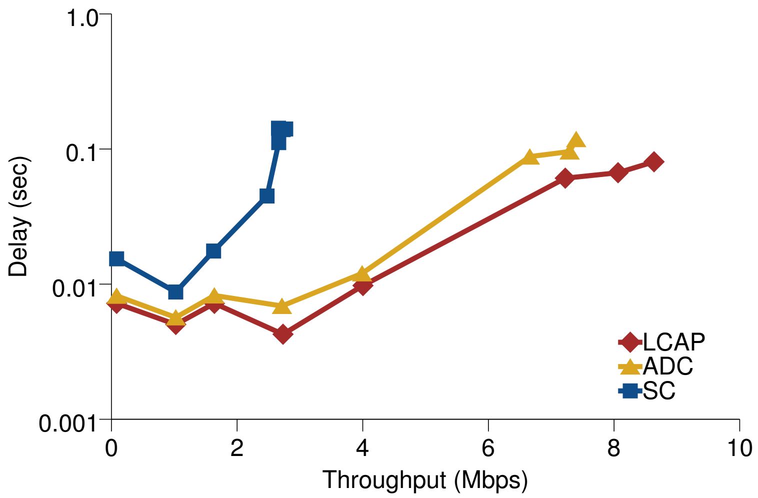


(b) Average Delay at Link Layer

Figure 4.5: Link layer performance with LCAP and ADC protocols in a 802.11-based multi-radio mesh network.



(a) Random Traffic



(b) Internet Traffic

Figure 4.6: Throughput and delay performance of LCAP, ADC and single channel case with two types of multihop traffic patterns: random and gateway.

increase in overhead messages compared to single interface, single channel case. Finally, ADC has about 60% greater overhead compared to LCAP, primarily because of the negotiation-based approach taken by ADC. Also given that all control traffic with ADC is carried on a common channel, higher control overhead means that the common channel has lower available bandwidth for data traffic, essentially reducing the effective number of available channels. We also looked at the impact of increasing the network size on LCAP protocol overhead (not including the routing protocol overhead) while having the same node density. As is evident from Table 4.2, the LCAP overhead is pretty much constant regardless of the network size, which demonstrates its scalability property.

Protocol	Control Overhead (msgs/node)
ADC	4486
LCAP	2777
SingleChannel	2378

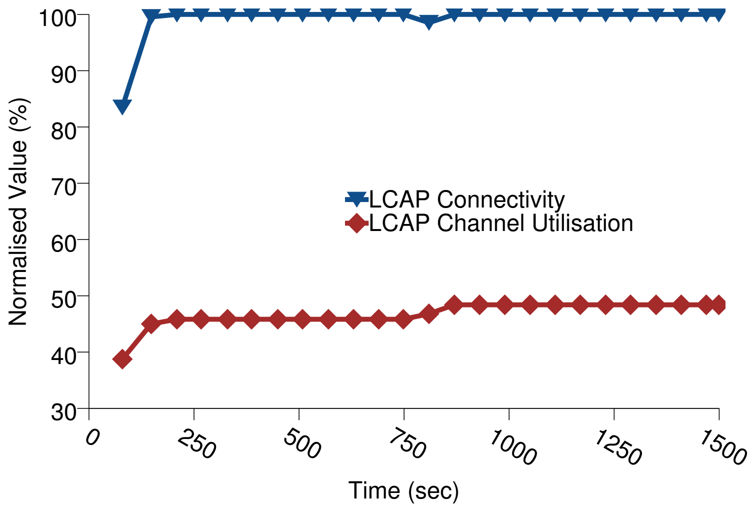
Table 4.1: Communication overhead with LCAP relative to ADC and single channel case.

Network Size	Control Overhead (msgs/node/s)
16	0.76
32	0.78
64	0.77
128	0.77

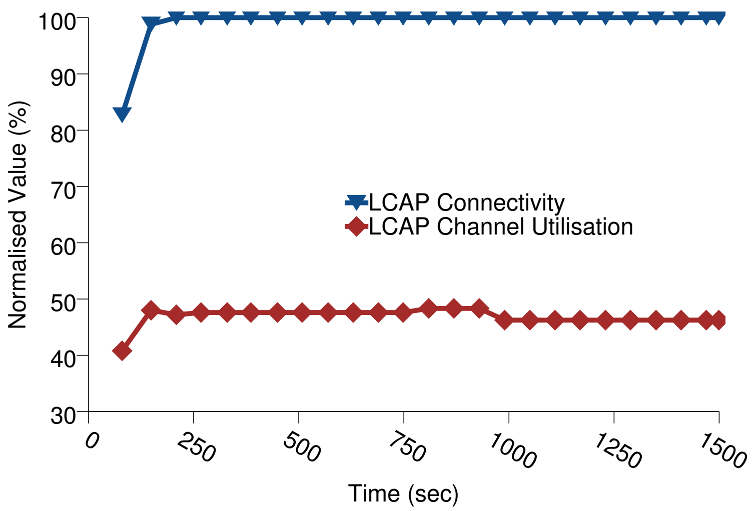
Table 4.2: Communication overhead with LCAP for different network size.

4.6.3 Adaptivity

Here we consider the adaptivity of LCAP to network topology changes and the presence of external interference that affects the usability of available channels. Figures 4.7 and 4.8 show the results. In all cases, the topology change or external interference event happens at time 800s. When a new node joins the network (Figure 4.7(a)),



(a) Node Join



(b) Node Failure

Figure 4.7: Adaptive behaviour of LCAP in the presence of network topology changes: (a) node join (a) and (b) node failure.

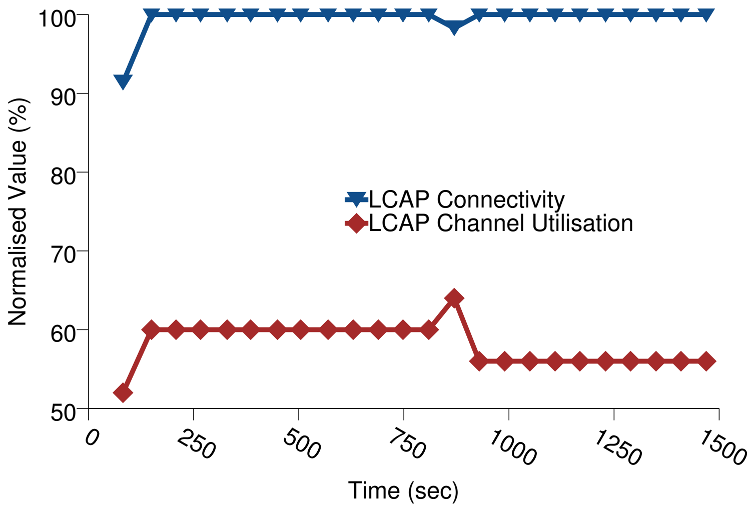


Figure 4.8: Adaptive behaviour of LCAP in the presence of external interference.

connectivity is temporarily affected briefly because the new node and its neighbours may not share a common channel to begin with, but we can see that LCAP quickly resolves this situation. The channel utilisation (interference) metric worsens a bit because the new node forces reuse of fewer set of channels to ensure its connectivity. The opposite happens when a node fails, as seen from Figure 4.7(b). Finally, we also studied the impact of external interference that affects spatio-temporal availability of usable channels. We model external interference via jamming of a subset of channels for a specified time period in a circular region of radius 300m (compare with 1000m x 1000m field), making those channels unusable during that period. This causes LCAP to adapt the channel assignment to ensure connectivity (Figure 4.8). There is an interesting point to note about LCAP's adaptation mechanism. The interference (channel utilisation) metric gets better after external interference causes a disruption compared to its prior value, which happens because of the resumption of exploration (probability update process at each of the affected nodes) and show that such disruptions can in fact be beneficial to the channel assignment.

4.7 Conclusions

In this work, we have developed LCAP, a distributed multi-radio channel assignment protocol for mesh networks. LCAP takes a fundamentally different approach from existing protocols by using a probabilistic channel adaptation mechanism based on learning automata. This allows nodes to autonomously determine their channel allocation aided by a novel neighbour discovery mechanism that is based on channel quieting and allows neighbours to find each other even when not using a common channel. We have presented extensive simulation-based evaluation of LCAP relative to the state-of-the-art ADC protocol. Our results show that LCAP provides significant improvements in channel utilisation and network performance (up to 40%) while being more scalable (with 60% less overhead) and adaptive to factors such as external interference. A prototype implementation of the neighbour discovery module is presented in [27].

Chapter 5

A Deterministic Approach for Distributed Multi-Radio Channel Allocation in Wireless Mesh Networks

5.1 Introduction

In Chapter 4, we have proposed a learning-based distributed channel allocation protocol (LCAP) where nodes learn the optimal action independently and iteratively by means of learning automata. The goal of this solution is to assign channels to the interfaces of the nodes for the backhaul to achieve efficient channel utilisation and interference reduction, while maintaining connectivity. A key challenge, however, is to establish convergence in the network. Due to channel dependency among the nodes, a change in the allocation of a node can cause a chain of changes in the network (ripple effects). Moreover, the non-stationary[1] nature of the environment, where the "goodness" of the actions at a node is dependant on the actions of other nodes in the network, makes the problem analytically intractable.

In LCAP, we have developed an adaptive channel set exploration mechanism to aid faster convergence. This mechanism allows exploration (i.e., continuation of the probability vector updating scheme) until a channel set that provides connectivity to

[1]In the context of learning automata, an environment is referred to as non-stationary if the penalty probabilities corresponding to the various actions vary over time [129]. When a network of automata operates on the same environment, the action chosen by one automaton can change the quality of an action previously inferred to be the best by another automaton. In our scenario, the environment becomes non-stationary due to ripple effects caused by channel changes as an effect of channel dependencies among the nodes in the network.

all neighbours is found. Subsequently, exploration is resumed only in the event of any disruption (e.g., node join, node failure, external interference). Furthermore, we vary the mean adaptation intervals based on the achieved connectivity. More specifically, each node evaluates its current channel set choice in terms of the connectivity. If a node is connected to more than x% of its neighbours (50% in our implementation), it increases the mean adaptation interval (from 3.5s to 16.5s in our evaluations). This gradually creates a quasi-static view of the environment for each node in the network and facilitates convergence. A good convergence behaviour of LCAP has been demonstrated experimentally.

The worst case convergence time is hard to establish theoretically given the non-stationary nature of the network scenario. A *loose* upper bound can be obtained based on the constraint satisfaction problem formulation from [28], but such a proof is unsatisfactory. Motivated by this, we develop a deterministic alternative in this chapter. Our goal is to introduce stationary behaviour in the network and theoretically show convergence, while maintaining all the attractive properties of LCAP: *Efficient Channel Utilisation*, *Protocol Scalability*, *Adaptivity*, *Flexibility* and *Topology Preservation* (see Section 4.3)

The key idea behind our deterministic distributed channel allocation scheme is based on a *node prioritisation scheme*. More specifically, nodes are assigned *unique* priorities, which determine the order in which they allocate channels to their interfaces (incident links) — the higher a node′s priority, the sooner its turn for channel allocation. *The goal of each node is to connect to all higher priority nodes within communication range*. We refer to our new proposal outlined above as DCAP (Deterministic Channel Allocation Protocol).

The remainder of this chapter is structured as follows. Next section introduces notation and basic concepts underlying DCAP. The priority based channel allocation algorithm is explained in Section 5.3. Section 5.4 provides a proof for the correctness of the algorithm, while Section 5.5 evaluates the performance of DCAP relative to LCAP and ADC [24].

5.2 Preliminaries

Similarly to LCAP, the main tuning parameter in our channel allocation protocol is a channel set (Section 4.2). A channel set is ‘a subset of channels’ of size equal to the number of radio interfaces at a node. We assume that each node is equipped with

2 interfaces or more. With S denoting the set of all channel sets, c channels and m interfaces, the number of channel sets, $|S|$ = $\binom{c}{m}$. For example, for $c = 3$ and $m = 2$, there are $\binom{3}{2} = 3$ possible channel sets: $\{(1, 2), (1, 3), (2, 3)\}$.

Additionally, we use notation K_n to refer to the set of available interfaces at node n and notations N_n^1 and N_n^2 to denote the set of nodes in the one-hop and two-hop neighbourhood of node n respectively. We also use P_n to define the priority of node n (details on how nodes are assigned *unique* priorities is given in the next section). Based on these priorities. we use $hN_n^1 = \{m \in N_n^1 | P_m > P_n\}$ and $hN_n^2 = \{m \in N_n^2 | P_m > P_n\}$ to denote the set of all higher priority nodes in the one-hop and two- hop neighbourhood of node n respectively. Obviously, $hN_n^1 \subseteq N_n^1$ and $hN_n^2 \subseteq N_n^2$. Similarly, $lN_n^1 = \{m \in N_n^1 | P_m < P_n\}$ and $lN_n^2 = \{m \in N_n^2 | P_m < P_n\}$, are the sets of all lower priority nodes in the one-hop and two-hop neighbourhood of node n respectively. We also use $hN_n^{1^t} \subset N_n^1$, $hN_n^{2^t} \subset N_i^2$, $lN_n^{1^t} \subset N_n^1$ or $lN_n^{2^t} \subset N_n^2$ to refer to a subset of nodes in the higher and lower priority one-hop neighbourhood of node n with some specific property t. For example, $hN_n^{1^{\neg m}} \subset N_n^1$ denotes a set of higher priority one-hop neighbours of n excluding the one-hop neighbour m.

We use the term *connectivity array* to refer to an array of channels that are required to connect a node n to all its higher priority one-hop neighbours assuming there is no constraint in the number of available interfaces. The size of this array, therefore, can be possibly smaller or larger than the number of available interfaces. We use C_n to represent the set of all connectivity arrays of node n and $min(C_n)$ to denote the smallest connectivity array. Throughout this chapter, we also use notation C_n^t to refer to a set of all connectivity arrays, which involve a subset of higher priority one-hop nodes of node n with some specific property t. For example, $C_n^{\neg m}$ is the set of all connectivity arrays, which involve a subset of higher priority one-hop neighbours of node n that does not include the one-hop neighbour m.

Since channel allocation involves assigning channels to the available interfaces of node n, a node can connect to all its neighbours if there is a connectivity array $C_n[i]$ (where i is the index in C_n) such that $|C_n[i]| \leq K_n$. We call this constraint a *valid connectivity* constraint. Furthermore, we use $V_n \subseteq S$ (as in the previous chapter, S denotes the set of all channel sets) to refer to a vector of channel sets each satisfying the valid connectivity constraint. We call each channel set in V_n, a *valid channel allocation*.

5.3 Deterministic Channel Allocation Protocol

The neighbour discovery component of the Deterministic Channel Allocation Protocol (DCAP) is identical to that of LCAP (see Section 4.4). In this section we focus on our node prioritisation scheme and the channel selection algorithm.

5.3.1 Node Prioritisation and Topology Preservation

As mentioned before, nodes are assigned priorities, which determine the order in which they allocate channels to their interfaces. A node with a higher priority can decide sooner on its allocation. These priorities are determined as follows: Nodes with a larger number of neighbours are given a higher priority in channel assignment. Moreover, since the number of interfaces restricts the number of channels a node can use to connect to its neighbours, each node n is assigned a priority given by $P_n = |N_n^1|/K_n$. The above equation favours nodes with smaller number of interfaces and/or larger number of neighbours when assigning priorities since for these nodes channel reuse is required to maintain connectivity resulting in increased interference. Less "fortunate" nodes, therefore, should have more freedom in choosing channels with the least interference.

As opposed to LCAP, nodes seek to connect to only higher priority nodes rather than to all neighbouring nodes. More specifically, a node can be in two states: NOT CONNECTED or CONNECTED. *Each node n transitions from NOT CONNECTED to CONNECTED state if a valid channel allocation at node n connects n to every higher priority node q in its one-hop neighbourhood.* A node, however, cannot transition to a CONNECTED state unless it is its turn to commit to a channel allocation. (**Constraint (1)**). The state and the priority information at each node is carried in HELLO messages (Section 4.4). Also, ChannelUsageList carried in the HELLO messages is modified to report for each channel the number of interfaces using that channel by higher priority nodes only in the two-hop neighbourhood of the node generating the HELLO message.

Each node's turn can be determined among the one-hop higher priority neighbours and the node itself. This protocol, however, cannot guarantee that a valid channel allocation exists for every node in the network. To understand this, consider the topology depicted in Figure 5.1, which is composed of nodes n, l, q and m (the topology is a portion of a larger network). The number inside a parenthesis next to each node denotes its priority (e.g., the priority of node n is 6). In this example there are 8 available channels (c = 8) numbered from 1 to 8 and every node is equipped with two interfaces.

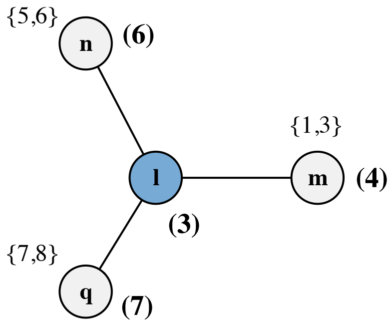


Figure 5.1: Nodes greedily connect to higher priority neighbours in a priority-based ordering: Node 3 needs three channels for a valid channel allocation, but $K_3 = 2$.

The set of channels in brackets next to each node corresponds to the chosen channel allocation for that node. Based on the priorities of the nodes, node l is the last node to choose its channels. As shown in the figure, however, node l needs three channels to connect to all its neighbours, but since K_l = 2, node l does not have a valid channel allocation.

To avoid this unwanted situation, we impose the following two additional constraints:

- Node n is prevented from choosing an allocation, if that allocation can result in invalidity to a lower priority neighbour l, $l \in lN_n^1$. (**Constraint (2)**) If such constraint is not used, higher priority nodes can utilise channels in a way that can cause lower priority nodes to need more channels than their available interfaces to connect to all higher priority nodes (e.g, the scenario described in Figure 5.1). The process via which n identifies potential invalid situations is described in the next paragraphs.

- A node n cannot transition from a NOT_CONNECTED to CONNECTED state unless all higher priority nodes q in its two-hop neighbourhood (i.e., $q \in hN_n^2$) are in CONNECTED state. (**Constraint (3)**) This constraint is related to constraint (2). All higher priority one-hop neighbours of a lower priority node l of n are a subset of higher priority nodes of n (q belongs to $hN2_n$) in its two-hop neighbourhood. Once each of nodes q belongs to $hN2_n$ is in CONNECTED state (i.e., has converged), node n is able to determine the number of channels its lower priority neighbours (l belongs to $lN1_n$) require to connect to nodes in $hN2_n$. Note that this constraint does not change the priority based ordering. Nodes with higher priorities are choosing their allocations earlier than lower lower priority nodes, as before.

To ensure that the constraint (2) is not violated at any node n, the channel allocation protocol needs to *simulate* the allocation at every node l belongs to $lN1_n$ for every channel set s in V_n. This is performed with the following sequence of steps:

1. Node n calculates the size of the minimum connectivity array that could connect node l to all its higher priority nodes q (excluding node n), which are a subset of higher priority nodes in the two-hop neighbourhood of node n. That is $q \in \{hN_l^{1^{\neg n}} \cap hN_n^2\}$. Note that since q belongs to the set hN_n^2, q has transited to CONNECTED state prior to node n (according to the priority-based ordering in channel allocation), therefore its allocation is final. We refer to the minimum connectivity array as $sim\_min(C_l^q)$ and to its size as $|sim\_min(C_l^q)|$. The algorithm, which finds $sim\_min(C_l^q)$, constructs a tree of channel allocations by iteratively processing the allocation at each node q (the order in which neighbours are processed does not matter). More specifically, the algorithm works as follows: It appends a new level in the tree for every processed node q. For the first node, it creates a new channel node for each channel in the allocation of node q. The second node creates an additional level in the tree. At this level, however, each channel node at the previous level is connected with a new channel node corresponding to a channel from the allocation of the second node. The third node adds an additional level and so on. We call this tree a *channel allocation tree*. Every path down the channel allocation tree corresponds to the group of channels connecting node l to all nodes q. Moreover, a channel node at each level is associated with a depth value. This value equals the level that has reached down the path of the tree (the value of the first level value is 1), if the channel is not found at the parsed path. If the channel already exists, the depth associated with the channel equals the depth of the channel at the previous level. The depth value at the leaf channel node corresponds to the size of the connectivity array connecting node l to all nodes q. For example, consider three nodes A, B and C $\in \{hN1_l^{\neg n} \cap hN2_n\}$ each equipped with two radios. Assume these nodes have chosen allocations $s_A = \{1, 2\}$, $s_B = \{1, 3\}$ and $s_C = \{1, 4\}$. The corresponding channel allocation tree is shown in Figure 5.2. The channel number is shown inside the nodes of the tree. The numbers in parenthesis correspond to channel

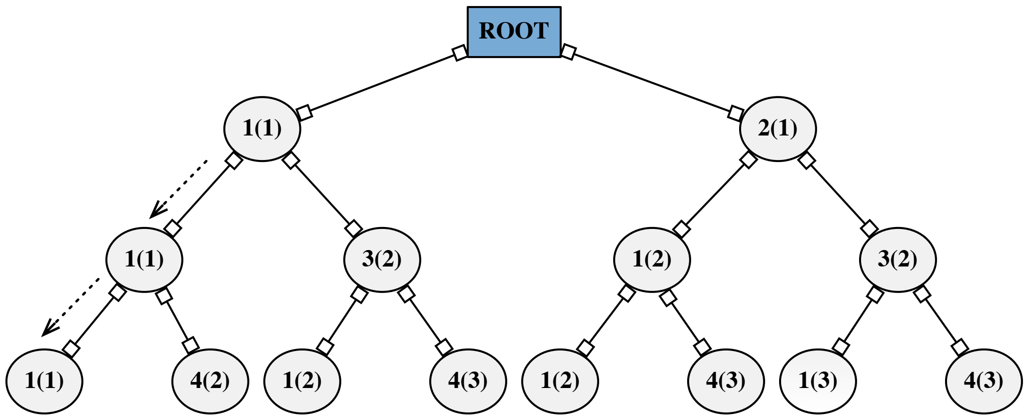


Figure 5.2: Channel allocation tree for three nodes A, B and C with s_A = $\{1, 2\}$, s_B = $\{1, 3\}$ and s_C = $\{1, 4\}$.

node depth. Path 1-1-1, pointed by the arrows, gives the minimum connectivity array needed to connect node l to all its neighbours q. Thus, $sim\_min(C_l^q) = \{1\}$ and $|sim\_min(C_l^q)| = 1$.

If the number of 1-hop neighbours for a lower priority node is large, the size of the corresponding tree becomes large making its construction and parsing computationally expensive. This, however, is not a problem since the algorithm does not need to construct the entire tree. The algorithm optimises the tree construction and search as follows: A new channel node is not appended to a path, if its value is already found on that path. To mark branches of the tree that are valid but do not contain all channel nodes due to value repetition, we use a *special* node (with an * value). Moreover, if the depth of a current leaf channel node exceeds the number of interfaces of a node, the algorithm stops appending new channel nodes to the corresponding path. To denote that such paths are invalid and should not be further expanded, the algorithm uses a *special* node (e.g., with an x value). For instance, if the number of interfaces at node l is two, the pruned channel allocation tree is shown in Figure 5.3. When node n parses the tree, it knows that path 1-* gives the minimum connectivity array and also that path 1-3-x is an invalid path for neighbour l.

2. Node l, however, may also have a higher priority one-hop neighbour m, which is a lower priority 2-hop neighbour of node n. (i.e., $m \in \{hN_l^1 \cap lN_n^2\}$). Since node m has not transitioned to CONNECTED state at the moment node n is deciding

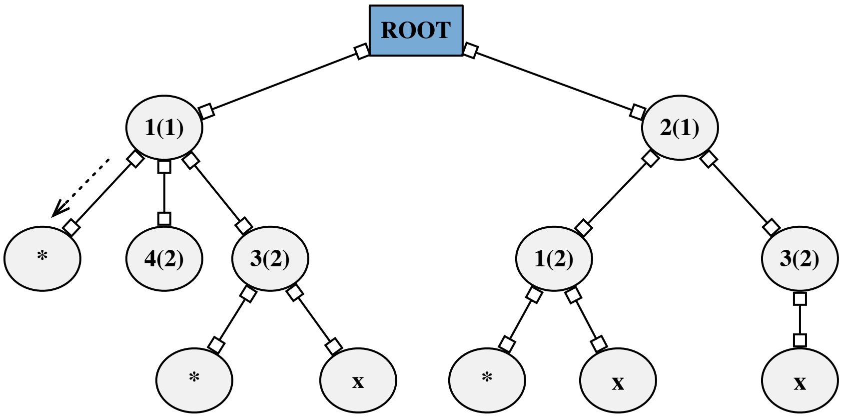


Figure 5.3: Pruned channel allocation tree for three nodes A, B and C with $s_A = \{1, 2\}$, $s_B = \{1, 3\}$ and $s_C = \{1, 4\}$.

on its channel allocation (because m waits for n to converge), its allocation is not yet known to n. For example, consider the scenario shown in Figure 5.1. Node n can choose a non-overlapping allocation to node q without considering node m, which is a lower priority node. If the allocation is as shown in Figure 5.1, node l will not be able to find a valid allocation. To account for this, node n calculates $|sim\_min(C_l^{q \cup m})|$ as $|sim\_min(C_l^{q \cup m})| = |sim\_min(C_l^{q})| + 1$, if such node m exists. In the scenario shown in Figure 5.1, following this algorithm, node n is now forced to share a common channel with node q.

3. At the final step, node n can decide on its allocation among the valid allocations in V_n. To avoid causing invalidity, node n needs to ensure that for *every* lower priority neighbour, its own decision $s \in V_n$ along with the simulated minimum connectivity array of that neighbour (obtained in the previous steps), does not violate the valid connectivity constraint. To do this, node n needs to calculate $sim\_min(C_l)$, which is the minimum connectivity array required to connect node l to all its higher priority nodes including node n for each lower priority node l. If there is a node l for which $|sim\_min(C_l)| > K_l$, channel set s must not be considered eligible for selection. We refer to this process as *channel set deactivation* and consider such sets as deactivated. To calculate $|sim\_min(C_l)|$ for s, node n needs to parse the tree and append its channel as a new level of the tree. If, however, $|sim\_min(C_l^{\neg n})| < K_l$ (this value includes any increase due to step (2) of the algorithm), tree parsing is not necessary, because, in the worst

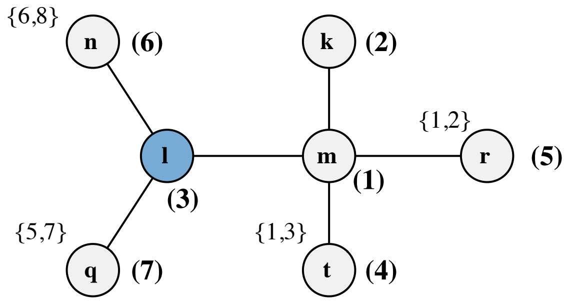


Figure 5.4: Priority-based channel assignment where nodes ensure valid allocations for lower priority nodes: Node l cannot find a valid channel set which connects it to higher priority nodes q and n and does not cause invalidity to lower priority node m.

case scenario $|sim\_min(C_l^{\neg n})| = K_l - 1$ and $\{s \cap sim\_min(C_l^{\neg n})\} = \emptyset$. In this case, $|sim\_min(C_l)| = K_l$, which does not violate our valid connectivity constraint $|sim\_min(C_l)| \leq K_l$. After all lower priority neighbours are checked and all channel sets that can cause invalidity are deactivated, node n can choose from the remaining channel sets that are still active as described in Section 5.3.2.

Even with this algorithm, however, invalidity can still occur. Consider the topology shown in Figure 5.4, where every node is equipped with 2 interfaces. Node n choses its channels such that node l requires two channels to connect to nodes n and q(i.e., {5, 6}, {5, 8}, {7, 6} or {7, 8}), without considering node m because m does not belong to hN_l^1. When it is the turn of node l to decide on its allocation, it knows that its lower priority 1-hop neighbour m needs a minimum of one channel (i.e., channel 1) to connect to nodes t and r (i.e., t,r$\in \{hN_m^1 \cap hN_l^2\}$). This means that $sim\_min(C_m^{\neg l}) = \{1\}$ and $|sim\_min(C_m^{\neg l})| = 1$. But, since there is also node k which belongs to set $\{hN_m^1 \cap lN_l^2\}$, node l will assume $|sim\_min(C_m^{\neg l})| = |sim\_min(C_m^{\neg l})| + 1$ following step 2. Thus, $|sim\_min(C_m^{\neg l})| = 2$. At the final step (step 3), node l searches its channel set space V_l to find a set that provides connectivity to its higher priority neighbours q and n and also satisfies the valid connectivity constraint $|sim\_min(C_m)| \leq 2$. Unfortunately, for every allocation a in V_l, $\{a \cap sim\_min(C_m^{\neg l})\} = \emptyset$. Node m, therefore, will require an additional channel to connect to node l. Thus, $|sim\_min(C_m)| = |sim\_min(C_m^{\neg l})| + 1 = 2 + 1 = 3 > K_m$. As such, there is no set ensuring connectivity between node l to its higher priority neighbours q and n, while ensuring that there will exist a valid channel set for lower priority neighbour m.

To resolve this, we modify step 2 as follows: Node n considers both higher and

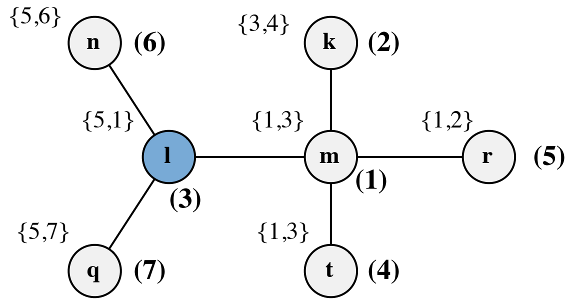


Figure 5.5: Following the steps of the algorithm, the invalidity presented in Figure 5.4 is resolved and every node can find a valid channel assignment.

lower priority neighbours 1-hop neighbours of every lower priority 1-hop neighbour l. Specifically, if there is some node m in the one-hop neighbourhood of node l that is also in the lower priority two-hop neighbourhood of node n (that is, if $\exists m, m \in \{N_l^1 \cap lN_n^2\}$), $|sim\_min(C_l^q)| = |sim\_min(C_l^q)| + 1$. Figure 5.5 shows how this modification results in valid channels allocations for every node in the topology. When it is the turn of node n to decide on its allocation, it first checks $sim\_min(C_l^q)$ for each $q \neq n$. It finds that $sim\_min(C_l^q)$ = 5 or 7 and $|sim\_min(C_l^q)| = 1$. It also realises that there exists node m, such that $m \in \{N_l^1 \cap lN_n^2\}$, thus $|sim\_min(C_l^q \cup m)| = |sim\_min(C_l^q)| + 1 = 2$. At the last step, node n finds that in order to ensure that $|sim\_min(C_l)| \leq 2$, it needs to share a channel with node q, such that l needs only one channel to connect to them. We assume that n chooses set 5,6 although any set containing 5 or 7 would still be valid. Now node l can use channel set 5,1 without causing invalidity to node m.

5.3.2 Channel Set Selection

The goal of the cost function, which was presented in Section 4.5, is to assess the channel set qualities in a way that "loosely" reflects the delay experienced for communication with neighbouring nodes when using a channel set. In the priority-based scheme, since nodes seek to connect to only their higher priority neighbours, rather than all neighbouring neighbours, we modify this function to consider only the higher priority neighbourhood of a node when determining the quality of a channel set. The quality of a channel set s, at node n is then defined as follows:

$$
\begin{aligned}
CSQ_n^s &= \sum_{q \in hN_n^1} NC_n^s(q), \\
&\text{where} \quad NC_n^s(q) = \min(NC_n^c(q)), c \in s.
\end{aligned} \tag{5.1}
$$

Similarly to LCAP, each backhaul mesh node has a decision maker unit to help determine the channel assignment for mesh interfaces at that node. Different from the decision maker at LCAP, however, this unit is not used to learn the optimal action, but to optimally choose the correct action when it is the node's turn to allocate its channels. The action set for each unit is the set of all possible channel sets denoted by S. When it is the node's turn to allocate its channels, the node executes the algorithm described in the previous section to *deactivate* the channel sets that cause violation of the valid connectivity constraint at some lower priority node. Then, the node computes the quality of each active channel set (equation (5.1)) based on the information obtained via the LCAP neighbour discovery module (see Figure 4.2 and Section 4.4). Among these sets, the node finally chooses the channel set with the minimum CSQ_i^s.

5.4 Protocol Correctness

For each node, convergence time is bounded by two factors: the number of nodes in its two-hop neighbourhood and the time needed to receive the "hello" messages from these neighbours for the node to be informed that the neighbourhood has converged. The total time required for the network to converge is bounded by the time for the last converged node. In the worst case scenario, that node waits for every other node in the network to converge. For a network with N nodes, this means that the bottleneck node will converge after N-1 nodes converge.

Theorem: If every node chooses its channel allocation following the algorithm described above, then there will be a valid allocation for every node l in the network.

Proof: The goal of each node is to connect to all its higher priority neighbours, while ensuring that each lower priority node can find a valid channel allocation. A violation of the valid connectivity constraint can occur at some node l concerning its own allocation or some lower priority one-hop neighbour m of node l . In the first case, the number of channels required to connect node l to all its higher priority nodes exceeds the number of its available interfaces, thus $|min(C_l)| > K_l$. In the latter case, the size of the minimum simulated connectivity array for node m exceeds the number of interfaces at node m. To prove these situations can never happen we consider the following two cases:

Case 1: Node l does not have a one-hop neighbour m that has lower priority than some node n where n is a higher priority one-hop neighbour of node l. In other words, for $n \in hN_l^1$, there *does not exist* node m, $m \neq n$ and $m \in \{N_l^1 \cap lN_n^2\}$. In this case, since $\{N_l^1 \cap lN_n^2\} = \emptyset$, all one-hop neighbours of l have higher priority than n (i.e., $N_l^{1^{\neg n}} \subseteq hN_n^2$). In this scenario, $P_m > P_n > P_l$. Moreover, every node m has converged (transitioned to CONNECTED state) before node n and thus n knows their allocations when it is its turn to decide its own allocation. So, as described under step 1 of simulation algorithm, when it is the turn of node n to allocate its channels, it will choose its $s \in V_n$, such that the minimum connectivity array connecting node l to all its higher priority nodes including node n is less than or equal to the number of interfaces of node l. That is $|sim\_min(C_l)| \leq K_l$. Since $hN_l^1 \subseteq N_l^1 \subseteq hN_n^2$, node n has considered all higher priority nodes of node l and as such $min(C_l) = sim\_min(C_l)$ and $|min(C_l)| = |sim\_min(C_l)| \leq K_l$. Therefore, $|min(C_l)| > K_l$ cannot be true.

Case 2: Node l has a one-hop neighbour m which has a lower priority than some node n where n is a higher priority one-hop neighbour of node l. In other words, for some node $n \in hN_l^1$, there *exists* some node m, $m \neq n$ and $m \in \{hN_l^1 \cap lN_n^2\}$. In this case, when it is the turn of node n to decide on its allocation, node m has not converged yet, thus its allocation is unknown to node n. Node m, moreover, can have either higher or lower priority than node l, thus we need to consider these two cases separately:

(a) Node m has *higher* priority than node l (i.e., $m \in hN_l^1$). To verify if condition $|min(C_l)| > K_l$ can be true, we need to show that the size of the set of channels needed to connect to every node n, $n \in hN_l^{1^{\neg m}}$ and node m exceeds the number of interfaces at node l. More specifically, in the worst case, we need to show that every node n, $n \in hN_l^{1^{\neg m}}$ chooses its channels such that $|min(C_l^{\neg m})| = K_l$. But, as per step 2 of our simulation algorithm, if $\exists m \in \{N_l^1 \cap lN_n^2\}$, node n assumes that $|sim\_min(C_l)| = |sim\_min(C_l^{\neg m})| + 1$ and ensures that $|sim\_min(C_l)| \leq K_l$, thus $|sim\_min(C_l^{\neg m})| \leq K_l - 1$. When it is the turn of node m to allocate its channels, in the worst case, it will choose a different channel from every other node n, which results in $|min(C_l)| = sim\_min(C_l^{\neg m}) + 1$. Thus, $|min(C_l)| \leq (K_l - 1) + 1 \leq K_l$ for node l. So node l will not get into an invalid channel allocation situation in this case.

(b) Node m has *lower* priority than node l (i.e., $m \in lN_l^1$). In this case, invalidity can happen if either $min(C_l) > K_l$ or $sim\_min(C_m) > K_m$ (among all possible allocation at node l that connect l to its higher priority one-hop neighbours). According to the modified step 2 of our simulation algorithm, however, if there exists $m \in \{N_l^1 \cap lN_n^2\}$, as in case 2 (a) node n chooses its allocation such that $|sim\_min(C_l)| = |sim\_min(C_l)| + 1 \leq K_l$, thus $|sim\_min(C_l) \leq K_l - 1$. Therefore, $min(C_l) > K_l$ cannot be true. When it is the turn of node m invalid situation can still occur, only if $sim\_min(C_m) > K_m$. Node l first calculates $sim\_min(C_m^t)$ where $t \in \{hN_m \cap hN_l^2\}$. If there exists $k \in \{N_m \cap hN_l^2\}$, $sim\_min(C_m^{-l}) = sim\_min(C_m^t) + 1$. Condition $sim\_min(C_m^{-l}) \leq K_m$ is guaranteed to hold, until it is the turn of node l, because every node runs the same algorithm. Since $|min(C_l)| \leq K_l - 1$, there is at least one $s \in V_l$, such that $\{s \cap sim\_min(C_m^{-l})\} \neq \emptyset$. As such, $sim\_min(C_m^{-l}) \leq K_m$ will still be true and the theorem statement holds even in this case.

5.5 Evaluation

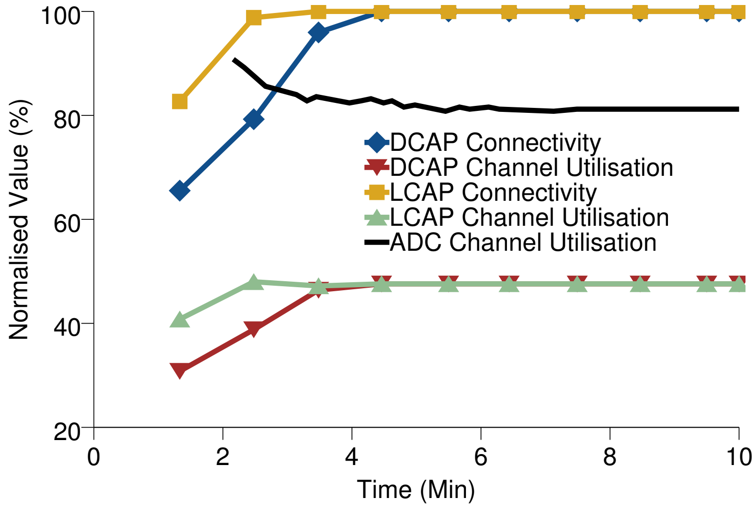
In this section, we compare LCAP to the deterministic alternative presented in this chapter. Our evaluation is via simulations. Similarly to LCAP, we use the QualNet [136] simulator and set the channel and physical layer parameters to reflect an urban mesh network scenario based on the earlier measurement work in [126]. Specifically, we use two-ray propagation model with pathloss exponent $\alpha = 3.3$, shadowing with standard deviation $\sigma_\varepsilon = 5.9$, omnidirectional antennae with 15dBi gain and placed at 10m height [126]. Transmission power and receive sensitivity values for different transmission rates are set referring to default values for commodity hardware (specifically, Atheros-based Compex WLM54AG mini-PCI cards used in our multi-radio mesh network testbed). For routing, we use the OLSR routing protocol [98] with the CATT metric [110]. CATT metric has been shown to outperform other routing metrics for multi-radio mesh networks, and additionally has certain attractive features such as isotonicity and a unified way of accounting both inter-flow and intra-flow interference. Experimental results have been averaged over several runs with different random seeds.

An important goal of DCAP, similarly to LCAP, is to efficiently distribute channels among the nodes in the network without hurting connectivity. To demonstrate this ability, we quantify channel utilisation and connectivity using the same performance metrics, we described in Section 4.6. Specifically, for channel utilisation we use the difference between the maximum and the minimum number of mesh interfaces assigned to any channel over all channels. A lower value of this measure implies better channel utilisation. This number is upper bounded by the total number of interfaces in the network. We use this bound to normalise utilisation and present it as percentage (see Figure 5.6(a)). We measure network connectivity as the percentage of links in a single channel network that are preserved by the multi-radio multi-channel channel allocation protocol.

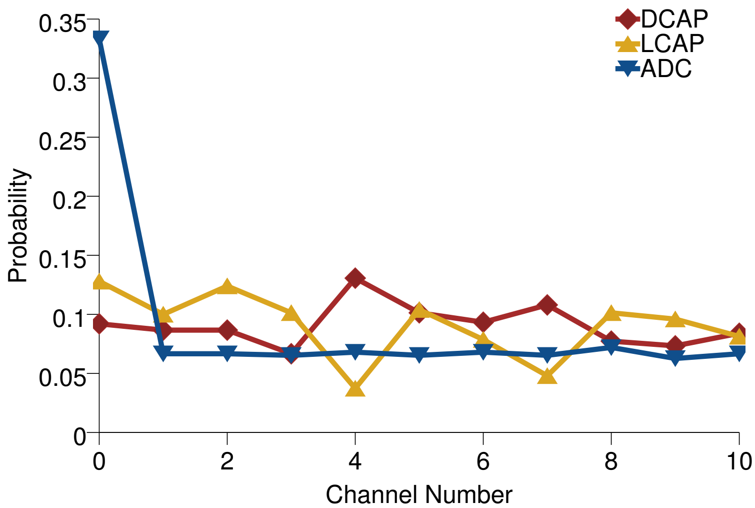
Figure 5.6 (a) shows the results corresponding to a 25-node 802.11-based multi-radio mesh network with nodes randomly distributed in a 1000mx1000m field. Each node is equipped with 3 mesh interfaces in the 5.470-5.725GHz band and there are 11 available channels. The figure shows that DCAP achieves 100% connectivity and similar interference to LCAP. Note that connectivity curve is not shown for the ADC protocol [24] (ADC was the protocol we used for comparative evaluation in Section 4.6 as it is the most practical solution in the literature that can also support diverse traffic patterns) as it is always connected due to the common channel. A key observation here is that DCAP converges slower than LCAP. This happens because DCAP imposes a priority-based ordering in channel allocation which prevents nodes from committing to a channel allocation until all higher priority nodes have converged and also because of the imposed conditions in LCAP that halt exploration. DCAP, however, still converges much faster than the ADC protocol. ADC converges slower, because channel assignment is performed via negotiations with 3-hop neighbours of a node over the common channel. Figure 5.6(a) shows that DCAP, similarly to LCAP, provides up to 40% improvement in channel utilisation over ADC. This is because both protocols do not require a common default channel (in ADC all nodes in the network share a common channel) and they manage to achieve diverse channel sets for interfering set of nodes. This is confirmed by the channel utilisation distribution plot in Figure 5.6(b), which shows that available channels are more evenly used with both DCAP and LCAP.

The improved channel utilisation of DCAP leads to its significantly better link layer throughput and delay performance compared to ADC and the single channel case (Figure 5.7(a, b)) for the same network scenario as before. These results are obtained by increasing packet generation rate on each link for fixed size (1KB) packets (the y-axis in the delay plot is in log-scale).

This study shows that DCAP and LCAP show similar performance behaviour with longer convergence time for DCAP. As explained earlier, this happens because of the imposed node prioritisation in the case of DCAP, which determines the order in which

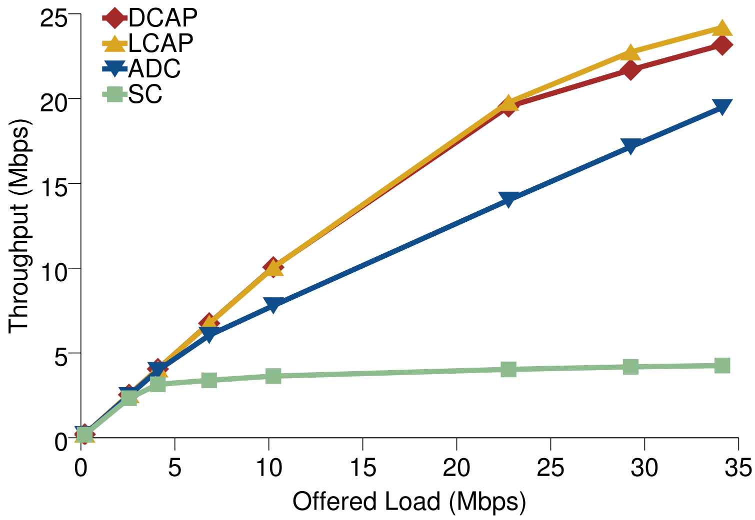


(a) Channel Utilisation and Connectivity

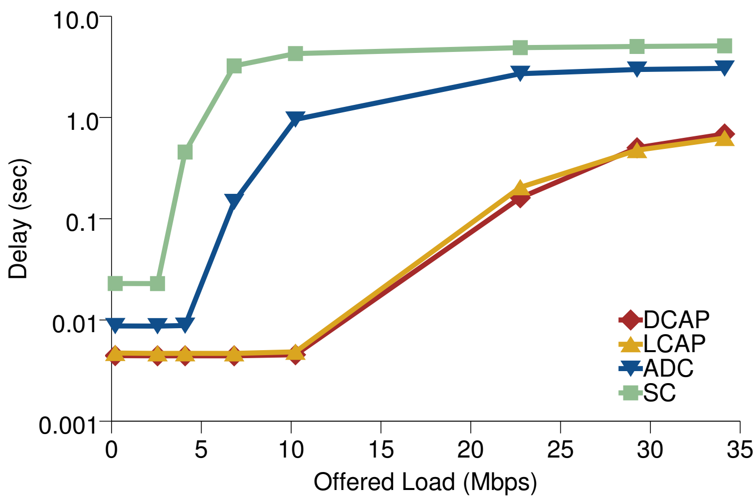


(b) Channel Utilisation Distribution

Figure 5.6: Channel utilisation, connectivity and protocol convergence with DCAP, LCAP and ADC protocols in a 802.11-based multi-radio mesh network.



(a) Aggregate Link Layer Throughput



(b) Average Delay at Link Layer

Figure 5.7: Link layer performance with DCAP and LCAP protocols in a 802.11-based multi-radio mesh network.

nodes can allocate channels to their interfaces. This restriction, however, is necessary to theoretically show convergence given the non-stationary nature of the network scenario. Moreover, LCAP allows exploration until a channel set that provides connectivity to all neighbours. If such stopping condition was not used, convergence time would increase significantly.

5.6 Conclusions

In this chapter, we have developed a deterministic alternative to the learning-based distributed multi-radio channel assignment protocol for mesh networks (LCAP) presented in Chapter 4. This alternative employs a node prioritisation scheme to guarantee convergence. This scheme, similarly to LCAP allows nodes to autonomously determine their channel allocation, but assigns priorities to nodes, which determine the order in which they can allocate channels to their interfaces. Key enabler of this approach is a novel neighbour discovery mechanism (also utilised by LCAP) that is based on channel quieting and allows neighbours to find each other even when not using a common channel. Simulation-based evaluation has shown that the deterministic alternative exhibits similar behaviour with LCAP and provides significant improvements over the state-of -the-art ADC protocol.

Chapter 6

Traffic-Aware Channel Width Adaptation in Long-Distance 802.11 Mesh Networks

6.1 Introduction

The remarkable success of WiFi (based on the IEEE 802.11 standard) has led to its use in originally unintended scenarios. Long-distance 802.11 mesh network scenario, the focus of this chapter, is one of those that is making a huge impact in the real world in helping bringing low cost Internet access to rural areas and developing regions (e.g., [11, 4]) by enabling affected communities and new Wireless Internet Service Providers (WISPs). The main impediment for provisioning broadband access in these regions is the deployment cost to serve either low density scattered communities or populations with limited incomes. It will take years to fully penetrate into these underserved regions offering limited profitability with broadband access technologies prevalent in urban areas (fibre, DSL, cable, 3G/4G) because of their high infrastructure costs. The long-distance 802.11 mesh scenario is also of interest as part of larger and scalable mesh networks in urban settings along the lines of the architecture considered in [137]. It also fits well with the needs of WISPs that span both rural and urban areas.

We consider a tiered 802.11 based mesh network model shown in Figure 6.1 applicable to rural and urban settings mentioned above. Two tiers are shown of which *our focus is on the topmost "directional backhaul" tier*. Nodes in the top tier could be separated potentially by long distances in the order of several Kms, hence their interconnection into a network is achieved with the use of a pair of high-gain directional

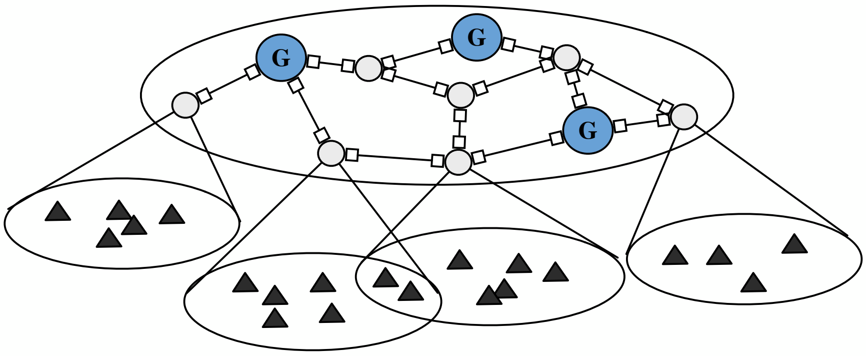


Figure 6.1: Multi-tier 802.11 based mesh network model.

antennae per link. As such this tier can be seen as a point-to-point wireless network. Some of these nodes in the top tier called gateway nodes connect to the wired Internet infrastructure (e.g., nodes labeled 'G' in Figure 6.1). While some nodes in the top tier only have the router role to forward data between other top tier nodes, several nodes additionally provide connectivity to the lower tier subnets using point-to-multipoint wireless links as illustrated. Therefore the latter set of nodes can be seen as traffic aggregation points in the directional backhaul tier. Each of the subnets in the lower tier could in turn be an omnidirectional mesh network with each node representing a rooftop mesh access point (in a village or urban neighbourhood). One can imagine an additional tier (not shown in the figure) connecting devices inside homes to a rooftop access point.

The directional backhaul tier in the network model is a specific type of multi-radio multi-channel mesh network. Each node in the backhaul has as many radio interfaces as the number of incident links (each connected to a directional antenna), and each of these links are assigned a different channel to avoid *side-lobe interference* that occurs with commonly used high-gain directional antennae [31] — non-negligible side-lobe energy from directional transmission on a link appears as interference to reception on other co-incident links, so such interference needs to be avoided. Moreover, for long-distance communication, besides directional antennae, higher radio transmit power may also be needed. Therefore, such long-distance point-to-point wireless communication is restricted by spectrum regulatory bodies to a few specified frequency bands with relatively higher transmit limits. The 5.8GHz frequency band is one such band and is available in most regions of the world. Consequently, the total amount of spectrum available for the directional backhaul tier is limited (e.g., 100MHz in the 5.8GHz band as opposed to more than 500MHz available for indoor wireless LAN used in the 5GHz unlicensed bands).

Since the directional backhaul tier serves as an intermediate data transport network between the wired Internet and large number of client devices in the lower tiers, the limited available spectrum needs to be managed judiciously and adaptively in response to varying traffic demands. Long-distance mesh deployments in practice tend to skirt around this important issue for lack of a suitable adaptive channel allocation framework. In fact, it is common to assign identically sized but possibly different channels to network links at deployment time and have them remain unchanged (e.g., [138]) or even use only a single channel for the whole network (e.g., [31]).

In this chapter, we aim to fill this void by viewing *channel width* as a knob to enable traffic-aware channel allocation in long-distance 802.11 based mesh networks, i.e., focusing on the directional backhaul tier in Figure 6.1. The intuition behind our approach is as follows: since the total amount of available spectrum is limited, adapting to spatio-temporal variations in traffic demand can be achieved by allocating "wider" channels to links with higher demand by taking spectrum away from links with less demand. In other words, greater capacity is assigned to heavily utilised links, thereby benefiting the flows passing through them. Following the work of Chandra et al. [29] who first demonstrated experimentally the throughput, range and energy efficiency benefits of channel width adaptation in an isolated 802.11 link scenario, other research efforts have since highlighted the value of channel width adjustment in 802.11 wireless LANs [33, 139]. To the best of our knowledge, we are not aware of work that considers channel width adaptation in the context of long-distance mesh networks.

Our contributions are as follows: (1) We present a graph theoretic formulation of the traffic-aware channel width assignment problem in long-distance mesh networks and show that it is NP-complete (Section 6.2). (2) We develop a polynomial time algorithm for assigning channel widths to links based on their relative traffic volume; the algorithm ensures that every node gets a valid channel allocation (Section 6.3). (3) Our simulation based evaluation of the proposed algorithm using real network topologies shows that it delivers substantial improvements in performance (40-70% throughput improvements) from adapting the channel allocation in response to variations in spatio-temporal traffic demands (Section 6.4).

6.2 Model and Problem Formulation

As stated at the outset, we consider a multi-tier 802.11 mesh network scenario as shown in Figure 6.1 and our focus in this work is on the topmost directional backhaul tier, especially keeping the rural wireless Internet access use case in mind. We model the network topology of the directional backhaul tier as an undirected graph, $\mathcal{T} = (\mathcal{N}, \mathcal{L})$. Each node n at the backhaul tier is equipped with $K_n (K_n \geq 1)$ 802.11 wireless interface cards, each attached to a directional antenna forming an end of a long-distance point-to-point wireless link with a neighbouring node. We use the notation $n_p, 1 \leq p \leq K_n$ to refer to the p^{th} interface at n. Note that K_n is equal to the number of point-to-point wireless links incident at node n.

We use (n,m) to denote the logical point-to-point link between two nodes n and m. And we use (n_p, m_q) to denote the actual physical bidirectional point-to-point link between the p^{th} interface of node n and the q^{th} interface of neighbour m. When we need to refer to the direction of a link, we will use the notation $n_p \rightarrow m_q$ to refer to the direction from n to m. Note that, in practice, each link in a long-distance 802.11 mesh network is determined at deployment time by pointing a pair of directional antennae located at two mast sites towards each other. These links remain fixed when the network goes into operational stage; our focus in this work is solely on adapting the "channel" used by a link based on the traffic volume measured over it.

We use $\mathcal{F}$ to denote the total available spectrum. In the case of widely used 5.8GHz band, $\mathcal{F}$ = 100MHz, ranging from 5.725GHz to 5.85GHz with small guard bands on either end[1]. This band can accommodate 5 20MHz channels (the default channel width in 802.11a) — channel numbers: 149, 153, 157, 161 and 165. The same band can be used to accommodate up to 2 40MHz channels. We assume the set of available channel widths to be 5, 10, 20, 40 based on what is currently supported by commodity 802.11 hardware.

A channel in our context is defined by the tuple $ch = < f_c, w >$, where f_c represents the center frequency and w the width of the channel taking one of the 4 values just mentioned — frequencies of ch range from $f_c - w/2$ to $f_c + w/2$. For example, 802.11a channel number 149 corresponds to a 20MHz channel centered at 5.745GHz. Given $\mathcal{F}$, the range of frequencies that fall within the spectrum and available channel widths, several channels can be realised by choosing various center frequencies and widths. We can alternatively look at ch using its start frequency, $f_s = f_c - w/2$ and width w;

[1] 10MHz at the lower end and 15MHz on the upper end.

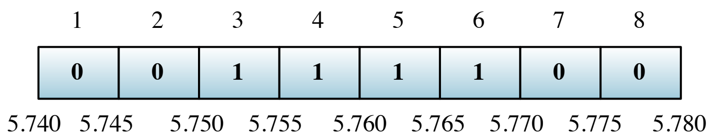


Figure 6.2: An example to illustrate *Spectrum Allocation Map (SAM) of a node.* In this example, the total spectrum available is assumed to be 40MHz, which results in 8 5MHz wide blocks. Each 5MHz wide spectrum block is shown using a box with a block identifier above the box and start frequency of the block underneath. Based on SAM of the node (i.e., the values shown inside boxes), blocks 3-6 are used while the rest are free. Assuming the node has only one link and all the used blocks correspond to the channel allocated to that link, the *block assignment (channel) for the link* is: $ch = < f_s, w > = < 5.75GHz, 20MHz >$ with center frequency, $f_c = 5.76GHz$.

in this case, ch ranges from f_s to $f_s + w$. We use the notation $ch_{(n_p,m_q)}$ to refer to the channel assigned to the link (n_p, m_q). Note that $ch_{n_p \to m_q} = ch_{m_q \to n_p}$

For convenience, we view the given spectrum as a sequence of atomic 5MHz wide *blocks*. For example, when the available spectrum is 100MHz, we have 20 5MHz wide blocks. If S denotes the number of blocks[2] (20 in the example), then we assume that $S \geq 2 * \Delta(\mathcal{T}) - 1$, where $\Delta(\mathcal{T})$ is the maximum node degree in $\mathcal{T}$. This is quite a reasonable assumption since a node in the backhaul directional tier typically has at most around a handful of incident point-to-point wireless links. The relevance of this assumption will become clear later on in Section 6.3.

We now define a *spectrum allocation map for each node n:* $\mathtt{SAM}_n$ that represents the spectrum usage of the interfaces at n. Specifically, this map is a sequence of bits associated with the blocks, where a bit is set to 1 if the corresponding block is occupied by some interface of the node. Otherwise, it is 0. Figure 6.2 shows an example. Using the notion of blocks, the channel assigned to a link (n_p, m_q), $ch_{(n_p,m_q)}$, can be seen as contiguous and identical set of blocks in $\mathtt{SAM}_n$ and $\mathtt{SAM}_m$; we refer to such assignment of contiguous set of blocks to a link (n_p, m_q) as the *block assignment for the link*, denoted by $\mathtt{BA}_{n_p,m_q}$ (see Figure 6.2 for an example).

Having described what a channel means in our model, we now introduce the three key constraints in our channel allocation problem.

[2]Henceforth, we just use the term 'block' as a shorthand for '5MHz wide block'.

Side-lobe interference constraint:

$$BA_{n_p,m_q} \cap BA_{n_r,l_s} = \emptyset; n,m,l \in \mathcal{N}, \exists(n_p,m_q), \exists(n_r,l_s), p \neq r, m \neq l \qquad \textbf{(C1)}$$

This constraint essentially requires that any two incident links at a node are assigned different *non-overlapping* channels[3].

Minimum channel constraint:

$$ch_{n_p,m_q} = < f_c, w > \ s.t.\ w \geq 5 \ ; \ \exists(n_p,m_q) \qquad \textbf{(C2)}$$

This constraint requires that each link is assigned at least a 5MHz wide channel (i.e., a block). This is to make sure that network topology always remains intact with each link having a usable channel, which can be used for exchanging at least control traffic (e.g., routing messages).

Total spectrum constraint:

$$0 < \sum_{m,\exists(n_p,m_q)} ch_{n_p,m_q} \leq \mathcal{F} \qquad \textbf{(C3)}$$

This constraint makes sure that channels allocated to incident links at a node do not exceed the total spectrum available.

Before going to the objective function, we need to model flow (traffic) on a link and the link capacity based on the channel allocated to it. Let f_{n_p,m_q} denote the total traffic flow passing through a link (n_p,m_q): f_{n_p,m_q}[4] $= f_{n_p \to m_q} + f_{m_q \to n_p}$. The capacity of a link (n_p,m_q) denoted by C_{n_p,m_q} is dependent on the channel it is allocated and link characteristics (link distance, etc.). Channel width and best bit-rate (modulation and coding scheme) supported by the link are inter-dependent, and together determine the raw link capacity, C_{n_p,m_q}[5].

[3]Here we make the simplifying assumption that side lobe interference can be avoided if co-incident links are assigned channels with frequency ranges that do not overlap. We can extend it to incorporate a sophisticated non-binary model of interference between any two co-incident links based on the work by Angelakis et al. [140, 141] that takes into account antenna radiation patterns, inter-antenna distance, separation between center frequencies of channels assigned to the two links and channel widths. We elaborate more on this latter in Section 6.5.

[4]A lightweight sampling method to continually estimate the total traffic flow on a link based on MRTG and SNMP is described in [142]

[5]Prior work [143, 144] has shown that typical rural long-distance wireless links, the particular focus of our work, experience negligible link quality variations. In such cases, we only need to consider interaction between channel width and bit-rate to estimate link capacity based on [29] for a given link quality (that can be obtained via measurement). As a corollary, bit-rate would also be stable in the fixed width case.

Objective function: our objective can be stated as *minimising the maximum excess link load across all links in the network* subject to constraints **C1**-**C3** at each node, where excess link load of a link (n_p, m_q) is defined as $max(f_{n_p,m_q} - \delta * C_{n_p,m_q}, 0)$. Here δ models the fraction of raw link capacity effectively available at network layer after discounting overhead related to link and physical layers (e.g., headers, inter-frame spaces) as well as routing control traffic overhead. For example, if 20MHz channel width can support 54Mbps physical layer bit-rate, then effective achievable capacity above the link layer is at most 30Mbps dependent on frame length [145]. Assuming some portion of it (say 10%) is consumed by control traffic, the maximum effective capacity is 27Mbps, leading to a δ value of 0.5.

The intuition behind using this objective function is to evenly distribute the available spectrum resource among links based on their traffic demands so that capacity assigned to a link matches its load as closely as possible.

We refer to the decision problem equivalent of the above optimisation problem as *Channel Width Assignment for MinMax Excess Link Load*, which can be stated as follows: Is there a channel width assignment such that the maximum excess link load $\leq$ B (where B is a non-negative integer)?

Theorem 1. *The* Channel Width Assignment for MinMax Excess Link Load *decision problem as stated above is NP-complete.*

Proof. A channel width assignment can be verified in polynomial time, thus the problem is clearly NP.

The rest of the proof is by restriction. We show that the above channel width assignment problem contains the minimum edge colouring problem (also called the minimum chromatic index) - a known NP-complete problem - as a special case [146].

Specifically, we show that a specific instance of the problem at hand is identical to the minimum edge colouring problem. For this instance, the following constraints hold: (i) only one channel width is allowed (5MHz), (ii) the total amount of spectrum available = maximum node degree * 5MHz, (iii) $f_{n_p,m_q} << \delta * C_{n_p,m_q}$, for all links (n_p, m_q) when using a 5MHz wide channel, and (iv) the graph is chosen to be identical for both problems and bound for number of colours (chromatic index) for the edge colouring is set to the maximum node degree.

The above specified instance of our problem is identical to the minimum edge colouring problem, which completes the proof. □

Note that using the above stated objective function and per-node constraints **C1**-**C3**, we can easily formulate this problem as a mixed integer linear program for obtaining a lower bound on the optimum.

6.3 Channel Width Assignment Algorithm

In this section, we describe a polynomial time greedy heuristic for traffic-aware channel width assignment in long distance 802.11 mesh networks.

In our approach, channel allocation is performed independently from routing but influences it and vice versa. Moreover, channel reallocation is done at a relatively slower timescale than routing. This is because channel width changes are more disruptive as each such change at least requires endpoints of a link to reconfigure (and even restart) their corresponding wireless interfaces. Exact frequency of channel width adaptation is a tradeoff between responsiveness to traffic dynamics and keeping network disruption and overhead low; we will discuss this issue further in Section 6.5. Keeping routing and channel allocation independent has the advantage that any routing protocol can be used on top of the channel width adaptation algorithm. But, since channel width adaptation involves overhead and cannot be done on a fast timescale, a traffic adaptive routing protocol such as [147, 148] would be an ideal companion for the channel allocation algorithm by helping between channel iterations. Some network deployments, however, may not plan for enough redundancy in the topology for cost reasons, making the complexity of using a traffic adaptive routing protocol questionable; in such cases, a single path routing protocol can be used with the burden of traffic adaptivity shifted largely to the channel allocation algorithm. For our simulation based evaluations, we have implemented P-STARA [147] and use it as the default routing protocol.

Before describing the algorithm, we introduce the concepts of *feasible* and *valid* channel allocations. A feasible channel allocation for a node n is an allocation that respects constraints **C1**-**C3** (see Section 6.2). As an example, consider node A in the example network shown in Figure 6.3 and suppose that the total amount of available spectrum is 40MHz. Also suppose that interface 1 (link to G) at A has a higher priority than interface 2 at A (link to C) — setting of node and link priorities is discussed shortly. Under these assumptions, feasible channel width combinations for node A are shown in Table 6.1 in the order of decreasing preference[6]. Not all of these com-

[6] Relative preference among channel width combinations at a node can be determined, for example,

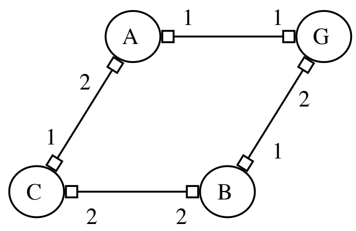


Figure 6.3: An example network.

binations are valid depending on when node A gets to do its channel allocation with respect to its neighbouring nodes. To see this, consider the network in Figure 6.3 again. Suppose that node G allocates a 20MHz channel to its interface numbered 1, thus colouring[7] link to A and corresponding interface at A. This colouring decision by G immediately reduces the possible width combinations to the set shown in Table 6.2. Moreover, depending on where channel for link (G_1,A_1) lies in the spectrum, the possible width combinations may reduce even further. If the $\texttt{SAM}_A$ after link (G_1,A_1) is allocated 20MHz channel looks like in Figure 6.2, then the combination (1) in Table 6.2 is no longer possible. In the worst case, for this example, depending on the width and center frequency used by node G for link (G_1,A_1), A may not have a possible width combination that ensures a minimum channel for its remaining interface (numbered 2, link to C). Thus, node G while colouring link (G_1,A_1) should make sure that A has at least a block for its remaining uncoloured interfaces. A valid channel allocation then is a channel allocation that is not only feasible from a node's perspective but also is consistent with channel allocations at other nodes.

Based on the above, we seek a channel allocation that results in a valid channel width combination at every node in the network. Before going to the actual algorithm, we need to introduce two more concepts: *guard block assignments (`gBAs`)* and *guard spectrum allocation maps (`gSAMs`)*. Recall from constraint **C2** in Section 6.2 that we require each link in the network to be assigned at least a minimum channel (block). We ensure that this constraint is met at all times (i.e., prior to, during and after completion of channel allocation algorithm execution) via `gBAs` and `gSAMs`. A valid block is identified for each link at the initialization stage of the algorithm as described below

by computing a function (e.g., product, sum) of *link utilisations* with each combination and then ranking the combinations based on their function values. Each link's utilisation is computed by taking the ratio of its load to capacity, the latter based on channel width corresponding to the link in the chosen width combination. We use product of link utilisations as the default method in this work.

[7] Henceforth we use the terms of colouring and channel allocation interchangeably.

	Interface 1	Interface 2
(1)	20	20
(2)	20	10
(3)	20	5
(4)	10	20
(5)	10	10
(6)	10	5
(7)	5	20
(8)	5	10
(9)	5	5

Table 6.1: Feasible channel width combinations for node A in Figure 6.3 under the assumption that A_1 has a higher priority than A_2.

	Interface 1	Interface 2
(1)	20	20
(2)	20	10
(3)	20	5

Table 6.2: Valid channel width combinations for node A in Figure 6.3 after its interface 1 is coloured by node G with a 20MHz channel.

in step 1. The block so identified for a link is referred to as the `gBA` for that link. The `gSAM` of a node is a collective representation of `gBAs` of all its incident links. Like `SAMs`, `gSAMs` are also bit-vectors. After every link gets a `gBA`, it is straightforward to determine node `gSAMs`. For example, consider the network shown in Figure 6.3 and suppose that the total amount of available spectrum is 40MHz with the block identifiers as in Figure 6.2. A possible (though not optimal) `gBA` assignment for links G-A, A-C, C-B and B-G is blocks 1, 2, 3, 2 respectively. For that assignment, $\texttt{gSAM}_A$ is $< 1,1,0,0,0,0,0,0 >$, $\texttt{gSAM}_B$ is $< 0,1,1,0,0,0,0,0 >$ and so forth. The `gBA` assignments can be seen as proactively *reserving* a minimum sized channel for each link that results in a valid channel allocation to start with. Later on when the algorithm finds a larger width channel that is commensurate with the load on a link and does not compromise validity of the channel allocation, the `gBA` for that link is *released* in exchange for a valid block assignment corresponding to the larger width channel; `gSAMs` and `SAMs` of the end nodes of that link are also accordingly updated then.

Our channel width assignment algorithm consists of the following sequence of steps:

1. *Initialize `gBAs` and `gSAMs`:* We do this by applying an edge coloring heuristic on the network, viewing each individual block in the given spectrum as a potential color. Even if this coloring is done greedily we are guaranteed to have a proper edge coloring given our assumption in Section 6.2 about the relationship between maximum degree of the network ($\Delta(\mathcal{T})$) and the total number of spectrum blocks (S). See [149]. Our assumption and choice of the heuristic are driven by the fact that greedy edge coloring can be easily implemented in a distributed manner [150].

2. *Assign node and link priorities based on traffic load:* The rest of the algorithm is also greedy, driven by priorities assigned to nodes and links. Node priorities determine the order in which nodes allocate channels to their interfaces (incident links) — higher a node's priority sooner its turn for channel allocation. Specifically, the priority of a node n, P_n is determined as follows:

$$P_n = \sum_{m,\exists(n_p,m_q)} f_{n_p,m_q} \tag{6.1}$$

   The above equation favours nodes with larger traffic volume when assigning priorities since the goal of the algorithm is to adapt based on traffic demands.

Priority of a link (n,m) is set to the average of the priorities of end nodes, i.e., $P_{n_p,m_q} = avg\{P_n, P_m\}$.

3. *Steps taken when a node x is the next highest priority node to be processed:*

   (a) Find the *list* of feasible width combinations at node x taking into account priorities of incident links at x and order the combinations based on their relative preference as described earlier in this section (see Table 6.1 and corresponding text).

   (b) Prune the list from the previous step (3a) to retain only potentially valid width combinations. Depending on the priority of node x relative to its neighbours, some of its incident links may already be coloured by higher priority neighbours. In such a case, some of the combinations from (3a) may not be valid causing their removal from the list. Table. 6.2 illustrates this step.

   (c) Find a valid channel width combination from the remaining list from step (3b) considering combinations in the order of preference and stopping when a valid combination is found. First check for validity of a combination by verifying if the widths in the combination for uncoloured incident links (x, y) at node x can be satisfied based on the current `SAMs` of x and all such neighbours y while not violating constraints **C1** and **C3**. If the first check is successful then the combination is checked for violation of `gBAs` for uncolored incident links (y, z) z $\neq$ x of neighbours y. If both these checks are successful, then search for a valid combination is successful. At that point, uncolored links of x are colored based on the combination found and block assignments for those links and `SAMs` of x and affected neighbours y are updated. Moreover, `gBAs` for the newly colored links of x are released and `gSAMs` of end nodes accordingly updated. Note that this step will result in a valid combination being found because the combination corresponding to `gBA` assignment for the uncolored links of x prior to this step is always among the combinations searched during this step. Before finishing this sub-step, node x tries to move the existing `gBAs` to increase flexibility of remaining channel width assignments.

At the end of the execution of the above algorithm, we are guaranteed a valid channel allocation because validity of the channel allocation is maintained at each step of the algorithm. The fact that the algorithm in fact terminates and runs in polynomial time is also evident from the above description. At termination, `gBAs` for all links are released and `gSAMs` of all nodes become null vectors. Theoretically characterising the approximation guarantee of this algorithm is an issue for future work. We discuss the practical aspects later in Section 6.5 and the distributed operation later in Chapter 9.

6.4 Evaluation

In this section, we evaluate the effectiveness of our channel width assignment algorithm described in the previous section using simulations to understand its ability to adapt to spatio-temporal variations in traffic demands. Our goal is to study the benefit of adapting channel width across a diverse set of scenarios in terms of effective and fair allocation of the limited spectrum resource. Since we are not aware of channel width assignment algorithms for long-distance mesh networks, we conduct this study in comparison with a variant of [114] that does (the more common) undirected edge colouring. Within this benchmark, we consider several alternatives each based on a different fixed size channel width, starting from 5MHz (minimum sized channels in current 802.11 systems). We focus on rural wireless access network scenarios because they are a compelling real-world use case for long-distance 802.11 mesh networks.

We use the QualNet simulator that has a built-in detailed model for standard 802.11 CSMA/CA MAC protocol. We have added the variable channel width functionality to QualNet and validated it against the results reported in [29]. We use the Traffic-Gen application in the simulator for flexible realisation of different traffic patterns with variable session durations and traffic loads. We use 1KB packets throughout. In all our experiments, we set the total available spectrum to 100MHz to match with the commonly used 5.8GHz band. For the bit-rate (modulation and coding scheme), we use 6Mbps unless mentioned otherwise. For the adaptive channel width case, the channel width assignment algorithm is executed periodically. Unless otherwise specified, we use a simulation length of 25 minutes with traffic flows starting after one minute.

For our evaluations, we use three real long-distance wireless network topologies:

1. Aravind telemedicine network in Southern India [4] consisting of 9 backhaul wireless nodes. Figure 6.4 shows the topology of this network — node 3 is the hospital situated in a town and nodes 1, 5, 6, 7 and 9 are remote vision centers.

2. Connected Communities (ConCom) network [57] is a relatively large broadband

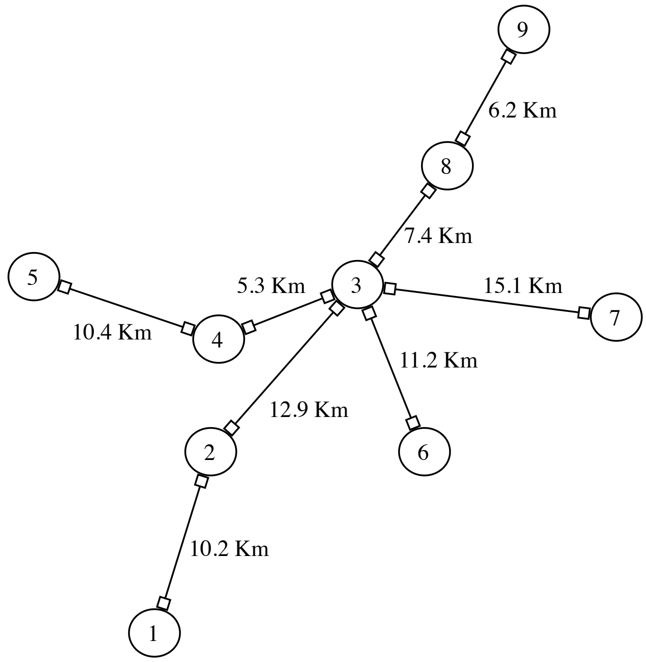


Figure 6.4: Aravind telemedicine network topology [4].

wireless access network covering the Western Isles of Scotland with a population around 26,000 spread across 11 islands and span of over 200Km. This network consists of 34 backhaul sites interconnected by point-to-point wireless links with widely different link lengths. It provides connectivity to public buildings (e.g., schools, community centers) as well as residential users.

3. Tegola consisting of 5 backhaul wireless nodes is a network we have deployed in rural Scotland [59]. Though originally intended as a research testbed, it currently also serves as a community wireless network connecting real users to the Internet. We have used this topology for our preliminary evaluations, but the results reported in this work consider the other two relatively larger network topologies.

In our paper [151] we considered *a key aspect that motivates the need for adaptive spectrum management mechanisms, i.e., the spatio-temporal variability in traffic seen by different backhaul nodes in a long-distance wireless mesh network*. The existence of variability in real deployments have been studied and illustrated using the traffic traces from two backhaul sites in the Tegola network. In the following, we examine the performance of our channel width adaptation algorithm against such spatio-temporal traffic variations.

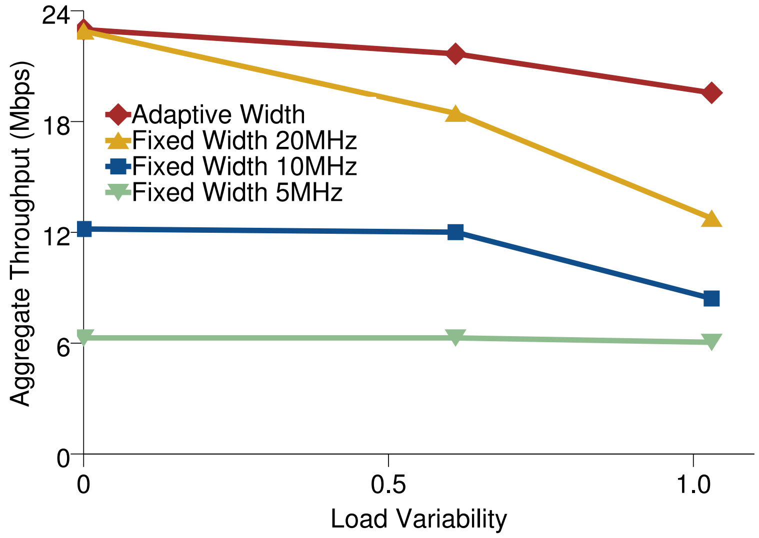
6.4.1 Spatial Traffic Variation

In the first experiment, we study the impact of spatial variation in traffic load. For this we consider the Aravind topology with 5 traffic flows from each of the edge nodes (1, 5, 6, 7, 9) to the middle node (3). We uniformly vary the traffic load across the flows while keeping the mean traffic load constant around 5Mbps. Figures 6.5 and 6.6 show the results for aggregate throughput, average end-to-end delay and packet delivery variation across flows as a function of load variability. Load variability is essentially the coefficient of variation[8] calculated using loads of individual flows. Packet delivery variation across flows shown in Figure 6.6 is also a coefficient of variation but calculated using the packet delivery ratios of individual flows. For the Aravind network topology (as well as the ConCom topology), all links cannot be assigned 40MHz channels given the limited total amount of spectrum (100MHz), so only 20MHz, 10MHz and 5MHz fixed width allocations are shown as alternatives to adaptive channel width. As expected, the opportunity for adapting channel width is marginal when the traffic is uniform, while significant gains are achieved as load becomes more variable, resulting in throughput improvement around 53%. Improvements in variation of packet delivery across flows (Figure 6.6) at high load variability are even more remarkable as all the fixed width cases fail to support flows with high load. The big drop in delay for 5MHz fixed width case (Figure 6.5(b)) can be explained by the fact that most of the high delay packets corresponding to high load flows are dropped. This is also reflected in the large variation of packet delivery across flows for this width in Figure 6.6. For this experiment, we also determined the optimal channel width allocation through exhaustive search and found that the optimal widths are identical to the widths obtained using our heuristic algorithm. Computing the optimal solution for the later experiments involving temporal variation and larger network scenario, however, proved to be prohibitively expensive.

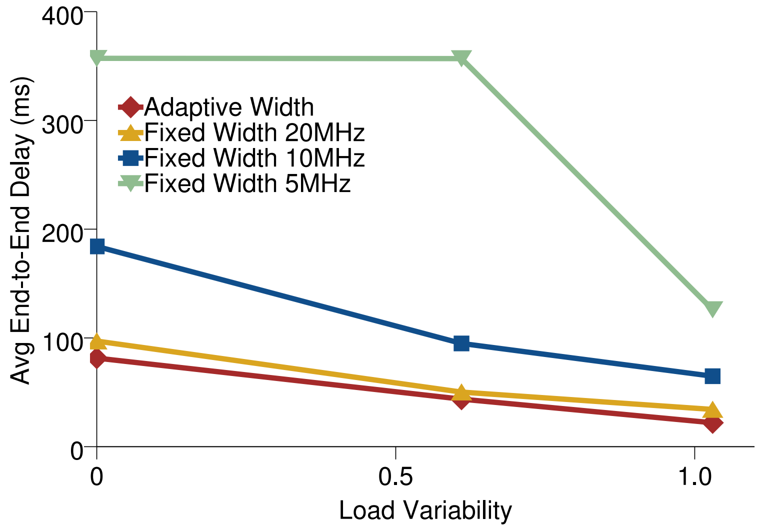
6.4.2 Temporal Traffic Variation

We now consider the impact of temporal variation in traffic demands, again using the Aravind network topology. For this experiment, we consider three flows (5-3, 6-3 and 7-3), each having the same load around 10Mbps but varying in session durations. Figure 6.7 shows the throughput and delay results as a function of session duration variability, computed as the coefficient of variation using session durations of individual

[8] The ratio of standard deviation to the mean.



(a) Throughput



(b) End-to-End Delay

Figure 6.5: Throughput and delay performance of the CWA algorithm with spatial variation in traffic demands (variable load across flows) for the Aravind network topology.

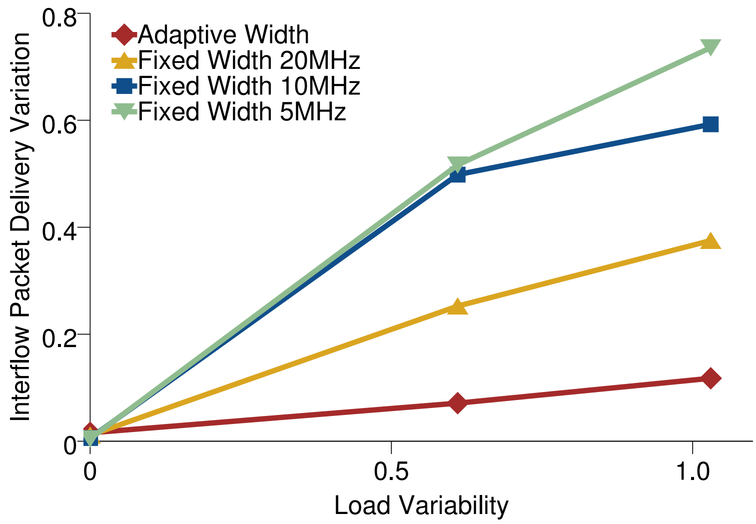


Figure 6.6: Inter-flow packet delivery variation with spatial variation in traffic demands (variable load across flows) for the Aravind network topology.

flows. Mean session duration was kept constant at 25 minutes for all the data points. Like in the previous spatial variation experiment, we find that adaptive width offers greater gains as temporal variability increases (up to 45% improvement in throughput) by adaptively reallocating spectrum as flows come and go.

6.4.3 Larger Network Scenario

We now examine the benefit of channel width adaptation in a larger network using the ConCom topology. For the traffic pattern, we consider a common use-case for the ConCom network, i.e., tele-commuting/tele-education. Sites connecting office buildings and schools act as traffic sources (8 in number) while traffic destinations for the flows are randomly distributed from among the remaining sites. We keep the load of each flow constant at around 10Mbps and increase the number of flows. Results are shown in Figure 6.8. We observe that increasing the number of flows has the effect of making the traffic pattern more uniform, limiting the benefit of adaptive width. When the traffic pattern is non-uniform and less constrained by the amount of available spectrum (left half of the figure), adaptive width results in throughput improvement over 70% compared to the best fixed width alternative. The drop in delay from midway (especially for fixed width cases) seen in Figure 6.8(b) is a result of packets with large delays getting dropped as contention increases and queues build up.

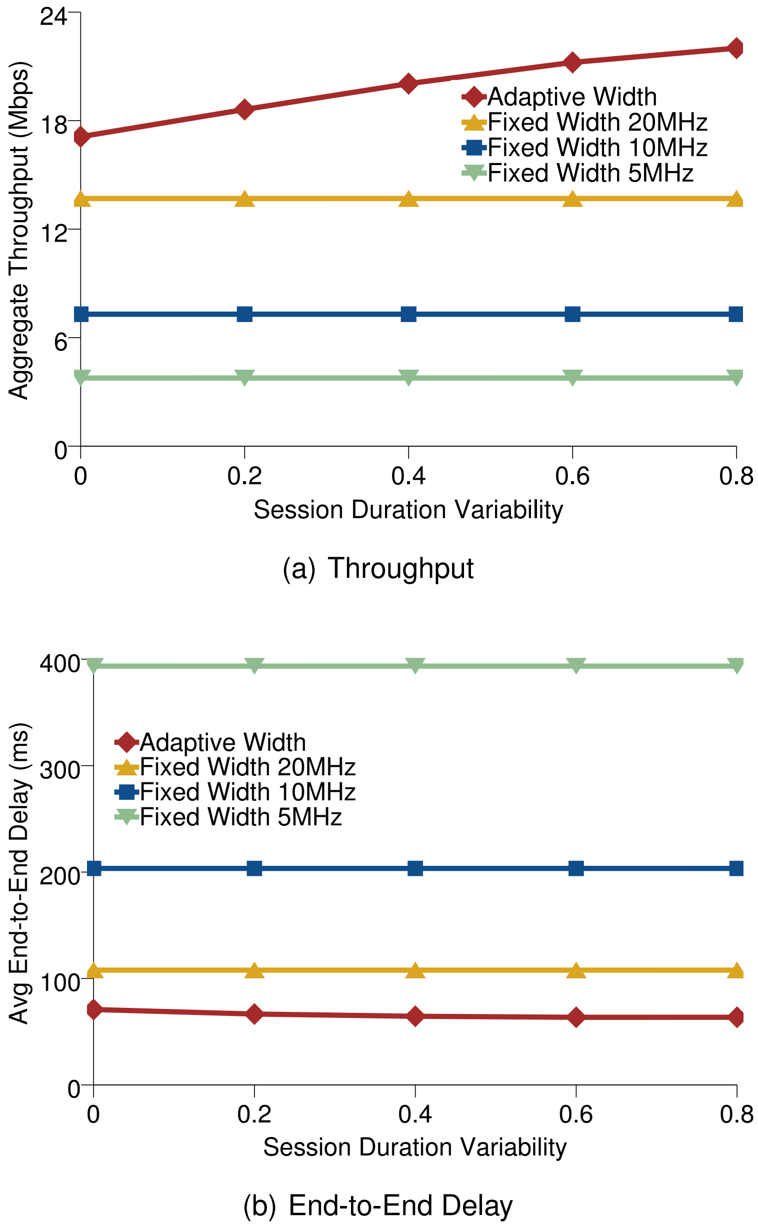
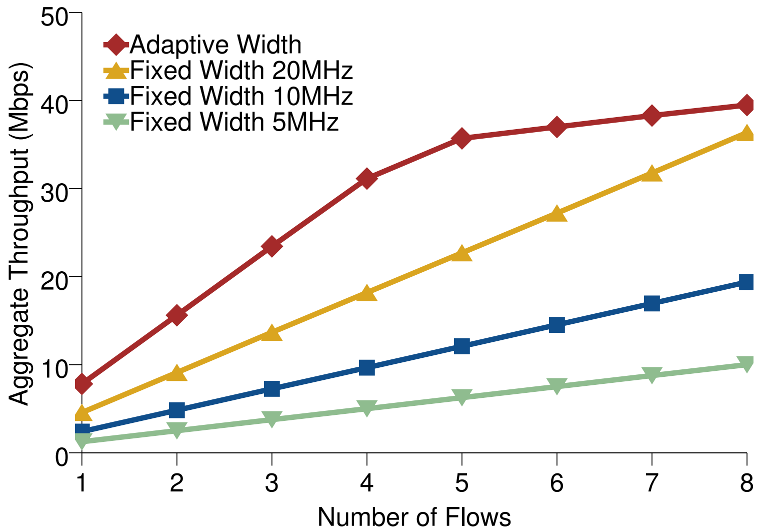
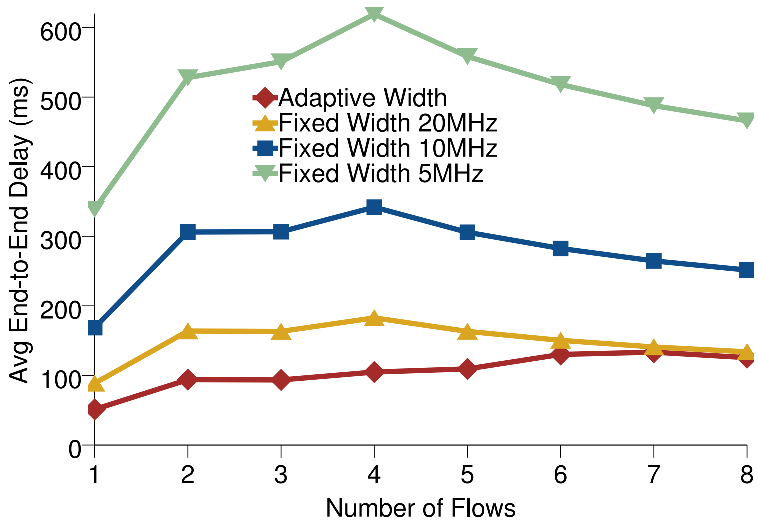


Figure 6.7: Performance impact of temporal variation in traffic demands (variable session durations across flows) for the Aravind network topology.



(a) Aggregate Throughput



(b) End-to-End Delay

Figure 6.8: Performance impact from using adaptive channel width for the larger Con-Com network and randomly distributed flows with increasing number of flows.

6.4.4 Effect of Bit-Rate

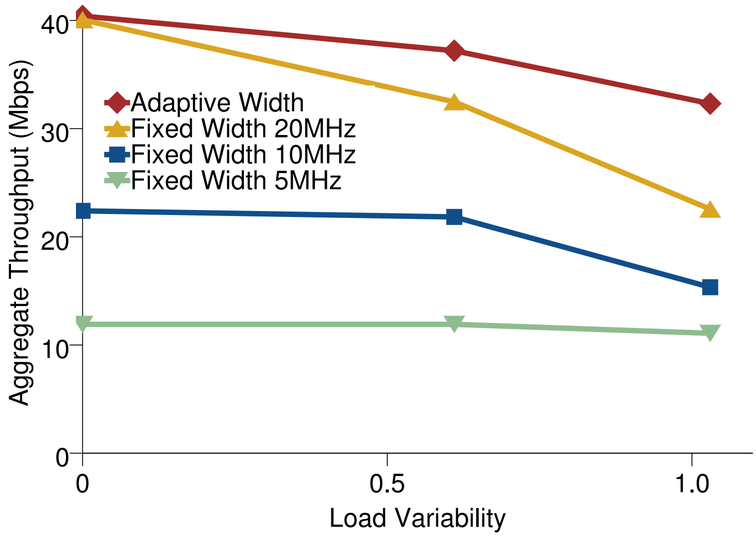
We also study the interaction between bit-rates and channel widths and their net effect on performance using the Aravind topology and considering two other bit-rates for the spatial variation experiment: 12Mbps and 24Mbps. The choice of these rates is based on the fact that 24Mbps is the maximum bit-rate that can be supported by link 3-7 for 40MHz. While the results shown in Figure 6.9 qualitatively are similar to those in Figure 6.5, latter corresponding to 6Mbps bit-rate, improvements from using adaptive channel width differ because the opportunity provided by use of increased widths somewhat reduces with increased bit-rates as also shown experimentally in Figure 2 of [29].

6.5 Discussion

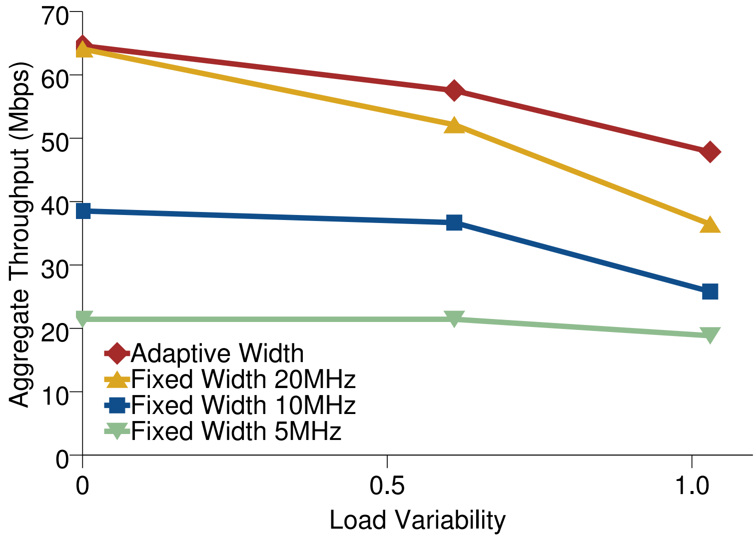
For small to medium scale scenarios like the ones considered in this work, channel width adaptation can be carried out in a centralised fashion at a gateway node. Gateway in such an implementation acts as a channel allocation server with each node periodically reporting measured link level traffic volume information to the server. Every adaptation interval, the channel allocation server uses that information and recomputes the new channel allocations for each link. The server then communicates them back to the network one node at a time, waiting for confirmation from the node that it completed channel reconfiguration locally through coordination with its neighbouring nodes. This approach to implementing traffic-aware channel allocation is practical as demonstrated earlier for the omnidirectional mesh scenario by Ramachandran et al. [9].

Concerning the length of the adaptation interval itself, it depends on the traffic dynamics as well as network overhead for channel reallocation. Due to the aggregation of traffic from individual users at the backhaul nodes, the variability of traffic seen at a backhaul node over time is slower in the order of several minutes; this observation is also confirmed by our traffic traces from the Tegola network (see paper [151]). Also in rural wireless networks such as Tegola, aggregate traffic patterns are reasonably predictable with highs and lows around the same time each day. This could be exploited to schedule global channel width adaptations a priori.

For larger networks like [138], distributed implementation is required for scalability reasons. This can be achieved via an algorithm which consists of the three phases corresponding to the three high level steps described in Section 6.3. A more detailed



(a) Bit-Rate=12Mbps



(b) Bit-Rate=24Mbps

Figure 6.9: Effect of inter-dependence between channel width and bit-rate on performance for the case of spatial traffic variation with Aravind network topology.

description of the distributed implementation of our proposed channel width assignment algorithm in Chapter 9.

The channel width assignment algorithm can be extended to consider inter-channel separation as a means to minimise adjacent channel interference as follows: We define the minimum required separation distance between any two incident channels ch1 and ch2 as a number of 5MHz blocks (i.e., $(f_{ch2} - w_{ch2}/2) - (f_{ch1} + w_{ch1}/2) \geq 5 * d$, where $f_{ch2} > f_{ch1}$ and d is the separation distance). We refer to these blocks as the *padding blocks*. Each link is then allocated the required channel for transmission as well as the *padding blocks*, which are chosen to the right of the *transmission channel* (except when the transmission channel lies at the upper end of the available spectrum, in which case no padding channel is necessary). Although this requires a larger number of total available blocks to ensure valid channel allocation, one block channel separation between co-incident links may be sufficient. This, however, should be experimentally validated by considering other factors, such as antenna separation.

Finally, the effect of frequency-dependant attenuation, which increases as the carrier frequency increases can be considered in the proposed algorithm as follows. As attenuation increases, the signal-to-noise plus interference ratio, which determines whether a packet is correctly decoded at the receiver, decreases. This causes links operating at higher frequencies to use lower data rates, which restricts the available capacity. To capture this, we consider the effect of frequency on the raw capacity in our algorithm by measuring the effective data rate at each width using the lowest frequency in the available spectrum and use a coefficient to scale down capacity as the frequency increases. Moreover, the feasible width combinations at a node are ordered based on their relative preference assuming the center frequency of each width is the lowest possible frequency (step (3.a) of our algorithm in Section 6.3). Then, as each combination is checked for its validity (step (3.c)), its preference is scaled down based on the part of the spectrum each width actually occupies. At the end, a set of valid width combinations is formed among which the node chooses the one with the highest preference.

6.6 Conclusions

In this work, we have studied the traffic-aware channel allocation in long-distance 802.11 mesh networks. We leverage the flexibility of using variable channel widths to adapt the channel allocation in response to spatio-temporal variations in traffic demands. We show that the traffic-aware channel width assignment problem is NP-complete by establishing a relationship with the well known edge colouring problem. Our proposed polynomial time greedy heuristic algorithm results in a valid channel allocation for every node. Our simulation based evaluation of the algorithm using real network topologies shows that it substantially improves network performance (e.g., up to around 70% throughput improvement) relative to the existing fixed width allocation approach.

Chapter 7

Coordinated TV White Space Spectrum Sharing for Home Networks via Micro Auctions

7.1 Introduction

To date both in the US and the UK, regulators have committed to allow cognitive radio access to TV White Space (TVWS) spectrum. Regulations are also underway in Europe and are being considered elsewhere [14]. The TVWS spectrum comprises of portions of spatially unused UHF/VHF TV broadcasting bands which could be used by cognitive radios provided their operation does not cause harmful interference to primary users of these bands, which in addition to TV broadcasting systems also include wireless microphones and other PMSE (Program Making and Special Event) equipment. To ensure protection for primary users, regulators have considered two main methods for cognitive access: sensing and the use of a database combined with geolocation. Due to the so-called hidden node problem with sensing [14], the geolocation database approach currently offers the best short-term solution. Both regulatory [152, 153] and industry efforts [154] are, therefore, currently underway to develop regulations and standards towards realising this approach. With the geolocation databases method, prior to accessing the TVWS spectrum, a white space device (WSD) has to register its location and, possibly, other characteristics with a designated database provider. The database then uses this information to determine, via a set of propagation modeling computations, a list of available TVWS channels at the location of the device along with the maximum transmit power to be used per channel. This information is then sent to the WSD, which selects from this list one or more vacant channels for its transmission.

The TVWS spectrum has attracted considerable attention from all quarters recently due to its superior propagation characteristics and the promise it provides for potentially large amount of additional spectrum for wireless data applications. However, in urban areas where the spectrum scarcity is most apparent, the presence of many TV channels and proposed regulatory protection requirements for broadcast TV receivers leave very little TVWS spectrum for high-power communications by secondary users [15]. Shorter range communications have more hope of exploiting this new spectrum. Fortunately it turns out that short range wireless technologies operating in the unlicensed bands, as exemplified by WiFi, are most affected by overcrowded spectrum and interference problems.

We therefore consider TVWS spectrum as an opportunity to offload traffic from short range wireless technologies (e.g., WiFi, Zigbee) that are increasingly subject to interference in unlicensed bands. Our focus in particular is on the home networking scenario in which in-home wireless networking among various devices in the household (e.g., home entertainment systems, game consoles, appliances, energy meters) is not only becoming more prevalent but also is currently done using WiFi or Zigbee operating in the congested unlicensed bands. We envision that such devices in future will be TVWS-capable and can opportunistically use TVWS spectrum to relieve congestion across various spectrum bands used by home wireless devices. The emerging TV white space standards such as IEEE802.11af [16] and ECMA-392 [17] support our view.

Cognitive access to TV white spaces is still evolving. In fact, compared with the large body of research on sensing (e.g., [155]), literature on geolocation databases is rather limited [156, 157]. Furthermore, most previous research [156, 157], as well as regulation [158] and standardisation effort [154] has focused on developing the required computational algorithms, protocols and rules for the provision on information on available channels to white space devices. *The question of how multiple potentially interfering devices with likely heterogeneous bandwidth requirements should share TVWS spectrum after access is granted is yet to be addressed*[1]. Conventional "politeness" (etiquette) protocols, such as CSMA (carrier sense multiple access) used for sharing the ISM bands are susceptible to the so-called tragedy of commons, which

[1]The recently proposed IEEE 802.19 standard focuses on coexistence solutions in the TVWS bands using a central manager that communicates to the database, but the standard is in early stages.

occur when self-interested devices pursuing short-term interests deplete a common spectrum resource. Access to TVWS poses an additional challenge. Services such as Freeview rely on interference-free TV-transmissions and given that these services are used by a large percentage of the population, their providers (e.g., BBC) are skeptical regarding the reliability of the location services and the sufficiency of the coverage predictions to provide reliable reception [18]. The question that arises is what happens if the devices or databases are compromised and whether the benefits of this new technology can outweigh the potential disruption to services enjoyed by a majority of the population.

To address the above challenges, we consider a business model for operating the databases which aligns with the objectives of both the TV and broadband providers as well as end-users. In this model, access to the TVWS is provided as a service from database providers, who own and maintain the database, to broadband providers who request access to the TVWS spectrum on behalf of their clients (i.e., home networks). The subscribers to this service can enjoy the additional capacity while reliably avoiding disruptions to TV services by *coordinated access to the TVWS spectrum*. Unlike the ISM bands where coordination is not practical, in this scenario coordination is feasible since the geolocation database has access to both location and transmit power of the subscribed devices.

To realise the above business model, we propose a spectrum management mechanism based on micro auctions to coordinate access to and distribute the TVWS spectrum among home networks. Unlike the auctions routinely used by regulators for long-term spectrum allocation nationwide involving few bidders, micro auctions refer to short-term (re-)allocations permitting greater sharing and reuse of available spectrum among a potentially large number of bidders. Specifically, we propose an efficient auctioning algorithm for adaptive sharing of TVWS spectrum in space and time among home networks (and their white space devices) with heterogeneous bandwidth requirements. Our approach combines the use of geolocation databases with an iterative auctioning mechanism for local access to white space channels. Interference-free assignment and re-assignment of white space channels are achieved by dynamic construction of interference graphs. To the best of our knowledge, our work is the first to develop a scalable micro-auctioning mechanism for TVWS spectrum sharing through a geolocation database with home networking as the target use case. We evaluate our auctioning algorithm using realistic TV white space availability maps in the UK and actual distribution of homes in urban, sub-urban and rural environments. Compared to previous work (e.g., [41, 42, 43]), our work offers an efficient mechanism that enables dynamic sharing of TVWS spectrum among large number of home networks, especially in a dense urban environment. It also offers incentives for providers and users alike. In contrast, previous work is largely oriented towards maximising revenue for the selling authority.

7.2 System Model and Preliminaries

In this work, we consider a combinatorial auction, where a geolocation database provider periodically auctions access to the TVWS spectrum to secondary users taking into account their mutual interference relationships. We assume that the provider maintains a geolocation database for TV white spaces that is also communicating to a PMSE database from which it receives periodic updates regarding the usage by PMSE. In our context, secondary user refers to a home network that represents all white space devices (WSDs) inside the home. Each home network participates in the auction via its home hub (or access point) provided by broadband providers. Each home hub acts as a master node that bids for TVWS channels on behalf of WSDs within the home. We assume that within an area where home hubs could interfere with each other (directly or indirectly), all TVWS channels carry the same price. This is discussed further in the next section when we introduce the notion of a connected cluster. We also assume channel lease periods are identical across all home networks. In chapter 9, we discuss extensions of our model to support varying prices for the channels and varying leasing periods. We assume that there is a mechanism available at each home hub to translate aggregate throughput demands from all in-home WSDs into the spectrum demand for the home in terms of number of TVWS channels.

The timeline for the system in operation is shown in Figure 7.1. Time is seen as a sequence of *epochs*, each consisting of a short *Auction Phase* (no more than a few mins) followed by a longer *Spectrum Use Phase* (could last several tens of mins). Each *Auction Phase* consists of one or more *rounds* involving interaction between the auctioneer (database provider) and bidders (home hubs) as part of the auction to arrive at a selling (clearing) price for requested TVWS channels. At the beginning of each round, the provider announces channels available in an area besides advertising initial or adjusted channel price. Home hubs respond with their bids within a *bidding period*. After the auction is complete, home hubs whose bids are successful proceed to use TVWS channels they are granted access to. The same process repeats in the next

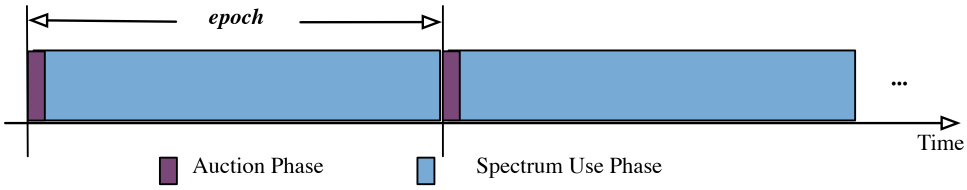


Figure 7.1: Timeline of the auctioning based coordinated TVWS spectrum access system.

epoch and so on.

A potential business model involving database provider, broadband providers and end users is as follows. Database provider offers the service of coordinating the interference-free allocation of TVWS spectrum among secondary users to broadband providers who in turn offer this as a service to their subscribers. Broadband users (subscribers) belong to different classes of users (e.g., "gold", "silver" and "platinum") depending on their subscription plan. These different classes correspond to different monthly credits for TV white space spectrum use. The use of monthly credits on any given day is limited by per day credits. This daily credit limit is the total budget/valuation of the TVWS spectrum by the user, which can be used for requesting one or more channels. The per channel valuation of the user is the ratio of total remaining budget to the number of requested channels. The per day credits are reduced every time a hub wins access to requested channels.

Unlike conventional nation-wide auctions, spectrum micro-auctions allow secondary users access to the same channel so long as they do not interfere. So the problem of allocating channels to the bidders given a set of bids is a type of interference-constrained resource allocation problem. For this, we model interference constraints using the commonly utilised protocol interference model[2] [102]. We use the center of a house as the location of the home network. We represent the interference relationships using an *interference graph* G composed of vertices that correspond to secondary users. We refer to secondary users as nodes in the interference graph. Two nodes in the interference graph have an edge if they interfere with each other (pairwise interference). We use notation N_i to refer to the set of nodes to which node i is connected in graph G. Figure 7.2 shows an example interference graph for a set of home hubs A-F within a

[2]In future, we plan on using more sophisticated interference relationships (e.g., via passive measurements similarly to [159]).

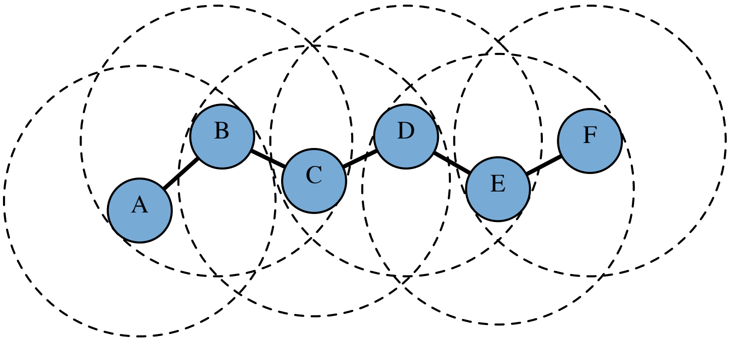


Figure 7.2: An example interference graph. Each dotted circle around a hub defines the interference range of the hub. Interfering hubs are connected by a solid line.

given area. Each dotted circle around a hub defines the interference range of the hub. Interfering hubs are connected with a solid line.

To represent the spectrum assigned to a node i, we use a bit vector C_i of size M, where M is the number of available TVWS channels[3]. We refer to this vector as the *channel allocation vector*. Each index of the C_i vector is associated with a distinct channel. $C_i[k]$ is set to 1 if the channel indexed by k is assigned to node i and 0 otherwise. The auctioning mechanism needs to ensure that for each node i in the interference graph, the following interference constraint is satisfied.

$$C_i[k] * C_j[k] = 0,\ \forall j \in N_i,\ 0 \leq k < M \tag{7.1}$$

Also, let b_i $(0 < b_i \leq M)$ denote the number of channels requested by node i (spectrum demand), then for each bidder the following demand constraint must hold:

$$\sum_{k=0}^{M-1} C_i[k] = 0 \text{ } or \text{ } b_i \tag{7.2}$$

The above equation states that at the end of the auction phase, each bidder is successful and so is given access to requested number of channels, or is unsuccessful and has no channels.

Our goal is to allocate the available TVWS channels such that constraints (7.1) and (7.2) are satisfied.

[3]We assume each TVWS channels is 8MHz wide, which is the case in Europe. In the US, the channels are 6 MHz.

7.3 Micro Auctioning Mechanism

We consider the problem of operating the geolocation databases and coordinating access to TVWS spectrum to provide interference-free operation among home networks, without disrupting the primary users of these bands. To address this problem, we propose an auctioning mechanism with the following design goals:

- *Consider both the seller and the buyer*: The spectrum under consideration is license-exempted, thus spectrum requesters should be given incentive to use the spectrum distribution service. To achieve this goal, the mechanism should include a low complexity bidding language to facilitate users bidding with ease. Bidding in bundles of channels, as required in this scenario, however, is challenging as it requires a complex bidding language to express users' desires (i.e., one or more set of channels to bid on and how much to pay for each possible set). Our mechanism aims at simplifying bidding.

- *Low complexity winner determination mechanism for the TVWS database provider*: This allows auctioning in real-time for dynamic allocation and re-allocation of TVWS spectrum. It also facilitates scalability in that it allows the auctioning mechanism to be used in topologies with a large number of users. Moreover, users are expected to have heterogeneous bandwidth requirements. With a large number of potential channel allocations, the complexity of finding the desired allocation is high. Our goal is to minimise this complexity.

- *Capture complex interference relationships*: Home networks are scattered within a given area forming complex interference relationships rather than "all-with-all" relationships (i.e., single collision domains). We opt for a mechanism, which provides interference-free allocations in such complex scenarios.

Motivated by the aforementioned objectives we propose an *iterative auctioning* mechanism which operates as shown in Figure 7.3. At the beginning of each new *epoch*, the auctioneer advertises the vacant channels to the home hubs. Each channel is associated with an initial price (called *reserve price*). Each participant responds with her spectrum request within a (small) *bidding period*. A spectrum request is the number of channels the participant wishes to purchase on behalf of the broadband user (and her in-home WSDs) according to the user class and daily credit (See Section 7.2). At the end of this period, the auctioneer determines if there is excess. Excess is defined

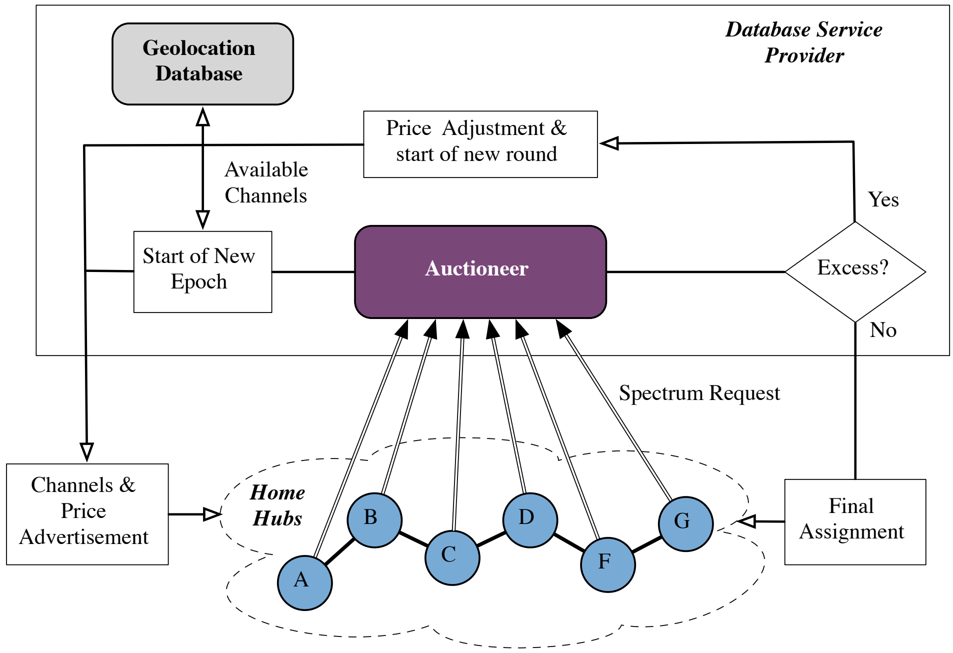


Figure 7.3: The auctioning mechanism. At each new epoch, the auctioneer advertises the vacant channels and their reserve prices to the home hubs. Participants request the number of channels they wish to obtain within a predetermined period. When this period elapses, if excess demand is found, the auctioneer increases the channel price starting a new auctioning round. Otherwise, the channels are sold to the bidders.

as either excessive demand or zero demand (excess supply). If excess is found, a new *round* is initiated, where the channel price is modified and the participating hubs are notified. Otherwise, the channels are sold to the bidders and the *auction phase* ends.

The goal of the mechanism is to adjust the prices of the channels such that excess demand is naturally driven out of the system, while ensuring that there is still demand for the channels. This removes the need for a sophisticated channel allocation method to efficiently distribute the channels to the bidders, which would be computationally expensive. The auctioning mechanism, however, still needs a method to determine the minimum number of channels that are required to satisfy the given spectrum demands (called chromatic number in graph theory) and determine if there is excess demand. This can be done by attempting to allocate each bidder $i \in G$, the channels it requests (i..e b_i channels), while ensuring that constraints (7.1) and (7.2) are satisfied.

To determine excess demand, the length of each node's channel allocation vector is assumed to be equal to the summation of b_i (let that be denoted by B) and, as before, each index of the C_i vector is associated with a unique non-overlapping 8MHz channel.

$C_i[k] = 1$ if the channel indexed by k is assigned to node i and 0 otherwise. Then, the mechanism needs to ensure that for each node i in the interference graph the following interference constraint in satisfied.

$$C_i[k] * C_j[k] = 0,\ \forall j \in N_i,\ 0 \leq k < B \tag{7.3}$$

Moreover, for each bidder, the following constraint must hold:

$$\sum_{k=0}^{B-1} C_i[k] = b_i \tag{7.4}$$

The above equation now states that each participant that has placed a bid must be allocated all requested channels. $|C_i|$ denotes the size of the vector.

The above constraints are used to calculate an interference-free channel allocation which satisfies the spectrum demand. Excess is found as long as the chromatic number of the "best" channel allocation exceeds the number of available channels. Such allocation is *infeasible*. We define the *feasibility* constraint as follows: Let M denote the number of available channels at a given location. Then, the total number of channels that a node i and its interferers are assigned must not exceed M. This can be expressed as:

$$\sum_{k=0}^{B-1} (C_i[k] \vee C_j[k]) \leq M,\ \forall j \in N_i \tag{7.5}$$

where the operation $C_i[k] \vee C_j[k]$ performs the logical OR between the two vectors at index k.

Unfortunately, finding the "best" allocation in a multi-channel allocation problem is a special case of the fractional colouring problem[4], for which finding an optimal solution has been shown to be NP-hard [160]. Moreover, the mechanism must ensure that the total spectrum demand is not overestimated for two reasons: First, to avoid unnecessary increase in channel prices, and second, to accommodate as many winning bids as possible. Our approach to address this is greedy. Essentially, the idea is to sort nodes in a non-increasing order of their degrees[5] and use this prioritisation to determine the order in which nodes are allocated spectrum. This degree-based greedy

[4] In fractional colouring, each vertex is assigned to a set of colours and every two vertices connected by an edge must be assigned different colours. Our problem is a special case of fractional colouring, since the sizes of the sets of channels assigned to different vertices can differ (i.e., users may have heterogeneous bandwidth demands.).

[5] The degree of a node is the number of edges connecting the node to other nodes in the interference graph.

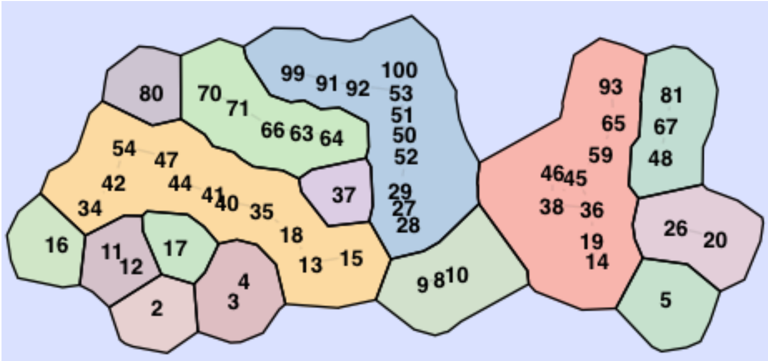


Figure 7.4: The connected clusters for an example topology. Differently coloured areas surrounding the nodes correspond to different connected components.

allocation is a relatively standard approach, which has been shown to provide sufficient flexibility in allocating channels at every newly considered node [161].

After nodes are prioritised, the algorithm finds the different connected components within the interference graph. A connected component is a cluster of nodes where starting from any randomly chosen node any other node in that cluster could be reached within a finite number of hops. An interference graph can be fully connected consisting of just one connected component, or can be a collection of isolated components. In the latter case, channel assignment is performed separately for each component using the spectrum demand within each component. Figure 7.4 depicts the formed connected components for an example topology and interference relationships among them. Different connected components are shaded with different colours. We note that the construction of the interference graph and identification of the connected components have to be performed at each round since the number of home hubs that bid for spectrum varies from round to round resulting in a modified interference graph.

For each connected cluster, nodes are processed in the order of their priorities. For each node i, the channel allocation vector C_i is updated such that constraints (7.3) and (7.4) are satisfied. A feasible solution is found for a cluster if constraint (7.5) is satisfied. Otherwise, channel prices are increased for that cluster such that excess is removed in subsequent rounds. Note, however, that each bidder has a budget which determines the hard upper limit on the price that can be charged for the spectrum allocated. Figure 7.5 depicts the relationship between the channel price and the number that users are able to purchase at each price. In the worst case scenario, after a price increase, the cost for obtaining the required channels exceeds the available budget of every bidder within the connected cluster. In this scenario, the demand for channels

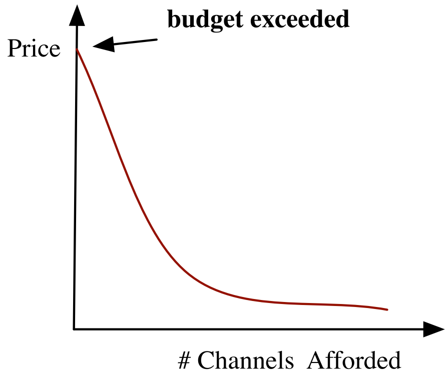


Figure 7.5: The relationship between channel price and number of channels afforded. As the per channel price increases, the number of afforded channels decreases. In the worst case scenario, the price exceeds user budget, resulting in zero afforded channels.

on the cluster becomes zero. In such a zero demand situation, we decrease the channel price for that cluster.

Specifically, channel prices are adjusted as follows: for a cluster with excess demand, if p_t is the price of a channel and e_t is the excess found at time t, then the price of a channel at time t+1 is calculated as:

$$p_{t+1} = \begin{cases} p_t + \alpha * f(e_t) * p_t, & p_d = 0 \\ p_t + \alpha * f(e_t) * (|p_d - p_t|), & p_d > 0 \end{cases} \tag{7.6}$$

where $f(e_t) = \frac{e_t}{e_t+1}$ and p_d (initialized at 0) is the minimum price at which zero demand occurred (*minimum declined price*). We use $|p_d - p_t|$ to set an upper bound to the increase of prices. This ensures that in the event of excess demand, channel prices are increased to a price that is less than the price at which zero demand occurred. In the above formulas, $\alpha \in (0, 1]$ is a parameter which governs the speed of convergence of the auctioning mechanism. We refer to this parameter as *price increase parameter*. Lower values of this parameter enforce the prices to increase in smaller steps thus they suppress the aggressiveness of the mechanism, but they result in an increased number of rounds. This tradeoff becomes clear in Section 7.4, where we study its impact. The function $f(e_t)$ has been chosen to allow the channel price in clusters with higher excess demand to be increased more aggressively so that excess is removed faster and

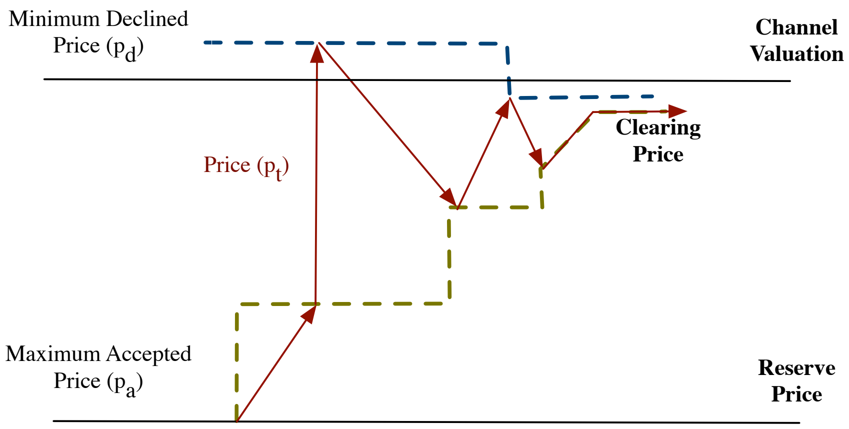


Figure 7.6: Price Adjustment. The price is adjusted based on estimations on the maximum declined price and minimum accepted price.

convergence time is improved.

For a cluster with zero demand, the auctioneer adapts the channel price as follows:

$$p_{t+1} = p_t - \frac{p_t - p_a}{2} \tag{7.7}$$

where p_a is the maximum historic price at which excess has been positive (*maximum accepted price*). Initially, the maximum accepted price is set to the reserve price. The term $(p_t - p_a)$ is used to set a lower bound to the decrease in the price, since the new price should not decrease below the previously accepted price. The equation (7.7) aims at decreasing the convergence time.

The aforementioned formulas aim at adaptively adjusting the prices at each round based on historic accepted and declined prices such that excess is removed from the system. The clearing (selling) price, however, cannot exceed the upper limit (i.e., budget). Figure 7.6 shows how the price is adjusted based on the historic minimum declined price and maximum accepted price to get the channel price within the bidder's per channel valuation. If the budget of multiple bidders is very close and the demands leads to positive excess, the difference between the minimum declined price and maximum accepted price is very small. To avoid a large number of rounds until exact equilibrium between demand and supply is reached, we terminate the auction when this difference becomes very small. At this point, the bidders are prioritised based on their degree in the interference graph and the spectrum is sold at the maximum accepted price per channel.

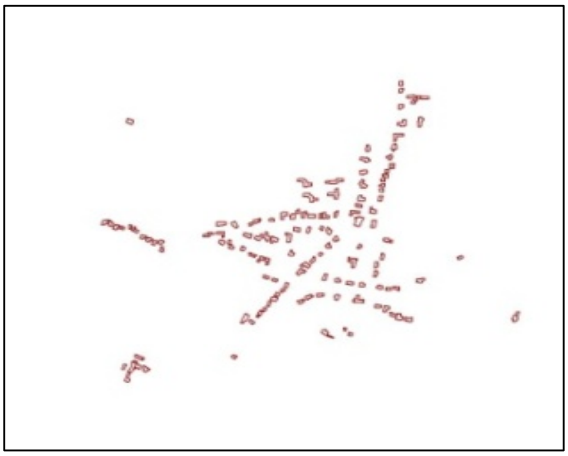
The proposed mechanism has several benefits: It provides a polynomial time interference - free heuristic to an NP-hard channel allocation problem. Additionally, it offers a simpler bidding mechanism. Each bidder simply multiplies the per channel price with the number of channels she wishes to purchase access for and continues to bid as long as the total cost does not exceed her maximum total valuation (budget). This also allows each bidder to flexibly adapt her channel requests, increasing/decreasing the number of requested channels while staying within their budget. Note that bidders can only accept the prices set by the auctioneer and bid at any round knowing that the auction can terminate at that round. This removes the need for strategizing over other bidders' actions, which can induce unnecessary overhead and may even discourage bidders from participating. Moreover, as the prices of the channels get raised, excess demand is naturally driven out of the system. Winning bidders are the standing bidders, who are those that value the spectrum the most. This aligns with the requirements set forth by the UK and US governments [162].

7.4 Evaluation

In this section, we evaluate our coordinated access method based on micro auctioning. To examine the impact of user density, we use three different real residential environments: rural, urban and dense-urban [5]. The house and building layout data for each of these environments represent 1 square kilometer areas. These data are obtained from Geographical Information Systems (GIS) database for the UK [5]. The dense-urban residential environment comprises of 5456 houses and buildings, followed by 2435 houses/buildings in urban and 152 houses in the rural environment. The topologies are shown in Figure 7.7. We model the system described in Section 7.2, where a TVWS spectrum database service provider periodically auctions the available spectrum to home hubs (users).

Although our evaluations in this work are based on simulations, we have also implemented a prototype of the system, which consists of a TVWS geolocation database which contains pixelised data of coverage maps for UK TV transmitters and uses this information to compute the number of TVWS channels available at any given location. The database reports 9 channels for the dense-urban area and 24 channels for both the urban and rural residential areas.

The geolocation database communicates through an auctioning module with a set of home hubs, which are pre-registered with the database using TCP sockets, follow-



(a) Rural

(b) Urban

(c) Dense-Urban

Figure 7.7: Examples of representative residential environments: (a) Rural, (b) Urban and (c) Dense-Urban [5].

ing a client-server architecture. The geolocation database and the auctioning module are implemented in Python. The computation performed in the geolocation database to obtain pixelised TVWS availability maps follows the simplified approach described in [72, 74]. The geolocation database used for our evaluation is a proof of concept implementation, but it should be noted that the auctioning module could, in principle, work with any geolocation database module. In the current implementation we consider a push methodology where the auctioneer periodically broadcasts the available channels to all registered devices.

The results presented in this chapter correspond to an interference range of 20m — two nodes (homes) interfere with each other if they are within 20m of each other. Unless otherwise stated, the reserve price of each channel has been set to 0.9 times the minimum per channel budget across all users. The impact of other reserve price settings is studied in Section 7.4.3. Home networks are assumed to have diverse and time-varying bandwidth demands, which translate to a corresponding variation in the number of required white space channels. For each bidder the demand is chosen randomly from 1 to 6 channels and is assumed fixed within an epoch. Such demands are based on the fact that the spectral efficiencies of the TV channels range from 0.5 bit/(sec/Hz) up to 5 bit/(sec/Hz) [163]. A minimum spectral efficiency of 0.5 bit/(sec/Hz) corresponds to 4Mbps in a 8MHz channel. Assuming a request for a HTDV streaming which requires 20Mbps and an extra loss in efficiency due to the aggregation of non-continuous channels, this throughput demand corresponds to 6 channels. The per channel budget of each bidder is modelled using Pareto distribution with scale and shape parameters set to 2 and 1.8 respectively. Experimental results have been averaged over several per channel budgets and channel demands.

For each environment, we study the following performance metrics:

- *Revenue*: The revenue the database provider obtains for managing access to TVWS spectrum in an interference-free manner. Let N denote the total number of home networks and x_i be a variable associated with each home network i, which equals to 1 if home network i is a winner and 0 otherwise. If p_i expresses the per channel price, the amount user i needs to pay is given by $x_i * b_i * p_i$. This price depends on the demands in the clusters that user i belongs to in the different rounds until the end of the auction phase. The total revenue a spectrum provider obtains is given by $\sum_{i=1}^{N} x_i * b_i * p_i$. Our goal is to balance the revenue and the cost of obtaining channels (i.e., to be considerate to both the spectrum provider and the users). Towards this end, we associate channels with small initial (reserve)

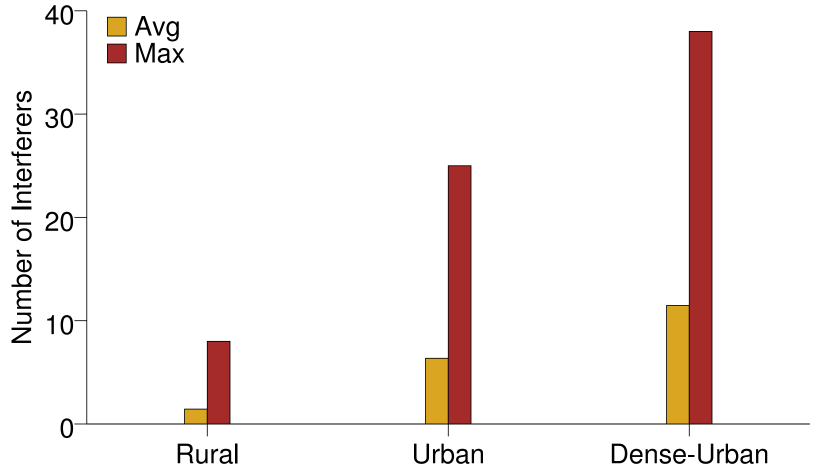


Figure 7.8: Potential interferers with uncoordinated TVWS spectrum access and *identical, high traffic* demand across all home networks.

prices and increase the prices only to remove excess demand.

- *Percentage of Winners*: The percentage of bidders who are allocated channels at the end of an auction. A higher value of this metric is preferred as that indicates users have incentive to successfully participate in the auctioning based coordinated access method. The number of winners, however, is constrained by the density of the area and the interference among them.

- *Convergence*: Number of rounds required in the auction phase of an epoch. This reflects the efficiency of the mechanism.

7.4.1 Interference with Uncoordinated TVWS Spectrum Access

In this section, we consider the uncoordinated access method and show that interference among TVWS users is a major concern, especially in a dense-urban environment.

We first look at the number of interferers in different environments assuming a high and uniform traffic demand across all home networks, i.e., all home hubs attempt to use all available TVWS channels. Figure 7.8 shows the average and maximum number of potential interfering neighbours among all home networks in the rural, urban and dense-urban cases. Potential interfering neighbours of a home network i are home networks that lie within the interfering range of i. Note that although the average number of interferers shows the average interference, we cannot design with this in mind as

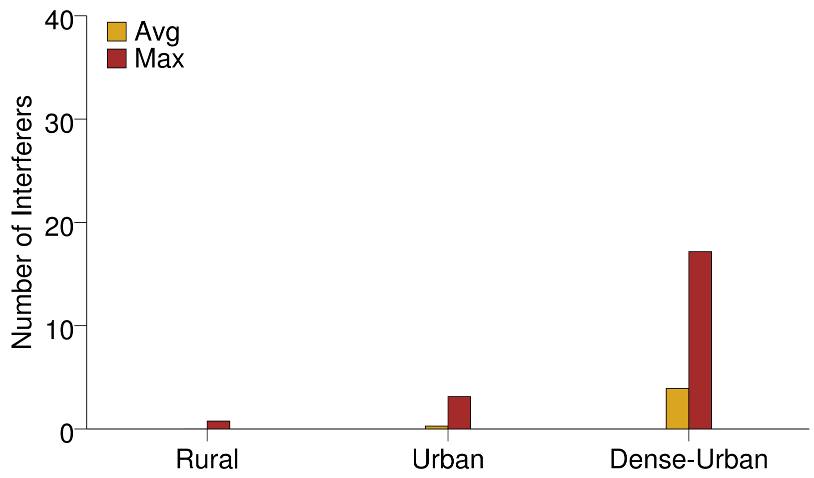


Figure 7.9: Potential interferers with uncoordinated TVWS spectrum access and *diverse* traffic demand across all home networks.

it is only part of the story. To provide the same service quality to all users, we need to also take into consideration the worst case interference gleaned via maximum number of interferers. From Figure 7.8, we observe that there is a significant gap between the average and the worst case interference. The maximum number of interferers for a home network in the rural case is 8, whereas it goes up more than four-fold to 38 in the dense-urban case.

We now consider a more realistic situation in which home networks have differing traffic requirements among them, thus requiring differing numbers of TVWS channels. In such a situation, uncoordinated spectrum access can be modelled as follows. Each home hub will determine the number of available TVWS channels to it via a geolocation database. Then depending on its traffic requirement, the hub can choose a subset of available channels that are least congested independently of other hubs in its neighbourhood, much like how WiFi access points can autonomously and intelligently pick their channel of operation. We applied the above method of channel selection for different environments and resulting maximum/average number of interferers is shown in Figure 7.9. We see that in the dense-urban case, the maximum number of interferers is still quite high (nearly 17). Moreover, the difference between average and maximum number of interferers is small (Compare with the situation in Figure 7.8 which corresponds to identical, high traffic demand across all home networks.), which is even more worrying as every home network is likely to experience a high level of interference.

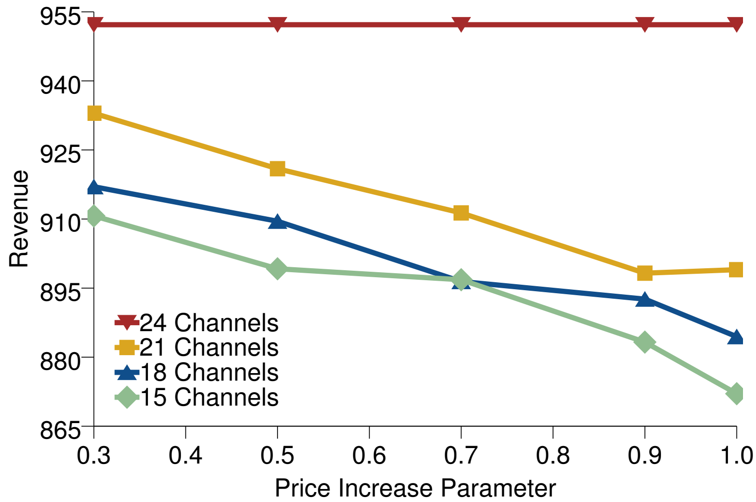


Figure 7.10: Impact of available channels and price increase parameter on the obtained revenue for a rural residential environment.

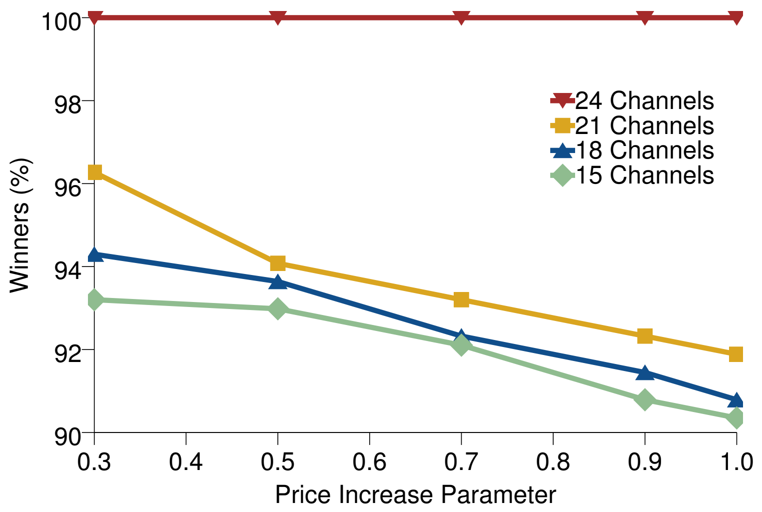
The results in this section clearly call for a interference-free allocation of TVWS spectrum through better coordination among home networks. In the following sections, we evaluate our proposed method of coordinating access via the geolocation database provider and auctioning with respect to underlying system parameters.

7.4.2 Effect of Price Increase Parameter and Available Channels

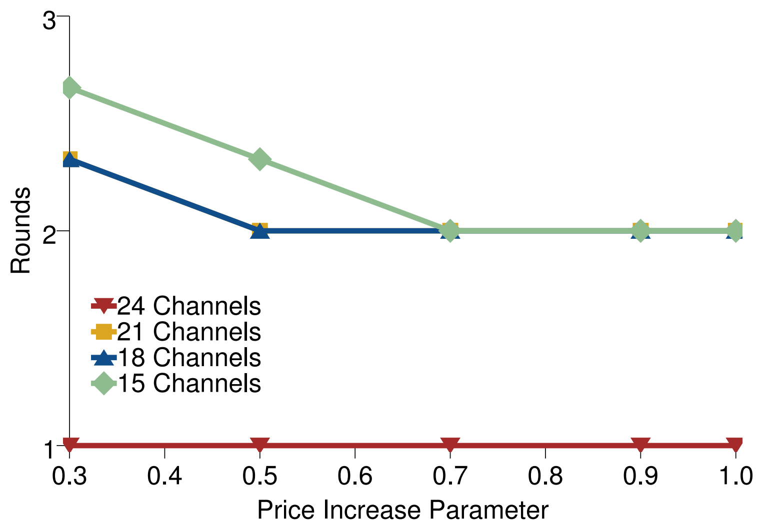
In this section we study the performance metrics for different values of the price increase parameter. As described in Section 6.3, parameter α controls the increase of channel prices in the presence of excess demand. We also study the impact of number of TVWS channels available for each type of residential area. This allows us to evaluate the proposed mechanism in environments with similar densities, but different channel availability due to different positioning of active TV stations or signal propagation. This also captures scenarios where the presence of wireless microphones and other PMSE equipment further limits the number of available channels.

7.4.2.1 Rural Residential Area

Figure 7.10 shows the obtained revenue for different values of the α parameter and different number of available channels. The figure shows that when the number of available channels in 24, the α parameter does not affect the revenue.This is explained



(a) Winners



(b) Convergence

Figure 7.11: Impact of available channels and price increase parameter on the (a) Winners and (b) Convergence for a rural residential environment.

in Figure 7.11(a) that shows the percentage of bidders who are allocated channels at the end of the auction. This figure shows that when the number of available channels is 24, 100% of the bidders win the channels. Moreover, Figure 7.11(b) demonstrates the convergence in terms of required number of rounds for the auction. When the number of channels is 24, the channels are allocated to the winners from the first round, thus the winners purchase the channels at the reserve price. This explains the independence of the revenue on the price increase parameter.

As the number of channels decreases, the revenue decreases with increasing α. This happens because the excess demand gets higher, causing the prices of the channels to increase at larger steps. As the mechanism becomes more aggressive, the number of bidders having a lower per channel budget than the per channel price increases. Those bidders are forced to quit resulting in a lower number of winners, which is confirmed in Figure 7.11(a).

For a given number of channels, a lower value of the price increase parameter leads to less aggressive price increases. Lower values of α, however, result in increased number of rounds (Figure 7.11(b)). This presents the fundamental tradeoff between the obtained revenue and the speed of convergence of the auctioning mechanism.

7.4.2.2 Urban Residential Area

As before Figure 7.12 shows the obtained revenue for different values of the α parameter and different number of available channels. As expected, the revenue in this scenario is higher than in the rural area due to the larger number of houses in this area. As in the rural scenario, the revenue decreases as the number of channels decreases or the α parameter increases for a given number of available channels. In this scenario, the impact of the channels and the α parameter is more profound compared to the rural scenario, because the excess demand is higher due to the higher density of the topology.

Figure 7.13(b) shows the convergence of the mechanism for different channels and values of the α parameter. Similarly to the rural scenario, the number of rounds increases as the number of channels decreases. Interestingly though, the convergence of the mechanism does not follow a monotonic behaviour with respect to the α parameter. This happens because in this scenario there is a higher competition for the available resources. When the number of channels decreases to 18, the number of rounds decreases as the price increase parameter increases, but when $\alpha = 1$, the number of rounds increases noticeably. This can be explained by the fact that when the number of avail-

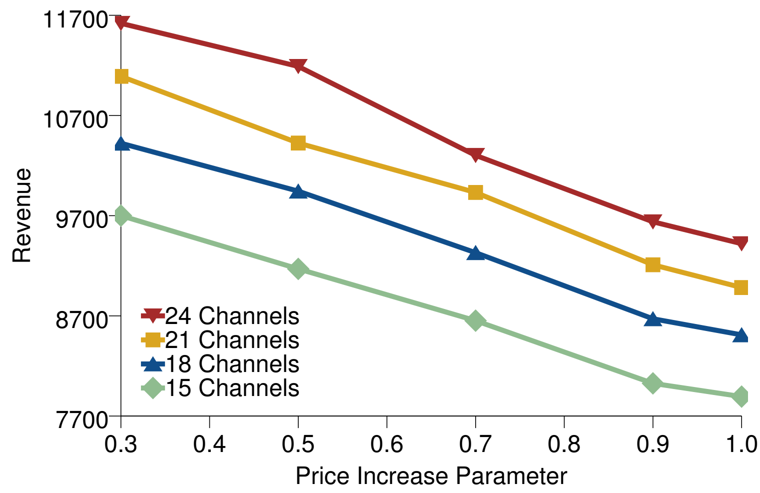


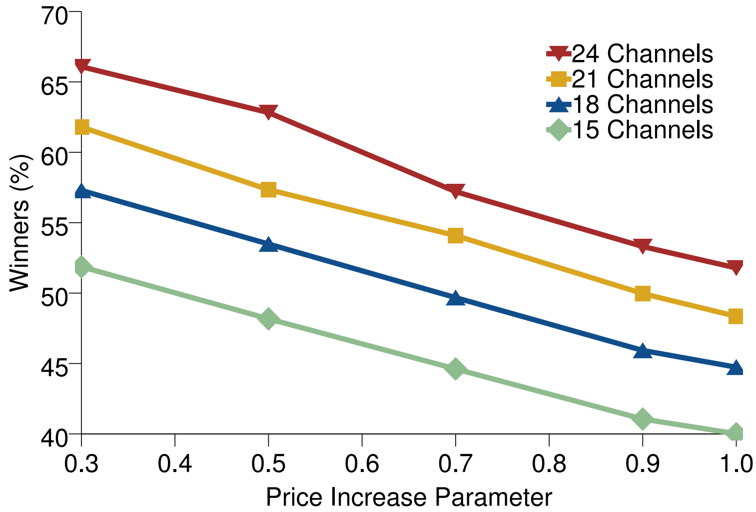
Figure 7.12: Impact of available channels and price increase parameter on the obtained revenue for an urban residential area.

able channels is lower, the excess demand is higher causing the prices of the channels to increase at larger steps. The high excess demand together with a high α parameter, causes aggressive increase in the per channel price. This results in situations where none of the buyers places a bid (zero demand situations). The algorithm then needs to decrease the price to attract bidders, which results in additional rounds.

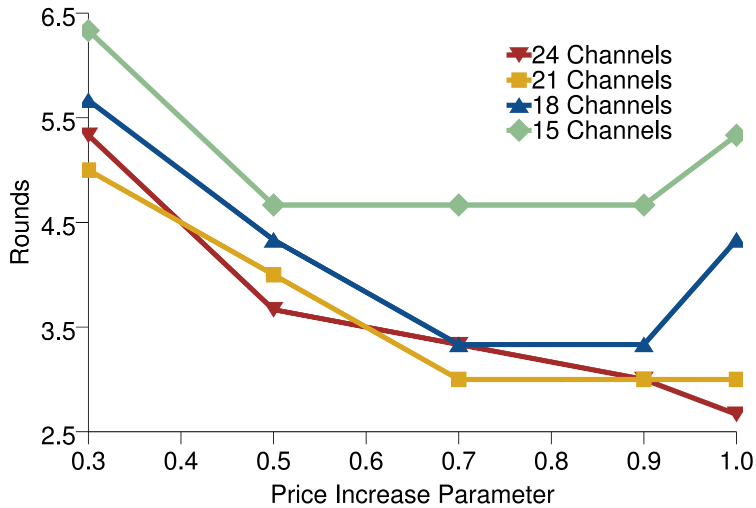
7.4.2.3 Dense-Urban Residential Area

Figure 7.14 shows the revenue for the dense-urban residential area. Similarly to the urban scenario, the figure shows a decrease in revenue when the price increase parameter increases. This is explained by the decreased number of winners as shown in Figure 7.15(a). This happens because at higher values of the price increase parameter, the mechanism becomes more aggressive in removing the excess demand, forcing more bidders to quit.

The trade-off between trying to increase the obtained revenue and the number of winners, while maintaining fast convergence is even more difficult in this scenario compared to the urban residential area, because the number of resulting rounds is higher (Figure 7.15(b)). Moreover, compared to the rural and urban setting, this scenario is significantly restricted by the fewer number of available channels and user density. Due to these constraints and our assumption about positive demands for all users, we cannot satisfy every user's demand no matter how much we charge them.



(a) Winners



(b) Convergence

Figure 7.13: Impact of available channels and price increase parameter on (a) Winners and (b) Convergence for an urban residential area.

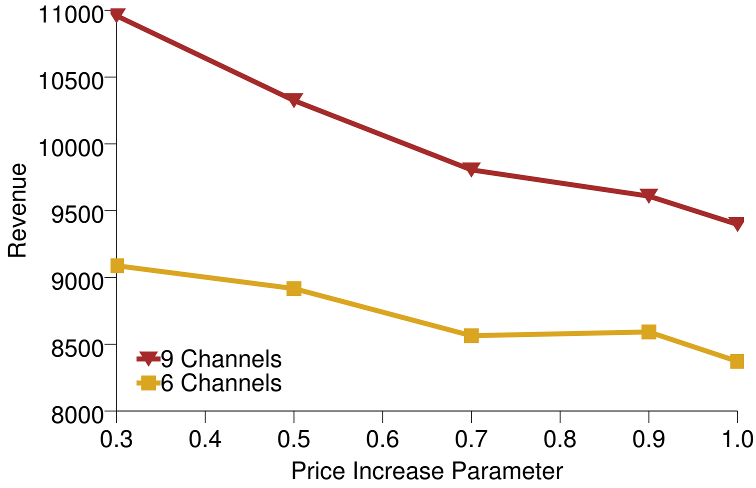
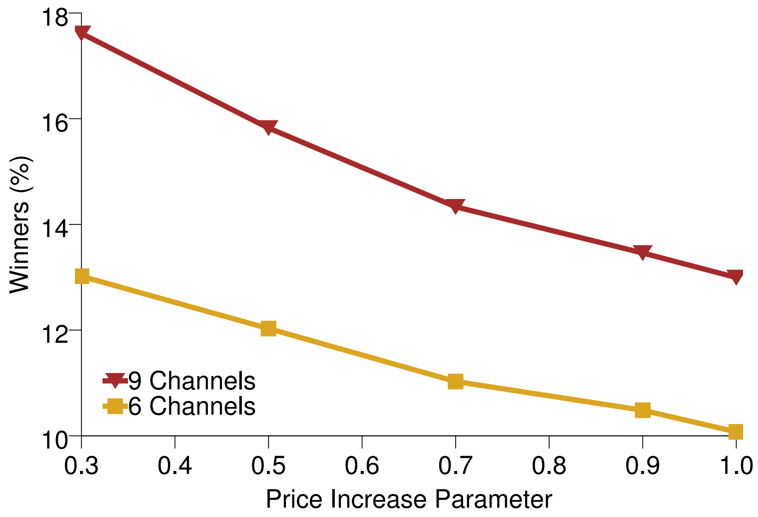


Figure 7.14: Impact of available channels and price increase parameter on the obtained revenue for a dense-urban residential area.

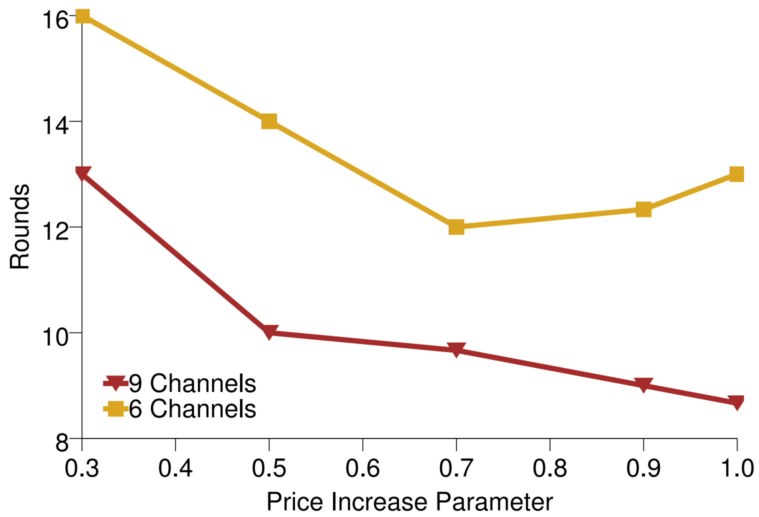
This explains the smaller percentage of winners in Figure 7.15(a).

7.4.3 Effect of Reserve Price

In this section we study the impact of reserve price to revenue, number of winners and convergence of our auctioning mechanism. The price increase parameter is set to 0.7 and the available number of channels is assumed to be equal to the number reported by the geolocation database (9 channels for the dense-urban area and 24 channels for both the urban and rural residential areas). Figure 7.16 shows the average revenue for different reserve prices. Note that the different values of reserve price correspond to different percentages of the minimum channel budget across all bidders. We see that the revenue increases as the reserve price increases. The significance of this increase, however, varies between areas with different user densities. More specifically, the improvement in revenue when going from 10% to 90% reserve price is 9x, 1.76x and 0.056x for the rural, urban and dense-urban area respectively. This happens because as the reserve price increases, so does the revenue obtained by the bidders who are granted channel access at the reserve price (i.e., at the first round). The number of those bidders, however, depends on the density of the topology. The higher the density, the lower the number of reserve price winners, and thus the lower the impact of the reserve price. We can also observe that when the reserve price is high the revenue of the urban area exceeds the revenue of the dense-urban area. This can be explained by the higher



(a) Winners



(b) Convergence

Figure 7.15: Impact of available channels and price increase parameter on (a) Winners and (b) Convergence for a dense-urban residential area.

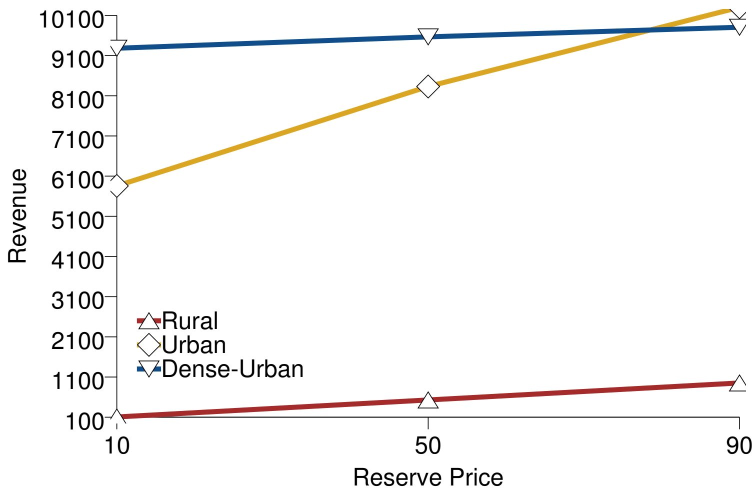
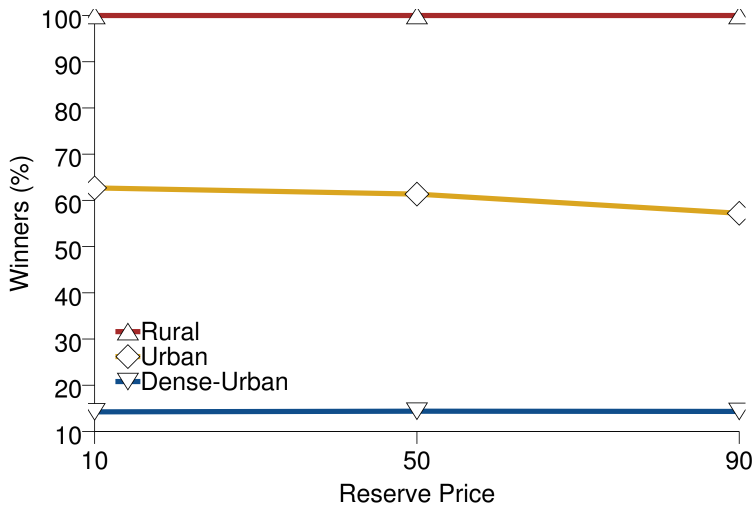


Figure 7.16: Impact of reserve price on the obtained revenue of the proposed auctioning mechanism in different types of residential areas.

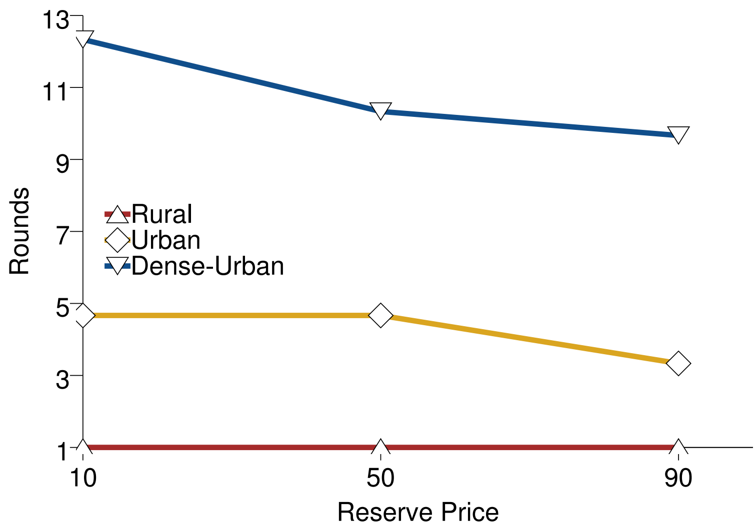
percentage of winners in the urban area, due to the lower level of competition compared to the dense-urban scenario which in turn is because of the higher number of available channels and lower density of the urban residential area.

Figure 7.17(a) shows that the number of winners is almost constant across different reserve prices. This is explained by the fact that the number of winners depends mostly on the interference constraints and the budget of bidders, which are fixed in this experiment. However, the number of winners shows a slight decrease in the urban scenario when the reserve price is 0.9. This happens because differently from the rural area, in the urban scenario the competition for channels is higher due to the higher density. This results in more than one rounds until the end of the auction, which in turn leads to price increase. A higher reserve price leads to higher prices at subsequent rounds, which makes the mechanism more aggressive. More bidders are, therefore, forced to quit. This also holds for the dense-urban area, but the decrease is very small. In this case, the lower number of available channels and the denser environment force the mechanism to increase/decrease the prices to cope with positive excess and zero-demand cases.

Finally, Figure 7.17(b) shows the effect of reserve price on convergence time. It is evident that for the dense-urban area and urban area, the number of required rounds decreases as the reserve price increases. This happens because at higher initial prices, the price increase needed to remove excess demand from the system is reached in fewer



(a) Winners



(b) Convergence

Figure 7.17: Impact of reserve price on (a) Winners and (b) Convergence of the proposed auctioning mechanism in different types of residential areas.

rounds. In dense-urban scenarios, the effect is more profound because the number of conflicts, hence the excess demand, is higher due to the higher density. In the rural scenario, the reserve price has no effect on convergence time, since the auction terminates at the first round. An important conclusion from this figure is that in areas where excess demand is expected to be high, the reserve price should be close to the expected bidder budget to facilitate quick convergence.

7.5 Conclusions

Geolocation databases are emerging as the preferred approach by regulators and industry for enabling secondary access to TV White Spaces. In this chapter we explored how this approach could also be used to enable efficient and interference-free sharing of this resource among home networks systems. We argued that a coordinated form of access is more preferable and proposed a business model for mitigating contention on the vacant TV frequency bands, while avoiding disruption to the remaining TV stations. In our model, the auctioneer uses the location information which is available in the geolocation database to adjust white space spectrum prices dynamically and locally based on the difference between spectrum availability and demand. Consequently, interference-free and efficient allocation of TVWS is achieved while also satisfying bandwidth requirements of those who value the spectrum most. The auctioning mechanism also generates revenue, hence creating new business incentives for database providers. We investigated the performance of our auctioning mechanism through simulation studies of white space spectrum sharing among home networks in realistic scenarios. Our results show that our mechanism aligns with our objectives of balancing the desires of the database providers and spectrum requesters, scalability and low complexity for dynamic spectrum distribution.

Chapter 8

Concluding Remarks

In this thesis, we have looked at the problem of adaptively managing the unlicensed spectrum in the context of 802.11 wireless mesh networks and TV white space networks considering three emerging application scenarios each posing distinct challenges: public/neighbourhood wireless access, rural broadband and in-home wireless networking. For each of these scenarios we introduced novel spectrum management algorithms which aim at efficiently utilising the spectrum under consideration, minimise contention by suppressing interference and ultimately improve performance.

For neighbourhood wireless access, we considered the use of the IEEE 802.11-based multi-radio wireless mesh network technology with adaptive channel allocation to increase capacity of urban neighbourhoods or villages. The goal is to mitigate performance degradation due to contention via a distributed and adaptive solution without compromising connectivity. Specifically, we proposed a novel reinforcement learning-based distributed approach, termed LCAP, where nodes independently and iteratively learn their channel allocation using a probabilistic adaptation algorithm. LCAP addresses the limitations of previous work by not placing any restrictions on the interface use, the network structure or the traffic patterns. Neighbourhood and channel usage information is obtained via a novel neighbour discovery protocol, which is effective even when nodes do not share a common channel, while being compliant to the 802.11 standard. We evaluated LCAP relative to the state-of-the-art Asynchronous Distributed Colouring (ADC) protocol using extensive simulations and showed that LCAP provides significant improvements in channel utilisation and network performance (up to 40%) while being more scalable (with 60% less overhead) and adaptive to factors such as external interference.

Motivated by the non-stationary nature of the network scenario, which makes it difficult to establish convergence, we developed a deterministic alternative. This alternative employs a novel distributed priority-based mechanism where nodes decide on their channel allocations based on only local information. Key enabler of this approach is LCAP's neighbour discovery mechanism. This distributed alternative, similarly to LCAP, is independent of network structures and traffic patterns and does not assign specific roles to interfaces of nodes. Additionally, it provides a framework to assist the theoretical proof of convergence. We showed via simulations that this mechanism exhibits similar performance to LCAP.

For the case of rural broadband, we considered the use of long distance 802.11-based networks as part of a multi-tier architecture which uses directional antennae to establish long distance links and reach remote areas. Specifically, we proposed a novel channel width adaptation mechanism to support spatio-temporal variability in traffic demands with limited spectrum. We showed that the problem is NP-complete and proposed a polynomial time greedy channel allocation algorithm that guarantees channel allocations for all nodes. This algorithm exploits the capability of the 802.11 hardware to use different channel widths and assigns spectrum to links based on their relative volume. Specifically, the algorithm facilitates adaptation to spatio-temporal variations in traffic demand through allocating wider channels to links with higher demand by taking spectrum away from links with less demand. The proposed algorithm is the first to consider channel width adaptation based on traffic demands for all possible channel widths with commodity hardware (i.e., 5, 10, 20 and 40 MHz) and makes no assumptions about traffic demands, pattern and network topology. Our simulation based evaluation of the algorithm using real network topologies shows that it substantially improves network performance (e.g., up to around 70% throughput improvement) relative to the commonly used fixed width allocation approach. This improvement stems from the ability of the algorithm to adapt to spatio-temporal variations in traffic demands.

Finally, we considered the use of the recently available TV white spaces to increase the capacity of wireless home networks and relief the already congested unlicensed frequency bands. To the best of our knowledge, our work is the first to develop a scalable micro-auctioning mechanism for TVWS spectrum sharing through a geolocation database with home networking as the target use case. In our model, the auctioneer uses the location information which is available in the geolocation database to adjust white space spectrum prices dynamically based on the difference between spectrum availability and demand. Consequently, interference-free and efficient allocation of

TVWS is achieved while also satisfying bandwidth requirements of those who value the spectrum most. Our mechanism addresses the limitations of previous work by enabling dynamic sharing of TVWS spectrum among large number of home networks, especially in a dense urban environment and offering incentives for providers and users alike. We examined the effect of uncoordinated access to these bands and evaluated the performance of our auctioning mechanism via simulation of white space spectrum sharing among home networks in realistic scenarios. Our results show that our mechanism aligns with our objectives of balancing the desires of the database providers and spectrum requesters, scalability and low complexity for dynamic spectrum distribution.

Chapter 9

Future Work

The spectrum management mechanisms presented in this thesis have been evaluated via simulations. Simulation studies are a good starting point for studying the behaviour of proposed algorithms, since they provide the flexibility to experiment with diverse topologies, traffic patterns, environmental parameters and different parameters of the algorithms. Even with the most sophisticated network simulation tools, however, it is difficult to predict how these protocols perform in real hardware. A natural next step, therefore, is to experiment with the approaches presented in this thesis in a real test-bed to evaluate their performance. Furthermore, practical considerations and drivers for realising the multi-tier network model presented in Chapter 1 (Section 1.1) is an interesting topic.

For neighbourhood wireless access application scenarios, we developed two different mechanisms for distributed channel allocation in omnidirectional wireless mesh networks. The first scheme is a reinforcement learning-based approach, while the other is a deterministic solution. We demonstrated via simulations that these mechanisms exhibit similar performance. The motivation for developing the deterministic alternative was to introduce stability in the network scenario and facilitate convergence proof. The quality of wireless channels, however, is not constant. Even when wireless nodes are stationary, the movement of people and vehicles around the device affect the properties of the channels over time [164]. To avoid performance degradation due to channel variability, we envision an approach that incorporates learning into the proposed deterministic algorithm to tackle the ensuing uncertainty. We believe that in dynamic environments an ideal channel allocation protocol would be a hybrid solution that combines the probabilistic concept of LCAP with the imposed stationary behaviour arising from our deterministic approach. We note that both of the mechanisms described in this thesis as well as the envisioned hybrid solution can be extended to account for adjacent channel interference [134] and partially overlapping channels [135] by using a modified channel set quality metric.

In the case of long-distance scenarios, for larger networks like [138], distributed implementation of our proposed channel width assignment algorithm described in Chapter 6 is required for scalability reasons. We outline the distributed implementation below. Every instantiation of the algorithm consists of three phases corresponding to the three high-level steps described in Section 6.3: (1) initial distributed edge colouring for guard block assignments; (2) localised node priority assignment based on locally exchanging load information and using node IDs for breaking ties; (3) committing a node's colouring decision after finding a valid width combination — this phase requires the use of a distributed mutual exclusion mechanism along the lines of [24] to limit the number of nodes in a local neighbourhood that can concurrently update their channel allocation. We leave the detailed specification of this distributed algorithm and its prototype implementation for future work.

In wireless home network scenarios, we considered an auctioning mechanism to coordinate access to TVWS channels among home networks. This mechanism employs the database developed in [74], which assumes a pixel resolution of one square kilometer. This implies that within an one square kilometer area, the set and number of locally vacant channels is identical for all wireless home networks, which may not be realistic in some scenarios. Depending on the position of TV transmitters, houses within a smaller area may be prevented from transmitting in different set of channels. A higher resolution (i.e., smaller pixels), therefore is required to more accurately reflect the availability of the channels. In this case, neighbouring pixels have potentially overlapping TVWS channels and the auctioning mechanism needs to ensure that houses within each pixel as well as houses belonging to neighbouring pixels are allocated non-interfering channels. This modification could be incorporated in our algorithm by modifying the order by which nodes are processed and give higher priority to those exhibiting inter-pixel conflicts. This requires further investigation and is left for future work.

Additionally, the micro auctioning algorithm finds the different connected components within the interference graph and uses the excess of each component separately to adjust the channel prices for the bidders within that component. Within the same component, however, bidders may be more concentrated on one part and less concentrated on another. To avoid overly increase of prices in areas where contention is less, the algorithm can instead find the cliques within the interference graph and calculate the demand within each of them similarly to the solutions proposed for rate allocation in [165, 166]. Since, however, the clique decision problem is NP-complete, such an approach would need to employ a heuristic. An alternative solution would be to assign non-uniform prices to bidders within a component based on the extent to which they "pollute" the network in terms of their channel demands and number of surrounding interferers.

Moreover, although our auctioning model assumes that all home hubs request spectrum for the same time duration, it can be extended to varying leasing periods similarly to the "stickiness" concept used in [116]. Specifically, each channel can be associated with a minimum period of time T units, but home hubs are allowed to request each channel for multiplies of time T. However, longer demands prohibit spectrum access by other home hubs. Hubs, therefore, should be allowed prolonged spectrum access only if they pay proportionately higher price. This could be achieved by introducing non-uniform pricing in the model, where the per channel reserve price is set by the database provider independently for each hub depending on the requested leasing period.

Furthermore, as shown in the Section 7.4 the reserve price impacts the convergence time of the auctioning mechanism. More specifically, the closer the reserve price to the minimum valuation, the less rounds are required for our iterative mechanism. The reserve price, therefore, should be based on historical data, which will reflect the valuation distribution in different times of the day and in different regions.

Finally, our approach could be extended to enable sharing in other spectrum bands, such as radar bands, which may become available for secondary sharing through geolocation databases. An issue for future work is to further develop our approach for such future scenarios.

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