A new connectivity strategy for Wireless Mesh Networks using Dynamic Spectrum Access

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Declaration

I, Richard Maliwatu, confirm that the work presented in this dissertation is my own in both concept and execution. Where information has been derived from other sources, I confirm that this has been indicated in the work.

Signed by candidate

December 22, 2020

Abstract

The introduction of Dynamic Spectrum Access (DSA) marked an important juncture in the evolution of wireless networks. DSA is a spectrum assignment paradigm where devices are able to make real-time adjustment to their spectrum usage and adapt to changes in their spectral environment to meet performance objectives. DSA allows spectrum to be used more efficiently and may be considered as a viable approach to the ever increasing demand for spectrum in urban areas and the need for coverage extension to unconnected communities. While DSA can be applied to any spectrum band, the initial focus has been in the Ultra-High Frequency (UHF) band traditionally used for television broadcast because the band is lightly occupied and also happens to be ideal spectrum for sparsely populated rural areas. Wireless access in general is said to offer the most hope in extending connectivity to rural and unconnected peri-urban communities. Wireless Mesh Networks (WMN) in particular offer several attractive characteristics such as multi-hopping, ad-hoc networking, capabilities of self-organising and self-healing, hence the focus on WMNs. Motivated by the desire to leverage DSA for mesh networking, this research revisits the aspect of connectivity in WMNs with DSA. The advantages of DSA when combined with mesh networking not only build on the benefits, but also creates additional challenges. The study seeks to address the connectivity challenge across three key dimensions, namely *network formation*, *link metric* and *multi-link utilisation*.

To start with, one of the conundrums faced in WMNs with DSA is that the current 802.11s mesh standard provides limited support for DSA, while DSA related standards such as 802.22 provide limited support for mesh networking. This gap in standardisation complicates the integration of DSA in WMNs as several issues

are left outside the scope of the applicable standard. This dissertation highlights the inadequacy of the current MAC protocol in ensuring TVWS regulation compliance in multi-hop environments and proposes a logical link MAC sub-layer procedure to fill the gap. A network is considered compliant in this context if each node operates on a channel that it is allowed to use as determined for example, by the spectrum database. Using a combination of prototypical experiments, simulation and numerical analysis, it is shown that the proposed protocol ensures network formation is accomplished in a manner that is compliant with TVWS regulation.

Having tackled the compliance problem at the mesh formation level, the next logical step was to explore performance improvement avenues. Considering the importance of routing in WMNs, the study evaluates link characterisation to determine suitable metric for routing purposes. Along this dimension, the research makes two main contributions. Firstly, *A-link-metric* (Augmented Link Metric) approach for WMN with DSA is proposed. A-link-metric reinforces existing metrics to factor in characteristics of a DSA channel, which is essential to improve the routing protocol's ranking of links for optimal path selection. Secondly, in response to the question of "*which one is the suitable metric?*", the *Dynamic Path Metric Selection* (DPMeS) concept is introduced. The principal idea is to mechanise the routing protocol such that it assesses the network via a distributed probing mechanism and dynamically binds the routing metric. Using DPMeS, a routing metric is selected to match the network type and prevailing conditions, which is vital as each routing metric thrives or recedes in performance depending on the scenario. DPMeS is aimed at unifying the years worth of prior studies on routing metrics in WMNs. Simulation results indicate that A-link-metric achieves up to 83.4 % and 34.6 % performance improvement in terms of throughput and end-to-end delay respectively compared to the corresponding base metric (i.e. non-augmented variant). With DPMeS, the routing protocol is expected to yield better performance consistently compared to the fixed metric approach whose performance fluctuates amid changes in network setup and conditions.

By and large, DSA-enabled WMN nodes will require access to some fixed

spectrum to fall back on when *opportunistic spectrum* is unavailable. In the absence of fully functional *integrated-chip* cognitive radios to enable DSA, the immediate feasible solution for the interim is single hardware platforms fitted with multiple transceivers. This configuration results in multi-band multi-radio node capability that lends itself to a variety of link options in terms of transmit/receive radio functionality. The dissertation reports on the experimental performance evaluation of radios operating in the 5 GHz and UHF-TVWS bands for hybrid back-haul links. It is found that individual radios perform differently depending on the operating parameter settings, namely channel, channel-width and transmission power subject to prevailing environmental (both spectral and topographical) conditions. When aggregated, if the radios' data-rates are approximately equal, there is a throughput and round-trip time performance improvement of 44.5 - 61.8 % and 7.5 - 41.9 % respectively. For hybrid links comprising radios with significantly unequal data-rates, this study proposes an *adaptive round-robin* (ARR) based algorithm for efficient multi-link utilisation. Numerical analysis indicate that ARR provides 75 % throughput improvement. These results indicate that network optimisation overall requires both time and frequency division duplexing. Based on the experimental test results, this dissertation presents a three-layered routing framework for multi-link utilisation. The top layer represents the nodes' logical interface to the WMN while the bottom layer corresponds to the underlying physical wireless network interface cards (WNIC). The middle layer is an abstract and reductive representation of the possible and available transmission, and reception options between node pairs, which depends on the number and type of WNICs. Drawing on the experimental results and insight gained, the study builds criteria towards a mechanism for auto selection of the optimal link option.

Overall, this study is anticipated to serve as a springboard to stimulate the adoption and integration of DSA in WMNs, and further development in multi-link utilisation strategies to increase capacity. Ultimately, it is hoped that this contribution will collectively contribute effort towards attaining the global goal of extending connectivity to the unconnected.

Dedication

To Mom (aka "Mama"), and the memory of Dad. You always placed *mwasumba mano kusukulu* as high on the agenda as can be, an instruction time hasn't touched. You are the secret master-minders of my PhD journey.

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There would not have been much of this PhD if it had not been for my supervisors Dr. David L. Johnson (aka "Dr. DJ") and Dr. Melissa Densmore who shouldered so much in the line of admin and constantly kept their hand on the wheel to keep the boat of my thesis on course, and yet their only reward is me succeeding. I take my hat off.

I would also like to thank my technical adviser Dr. Albert A. Lysko for all his advice. Dr. Lysko's input sharpened the scientific rigour of my work starting from the research proposal stage of my PhD [...] and along the way enriched my RF knowledge and terminology use.

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To my brothers and sisters Harriet, Eddie, Charity, Barbara, Jane and Martin: I have covered some distance literally and metaphorically. Truth is, I would not have journeyed as far as I have if it had not been for your encouragement and support rendered from day one. To Jade: *thank you for loving me* is my favourite song.

Last but by no means the least, I'm indebted to Hasso Platnner Institute for the financial support, the Centre of Excellence (CoE) for financial supplements and the Computer Science Department for thesis fuel supplies among other things. By the way, "thesis fuel" is a super-technical term for coffee.

Above everything, it's all by God's grace.

Biography

The author hails from Zambia, in a rural community called Mporokoso where both his parents served as teachers at the time. He spent a tiny part of his childhood in Mporokoso, but as he grew up, he moved to other parts of the country and beyond. Between 2001 - 2003, in an attempt to jump-start a career in IT, he read for his CompTIA Network+, Cisco Certified Network Associate (CCNA), Microsoft Certified Systems Engineer (MCSE) at North Carolina State University/Computer Training Unit in Raleigh, North Carolina. Two years later, he pursued the Bachelor of Science degree in Computer Science at the Copperbelt University in Kitwe, Zambia. In 2012 he graduated with Bachelor of Science Honours specialising in Information Technology at the University of Cape Town. In 2014 he obtained the Master of Science in Computer Science degree from the University of Cape Town. His earlier industry certifications tipped him towards the networking side of things and this has continued to influence his research agenda to this day. But despite all these credentials, he still doesn't fully understand how his home router works.

Among the tenets held by the author is the view that, it's near-impossible to think of something without being able to mentally construct an image of it. To prove the point, give an opinion on the *itaic speelycaptor*? [...] exactly the point! For this reason, he tries as far as possible to use picturesque illustrations to convey ideas or concepts. A fair amount of this principle is reflected throughout this thesis.

The author is a Christian and currently serving as Deacon and Secretary at Mowbray Baptist Church. In between "computer sciencing", he plays acoustic guitar and electric guitar occasionally, practices all-style Karate and does some cooking, but that's not to say that he's good at any of that. *Contact*: rmaliwatu At cs.uct.ac.za

Publications

Some of the concepts, tables and figures in this dissertation were presented in the following publications:

- **Richard Maliwatu**, Albert A. Lysko, David L. Johnson, 2018, November. *Experimental propagation modelling without a dedicated transmitter*. In 2018 International Workshop on Computing, Electromagnetics, and Machine Intelligence (CEMi) (pp. 81-82). IEEE.

  `Contributed towards chapter 7.`

- **Richard Maliwatu**, Natasha Zlobinsky, Magdeline Lamola, Augustine Takyi, David L. Johnson, and Melissa Densmore, 2018, September. *Experimental analysis of 5 GHz WiFi and UHF-TVWS hybrid Wireless Mesh Network back-haul links*. In International Conference on Cognitive Radio Oriented Wireless Networks (pp. 3-14). Springer, Cham.

  `Contributed towards chapter 6.`

- **Richard Maliwatu**, Albert Lysko and David Johnson, 2016, November. *Exploring RSSI Dependency on Height in UHF for Throughput Optimisation*. In 2016 International Conference on Advances in Computing and Communication Engineering (ICACCE) (pp. 7-12). IEEE.

  `Contributed towards chapter 7.`

- **Richard Maliwatu**, Albert Lysko, David Johnson and Senka Hadzic, 2016, December. *A Correlation between RSSI and Height in UHF Band and Comparison of Geolocation Spectrum Database View of TVWS with Ground Truth*.

In International Conference on e-Infrastructure and e-Services for Developing Countries (pp. 243-250). Springer, Cham.

`Contributed towards chapter 7.`

- David Johnson, Natasha Zlobinsky, Albert Lysko, Magdeline Lamola, Senka Hadzic and **Richard Maliwatu**, 2016, December. *Head to Head Battle of TV White Space and WiFi for Connecting Developing Regions*. In International Conference on e-Infrastructure and e-Services for Developing Countries (pp. 186-195). Springer, Cham.

  `Contributed towards chapter 6.`

- **Richard Maliwatu**, Natasha Zlobinsky, Melissa Densmore and David Johnson, 2016. Work in progress: *A Road Map for Wireless Mesh Routing with DSA*. In Proceedings of Southern Africa Telecommunication Networks and Applications Conference (SATNAC) (pp. 46-47), George, South Africa.

  `Contributed towards chapter 1 and 6.`

Contents

List of abbreviations

ARR - Adaptive Round-Robin

BRR - Basic Round-Robin

CCC - Common Control Channel

DSA - Dynamic Spectrum Access

FSA - Fixed Spectrum Access

ICT - Information and Communication Technology

IEEE -Institute of Electrical and Electronics Engineers

IP - Internet Protocol

LOS - Line of Sight

NIC - Network Interface card

OSI - Open Systems Interconnection

POP - Point of Presence

QoS - Quality of Service

RF - Radio Frequency

TVWS - Television White Space

UHF - Ultra High Frequency

VSAT - Very Small Aperture Terminal

WCN - Wireless Community Network

WiFi - Wireless Fidelity

WMN - Wireless Mesh Network

WRAN - Wireless Regional Area Network

WSD - White Space Device

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Chapter 1

Introduction

Access to Information and Communication Technology (ICT) infrastructure has the potential to enable provision of services in sectors such as education, health and governance regardless of the distance to the community. ICTs have a bearing on many other areas, hence unsurprisingly the United Nations working group on sustainable development goals explicitly lists increasing access to ICT, and providing universal and affordable access to Internet in least developed countries by 2020. Although access to cellular phones and mobile broadband has been growing at a rapid rate in recent years, mobile penetration has not solved the issue of affordable access. Among the available options for the last mile, the roll-out cost of copper-wired links is comparatively high and the infrastructure may be targeted by thieves because of the high value of copper. Fibre optic networks are an alternative, but for low-income communities the capital required to set it up renders it less viable for extension beyond the point of presence (POP) and in some cases the terrain makes the implementation of cabled infrastructure impractical. VSAT is capable of covering remote areas but the required initial and recurring costs are prohibitively high. Therefore, open spectrum wireless access technology offers the most hope in extending connectivity to rural areas [1, 2].

In response to the need for network access, wireless community networks (WCN) such as TakNet [3], Zenzeleni [4], LinkNet [5] et al. have become a common trend as confirmed by the Global Information Society Watch 2018 [6] based on reports from 43 different countries on community networks. WCNs are established for purposes of resource sharing, which may encompass Internet connectivity and are typically community owned, decentralised and tend to expand organically.

It is in this WCN broad context that this dissertation is situated. Critical aspects of WCNs include selecting the right wireless technology suited to the terrain and population density, and using routing techniques to find the best routes through a heterogeneous set of radios and link technologies. Looking back at when wireless IP-networking emerged, it was quickly discovered that routing protocols ported from the wired environment were not suitable for use in a wireless environment due to peculiarities of the wireless media. Similarly, the emergence of Dynamic Spectrum Access (DSA) based WMN marks an important juncture in the development of networking that necessitates a re-adaptation of the routing solutions to suit the DSA environment. This research revisits the problem of routing in WMN to address some of the challenges and explore the opportunities that DSA brings.

1.1 Motivation

Firstly, improvement in broadband Internet capacity and access is identified among key actions required in establishing a strategic economic infrastructure in South Africa's National Development plan [7]. Therefore, the high concentration of population in Africa and parts of Asia that is still offline according to the International Telecommunication Union (ITU) 2016 report calls for concern. From the ITU report in Figure 1.1, it is clear that more effort is needed towards robust network performance and leveraging spectrum availability within the confines of regulation for extension of connectivity to rural and under-served populations.

Secondly, the ever increasing demand for high throughput implies that there is always a constant need for added improvement in network performance. It can be said that network technology develops over time with the aim of meeting user requirements. In line with that, the theory of *disruptive technology* [8] seems to suggest that a technological solution develops to a point where it meets user requirements as illustrated in Figure 1.2a. However, the theory of disruptive technology's assertion completely ignores the evolution of user requirements. For example, a study on the implication on performance and usage of Internet bandwidth upgrade revealed that performance improvement follows soon after an upgrade, but usage evolves over a short period of time thereby resulting in deterioration of network performance [9]. These findings though based on a specific case hints at the fact that wireless routing techniques that have been developed meet user Quality of Service (QoS) requirements but only for a brief period of time. Akin to *Parkinson's Law* [10], in the longer term, user requirements change and keep ahead of the network performance curve as illustrated in Figure 1.2b. Thus the question of how much network performance improvement suffices to meet user requirements and keep the solution curve ahead of QoS requirements permanently is still an open problem.

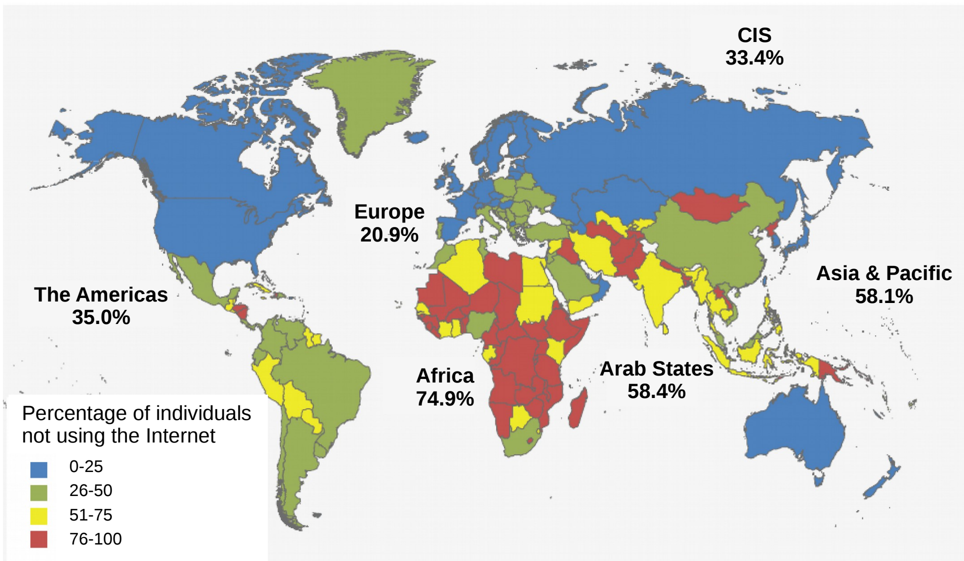


Figure 1.1: The world's offline population. Source: International Telecommunication Union (ITU), November 2018 ICT data.[1]

The current shift to 5G promises massive bandwidths, however the 2018 ITU report [11] and other analyses point out that the current cost of deploying a 5G network makes it viable only in densely populated urban areas, which have always been the most attractive for operators. With the operators seeing little incentive to invest in 5G for rural and suburban communities, the GSMA 2018 report [12]

[1]https://www.itu.int/en/ITU-D/Statistics/Documents/statistics/2018/ITU_Key_2005-2018_ICT_data_with%20LDCs_rev27Nov2018.xls

predicts that low-income regions such as sub-Saharan Africa for example, will be last in seeing the launch of 5G. The GSMA forecast further predicts that by the year 2025, 5G may only account for around 2.6% of the total connection base in these areas. Based on these analyses it is thought that 5G deployments may inadvertently contribute towards widening the digital divide rather than bridging it.

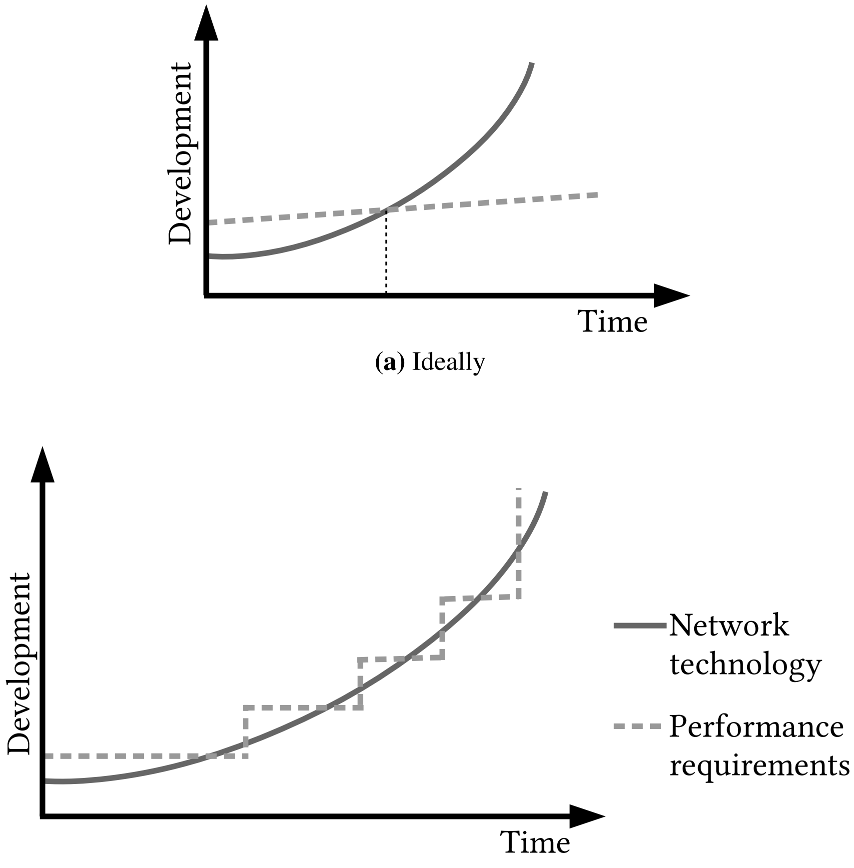


Figure 1.2: The intention behind network performance improvement is to develop a solution to a point where user requirements are met. In reality network performance improvements develop, meet user requirements for a short moment but, the QoS demands soon change and keeps ahead of the solution curve[2]. Some example causes of performance requirements stepping include the emergence of technologies such as virtual reality, home video streaming, etc.

[2]Inspired by a sketch used by Gary Marsden to illustrate the answer to the question, "is the electronic industry in a mature state?" The response to the question considered Clayton M. Christensen's ideas on disruptive technology [8].

1.2 Problem statement

While urban areas are faced with an apparent spectrum crunch, rural areas generally have a combination of poor connectivity and abundant spectrum. In this regard, adopting DSA potentially offers several connectivity benefits for both rural and urban region connectivity requirements (*see* section 2.3). However, there is little support for DSA in the current WMN related standards such as 802.11s whilst standards pertaining to DSA such as 802.22 offer limited support for mesh networking. Consequently, attempting to combine the benefits of optimal spectrum utilisation that DSA brings and the self-organising properties of mesh networking leads to several confounding challenges at different layers of the network protocol stack.

With the objective of building on the advantages of WMNs with DSA, the aim of this work is to design a network that makes optimal use of available spectrum and routes traffic over optimal paths. The network must require very little maintenance, auto-configure itself, be low cost and comply with applicable DSA regulation.

1.3 Research questions

This research attempted to address the problem by revisiting the challenge of routing in WMNs using DSA. The challenge was tackled across three key dimensions, namely *network formation*, *link metric* and *multi-link utilisation*. The network formation part encompasses measures to address regulation compliance concerns as well as routing based on spatial spectrum availability. The following three questions were posed to guide the research agenda:

(i) *How should a self-configuring TVWS network stay compliant in a multi-hop environment?*

Prior attempts at cognitive routing focus on the 'temporal' aspect of the spectrum opportunity and assume a uniform spectrum map for all the nodes. Envisaging deployment scenarios with several primary transmitters and possibly other secondary users under different administrative domains spread across the deployment area, this study addressed the problem of network formation and topology management amid temporal lack of common optimal channels among WMN nodes. The study leveraged spatial spectrum reuse with the aim of using a non-interfering optimal common channel between source and destination node pairs (*see* chapter 4).

(ii) *What characteristics of a DSA channel should be factored into a link metric for optimal route selection in WMNs with DSA?*

Given multi-hop path options comprising multi-radios using different frequency bands and variable channel widths, a metric to characterise links for optimal path selection is required.

(iii) *On what basis should WMN nodes select single-I/O, aggregate or split the operating radio link?*

The term single-I/O is being used to refer to a link using a single-radio transceiver. A split link in this context is defined as a configuration where a node uses one radio for sending packets and the other for receiving. An aggregate link refers to two or more radios combined to form a single logical link. The performance of radios operating in different spectrum bands or channels may vary. As a matter of fact, aggregating or splitting could improve or degrade performance depending on the type of radio and nature of the environment. Therefore, a framework and criteria are needed for determining when to use a single-I/O radio, and when to aggregate or split the link.

1.4 Dissertation overview

To start with, it was critical to get a firm understanding of the DSA regulatory framework applicable to this research's jurisdiction and identify the opportunities as well as challenges. The other significant prerequisite was to ascertain white space availability in the area as this forms the bedrock. Having considered the WMN spectrum requirements under the lens of regulatory framework constraints, the research agenda prioritised DSA regulation compliance concerns in a multi-hop environment identified through a careful analysis. The study attempted to address the compliance issue at the MAC layer and once that was accomplished, the next logical step was to explore network performance improvement avenues. The study identified gaps in the current state-of-the-art and explored opportunities to enhance performance at the physical layer and network layer in what might be viewed as a *middle-cut* approach with respect to the MAC layer. Figure 1.3 gives the broad layout of this dissertation. Given the opportunities and challenges informed by careful analysis, the research firstly addressed DSA regulation compliance concerns in a multi-hop environment at the MAC layer, and secondly tackled the much needed throughput enhancements at the physical layer and network layer. The ordering of tasks is a deliberate reflection of the principle that compliance rather than optimisation should be of foremost concern.

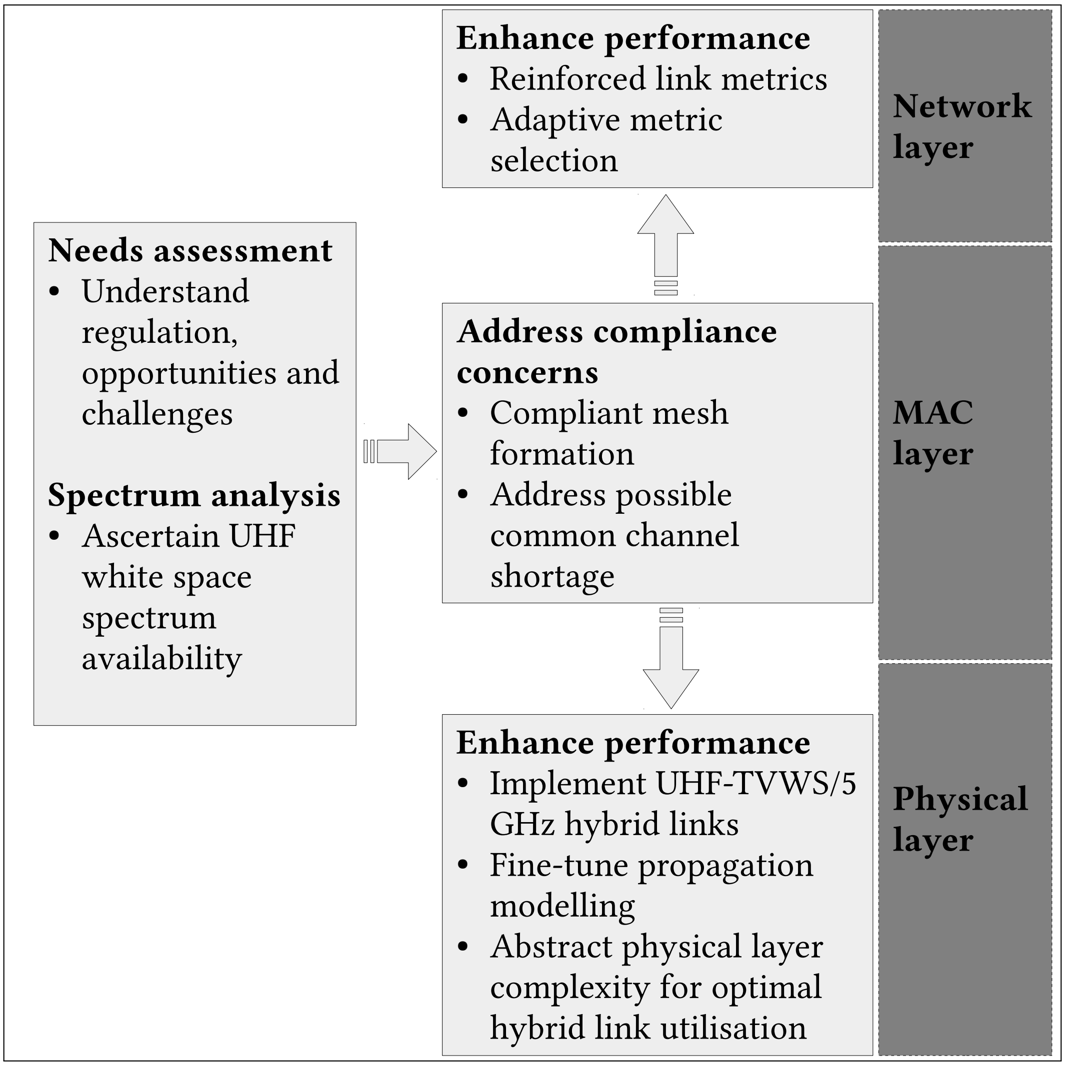


Figure 1.3: Dissertation overview.

1.5 Overview of the research approach

The main aim of the research was to contribute effort towards tackling the routing challenges arising from combining mesh networking with DSA. Guided by the research questions highlighted in the previous section, the study consisted of three main parts. An experimental approach was used to conduct the research and quantitative data was used to address the research questions. The South African regulator - Independent Communications Authority of South Africa (ICASA) have published TVWS regulation that specifies 470-694 MHz as the radio frequency range for white space devices (WSD) under the constraints of interference protection requirements. Thus this research started off with a preliminary spectrum analysis of the 470-694 MHz frequency range. The purpose of the spectrum analysis was twofold: (i) ascertain availability of TVWS in the area; and (ii) begin to understand the unique characteristics of UHF signal propagation such as degree and extent of obstacle penetration capabilities and the effect of factors such as antenna height. This was followed by an exercise of building actual WMN node prototypes that were later used for experimentation throughout the study.

The spectrum analysis results were used to understand white space availability and the extent of variations in spectrum usage over time. This informed the assumptions made in answering the first research question and influenced design choices such as appropriate spectrum sensing and route update intervals. A prototype was developed as proof of concept. The routing technique was evaluated by comparing performance with existing solutions using standard network performance metrics as criteria. This was done firstly using the test-bed implementation for validation and latterly using simulated mesh nodes for scalability. Figure 1.4 summarises the major research steps taken. The three parts of this research collectively aim at supporting two broad functions of a WMN protocol, which are maintaining connectivity and choosing paths with optimum throughput between any packet source/destination pairs.

To tackle the second research question, quantitative data was collected to identify factors influencing link performance and determine the extent to which each of the factors affect the link. The study used the concept of *weighted exponential sum* approach not to formulate an optimisation problem, but instead as a method of estimating the achievable throughput along a given multi-hop path. The resulting performance objective-based routing metric was implemented in *NS-3* network simulation environment. The evaluation process involved implementing the new metric used for estimating link and path quality, and comparing performance with existing routing metrics under different network topologies.

With reference to the overall research approach shown in Figure 1.4, building on existing elements within the simulation framework, some of the aspects that had to be modelled in answering the first and second research questions included spectrum availability, the extent and degree of RF interference on wireless links, position of nodes in a mesh network and so forth. The simulation on the other hand was conducted to mimic mesh network processes with a specific focus on formation and routing tasks.

To address the third research question, measurements were conducted to investigate link performance using different multi-radio settings, namely operating channel, transmission power, channel width and antenna polarisation. Performance was measured under different environmental variables namely, trees/vegetation, building structures and landscape. These environmental factors are known to impinge on the *Fresnel zone* and subsequently affect the Radio Frequency (RF) signal propagation. The WMN router consisted of 5 GHz WiFi and UHF-TVWS radios. A detailed description of the prototype is given in chapter 6.

The measurement process involved setting up the nodes on two ends of a site in different environments. With the help of a measurement script, throughput, delay, packet loss and other values of interest were recorded for various combinations of operating parameters. A custom measurement script was developed for this purpose that executed control commands between node pairs using a dedicated control link established using 3G modems. With a dedicated control link in place, the data collection process had minimal impact on the experiments conducted on the 5 GHz WiFi and UHF-TVWS links.

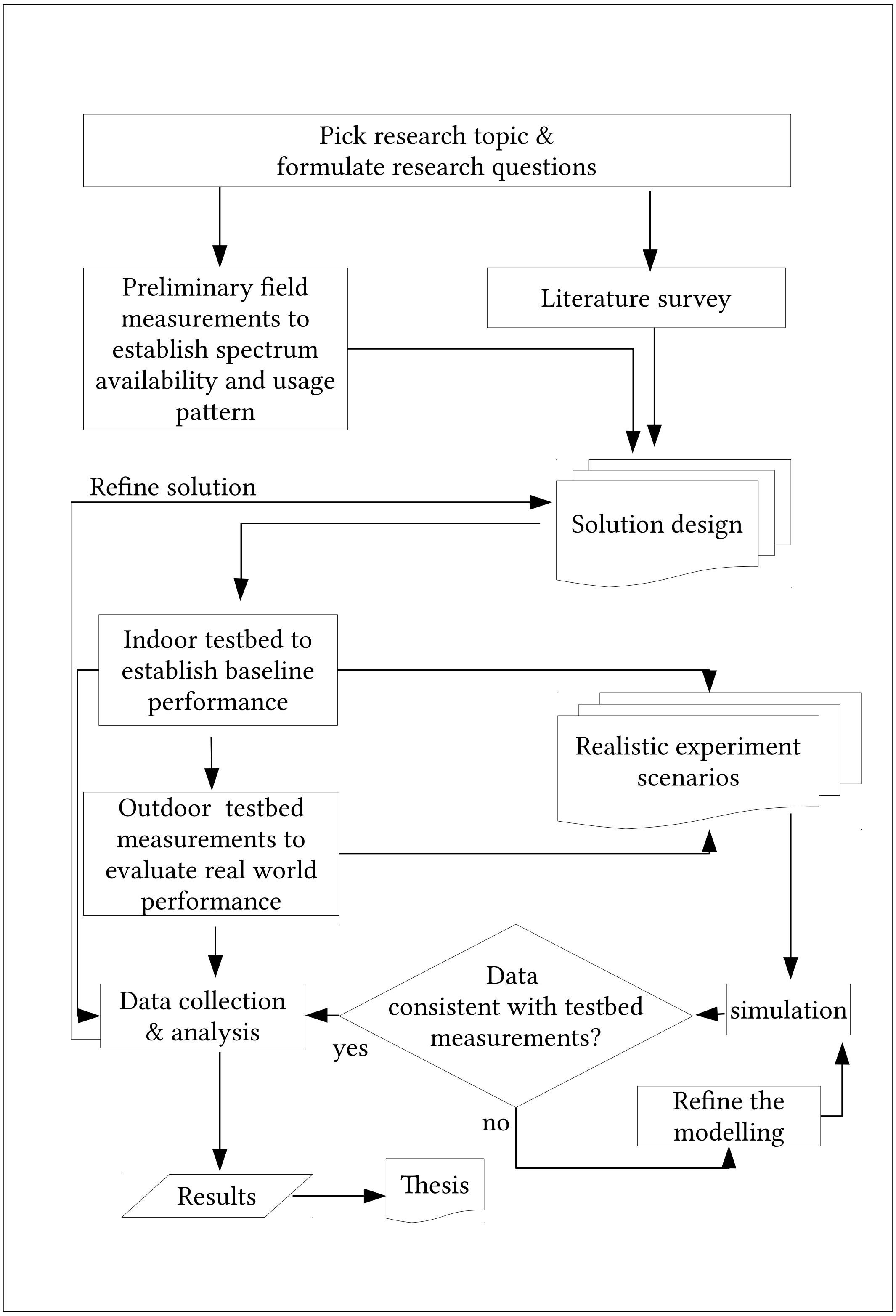


Figure 1.4: Overview of the research approach employed during the study.

1.6 Research contributions

Whilst addressing the research questions, this study makes the following four contributions pertaining to the design and implementation of WMNs with DSA:

- **DSA regulation compliant WMN formation, routing based on spectrum availability**
  This study identified a critical gap in the readiness of the current WMN MAC layer implementation to ensure DSA regulation compliance from device boot-up to complete network formation. The multi-hop nature and ad-hoc characteristics poses significant challenges in network formation when WMNs apply DSA. This research extends the existing 802.11s mesh standard by introducing a logical link MAC sub-layer procedure aimed at ensuring regulation compliance from device start-up through the complete multi-hop network formation process. Furthermore, envisioning a wireless network deployment scenario spanning a large geographical area with non-contiguous white space, when there is no clean operating channel available globally, a scheme of routing is developed that allows the mesh routing protocol to route traffic based on spectrum availability. Radio virtualisation was applied amid constraints of single-radio nodes to mitigate the problem of temporal lack of common clean channel and avoid interfering with primary transmissions. In addition to asserting the technical feasibility of realising a WMN compliant with TVWS regulation, an enquiry into the nodes' mechanism for correcting the potential risk of interfering with incumbents based on the current protocol to access white space (PAWS) culminated in two key findings. Firstly, there is a minimum Internet link speed that is required for mesh nodes to transact with the GLSD within a period of time that is small enough to minimise the impact of interference during that process. The Regulator can impose this as an additional requirement for TVWS in multi-hop environments. Secondly, GLSD protocols should be designed with this requirement in mind, for example by prioritising mandatory parameters and allowing the optional features to be turned on/off to reduce overhead especially for GLSD queries using

low-speed Internet connections. Refer to chapter 4 for more details.

- **Augmented link metric**

  The research highlights the inadequacies in existing link metrics that are based on implicit measurements. ‘implicit’ in the sense that they use higher layer parameters to deduce link layer status. The study provides a general framework and guidelines for reinforcing existing metrics to factor in characteristic of a DSA channel. To test the concept, the augmented link metric incorporates raw data obtainable from wireless network cards to infer link performance. The augmented link metric improves the routing protocol’s ranking of links for optimal path selection by prioritising high throughput links based on raw data from the radios, which gives a more accurate measure of link quality as opposed to applying network layer parameters to infer link performance.

- **Dynamic Path metric selection**

  Routing protocols perform differently using different metrics in different scenarios. Building upon the well known fact that when it comes to link metrics, there is no “one size fits all”, this dissertation introduces *Dynamic Path Metric Selection* (DPMeS). DPMeS extends the scope of the routing protocol to encompass mechanisms and criteria for determining the suitable routing metric for the network. DPMeS is an attempt to unify this and other prior studies on different link metrics. DPMeS is driven by a *pre-routing phase* component introduced in the routing process. Instead of configuring the routing protocol with a fixed routing metric, the pre-routing phase is initially a start-up process and latterly a periodic process that the routing protocol carries out to assess the network and auto-configure a suitable routing metric to use. Refer to chapter 5, section 5.3.5 for a more detailed description.

- **Multi-link utilisation framework, criteria and technique**

  Given multi-radio enabled nodes, this dissertation presents a framework for optimal multi-link routing for WMN hybrid back-haul links. A three-tiered framework that makes a distinction between possible link configurations and multi-link utilisation policies is proposed. This decomposition allows for the different link configurations to be coupled with an appropriate policy to meet the different performance objectives. In addition, an *adaptive round-robin* (ARR) based aggregation technique is presented to enhance efficiency of aggregate links with non-uniform data-rates.

The notion of ARR in itself is not a new concept. The principle has been applied over scheduling problems in different forms across several areas such as blocking of packets in the access point's buffer [13], uplink bandwidth allocation for mobile WiMAX [14], load balancing of distributed web servers [15], CPU scheduling [16] et al. However, to the extent of the author's knowledge, this is the first time the principle and technique is being applied for efficient utilisation of multi-rate hybrid links.

While the study focused on 5 GHz WiFi and UHF-TVWS based hybrid links, the proposed framework is technology-agnostic and thus can be applied to any multi-link capable nodes regardless of the underlying operating spectrum band. Background details of the multi-link utilisation framework are presented in chapter 6 with particular emphasis in sections 6.3 and 6.5.6.

1.7 Thesis outline

The rest of this thesis is organised as follows:

Chapter 2 presents the underpinning background theory used throughout this study. More specifically, the chapter gives an overview of WMNs and outlines the routing problem in WMN. The chapter also introduces DSA and discusses regulatory and incumbent protection approaches.

Chapter 3 reviews the current state-of-the-art and existing literature most closely related to this study. The chapter ends off with a summary of gaps identified in related work and highlights elements that set this research apart from related work.

Chapter 4 highlights the challenge of meeting TVWS regulation compliance in a multi-hop environment comprising long distance links. The chapter presents the proposed mesh formation protocol aimed at achieving TVWS regulation compliance right from the network formation phase.

Chapter 5 focuses on the link metric aspect of routing in WMNs using DSA. The chapter pinpoints inadequacies in existing link metrics and discusses the proposed approach.

Chapter 6 motivates the need for a performance prediction model. The chapter presents the design and evaluation of the proposed framework for optimal multi-link utilisation.

Chapter 7 explores the dependency of received signal strength indicator on height for throughput optimisation and discusses additional considerations relevant to the deployment of TVWS-based networks.

Chapter 8 recapitulates the research problem and summarises the key findings and contributions of this research. The chapter concludes with a discussion of limitations of the study and future research directions.

Chapter 2

Background

2.1 Wireless mesh networks overview

Due to low up-front costs and easy expansion associated with wireless mesh networking, the technology presents a viable alternative solution towards effort aimed at extending connectivity to rural and under-served areas. A wireless mesh network (WMN) comprises mesh clients and mesh routers. Mesh routers take part in the relaying of network traffic and play the role of gateway or repeater. Mesh clients on the other hand refers to end-user devices such as laptops and phones that connect to the mesh network for services via Ethernet or mesh access points. Mesh network architectures may be placed in three generic categories namely *infrastructure*, *client* and *hybrid* WMN. WMNs may further be classified as point-to-point, point-to-multi-point, and multi-point-to-multi-point depending on the nature of connectivity.

2.1.1 Advantages of WMNs

Regardless of the type of architecture, the key attractive characteristics that set WMN apart from other types of networks include *multi-hopping*, *ad-hoc networking* and capabilities of *self-organising* and *self-healing*, multiple types of network access and interoperability with other wireless networks [17].

Furthermore, using masts as illustrated using dotted lines in Figure 2.1 to extend connectivity adds to the infrastructure costs. Secondly, analysis of signal strength measurements in the UHF band at different heights shows a high correlation between signal strength and receiver antenna height. On channels with high signal strength, the television transmitter signal increases by as much as 2.5 dBm per 1 m increase in height above the ground [18]. It is expected that the noise floor will have a stronger negative impact on mesh nodes at high sites especially when they move "spectrally" closer to television transmitters [19]. Mesh networking on the other hand (illustrated with solid lines in Figure 2.1), allows us to lower the radios, which reduces costs as well as the amount of interference inflicted by primary transmitters but, still able to extend connectivity using multi-hopping.

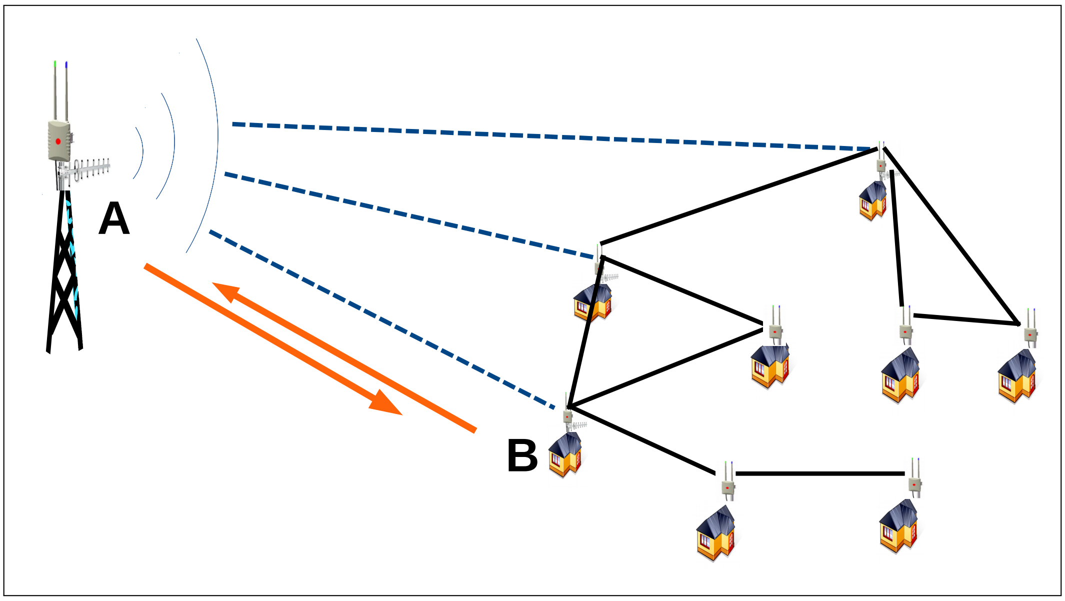


Figure 2.1: Using masts for point-to-multipoint coverage extension.

2.1.2 Limitations of wireless mesh networks

Multi-hopping in ad-hoc mode is not enabled by default, it is effected by applying routing. The ensuing disadvantage is that, it becomes difficult to use *dynamic host configuration protocol* (DHCP) when using Internet Protocol version 4 (IPv4). This is because a DHCP request will not be forwarded across a multi-hop link, and so IPv4 addresses have to be statically assigned [20], which can be tedious if the WMN consists of more than a few nodes. Possible workarounds include autoconfiguring IPv6 addresses from the devices' MAC address [21].

Furthermore, *General Systems Theory* (GST) describes the whole as being greater than the sum of its individual parts i.e. $2+2>4$. For a WMN this synergistic view holds substantially true in terms of coverage extension and fault tolerance, but not so in the throughput aspect. Effective end-to-end throughput reduces as the number of hops increases. For example, assuming a uniform transmission rate of W bits per second at each node, asymptotically the worst and best case throughput is respectively in the order of

$\frac{W}{\sqrt{n\log(n)}}$ and $\frac{W}{\sqrt{n}}$ where n is the number of hops [22].

Experimental results show that the TCP throughput under ideal conditions is given by

$\frac{W}{n^{0.98}}$ which is significantly less than the theoretical predictions [23].

2.2 Standards on WMNs

WMNs are commonly deployed using wireless technology based on IEEE 802.11. Besides proprietary solutions, WMNs are typically realised by combining the 802.11 MAC protocol with layer 3 ad-hoc routing [20], [24], or layer 2 ad-hoc routing [25] depending on the architecture and application as mentioned in section 2.1. One notable WMN specific standard is the 802.11s [26], [27]. The 802.11s standard specifies Independent Basic Service Set (IBSS) mode connection among mesh nodes and also supports client node connections to the mesh nodes.

2.3 Networking with dynamic spectrum access

Motivated by the increased demand for bandwidth in the license-free frequency bands and under-utilisation in the licensed bands, numerous proposals [28, 29, 30] have in recent years been put forward towards opportunistic spectrum access. Opportunistic spectrum access also referred to as Dynamic Spectrum Access (DSA) is a spectrum assignment paradigm where devices are able to make real-time spectrum usage adjustments and adapt to changes in their spectral environment to meet performance objectives. Spectrum is viewed as consisting of three abstract regions, namely *white space, black space* and *gray space* [31], [32], [33].

White space is the term used to refer to parts of the licensed spectrum that are vacant either spatially or temporally i.e. unused in a given geographical location or unused for an amount of time. When the white space under consideration is unused television channels around a given region, then it is defined largely in frequency terms.

Black space refers to the region inside the primary user's coverage zone such that the secondary system is able to detect the primary signal and therefore cancel the interference. Black space based communication is where a radio deliberately utilises the same frequency as the primary transmitter provided an inconsequential amount of interference is caused. The black space radio meets that requirement by turning the transmission power down to a sufficiently low level.

Gray space is the region outside the primary user's coverage area where the secondary system receives a significant amount of interference, but in principle is not close enough to cancel the interference from the primary user.

DSA potentially allows unlicensed users access to licensed portions of the spectrum when not in use by the licensed users. Researchers, industry and administrations have blamed the apparent spectrum shortage on inefficient spectrum resource utilisation associated with Fixed Spectrum Access (FSA) schemes currently in place. Therefore, DSA may be considered as a viable solution to the ever increasing demand for spectrum in urban areas and the need for coverage extension to unconnected areas as summarised in Table 2.1.

	Urban	**Rural**
Typical characteristics	spectrum crunch, dense population	abundant spectrum, sparse population, poor connectivity
Application scenario	MetroNets, IoT	last mile connectivity
Ideal spectrum features	high frequencies, short range	lower frequencies, long transmission range
Potential DSA benefit	efficient spectrum utilisation	lower cost of extending connectivity by using spectrum on a secondary basis

Table 2.1: Potential benefits of DSA for urban and rural community connectivity requirements.

2.3.1 Benefits of DSA based communication

Internet Protocol (IP) based wireless networks that use DSA have several benefits in comparison with their FSA counterparts. DSA benefits emanate from the capability to select spectrum with desired characteristics such as longer transmission range, better obstacle penetration and minimal interference caused/suffered. The benefits of DSA based communication can be substantiated by analysing path-loss and the physics of three basic propagation mechanisms, namely reflection, diffraction, and scattering characterising the operating spectrum. Studies have shown that wireless communication using alternative portions of the spectrum offers several improvements over the 2.4/5 GHz bands that WiFi uses. The electromagnetic properties of waves in the ultra high frequency (UHF) television band for example, have a number of advantages when used for communication, such as enhanced signal propagation, which allows for longer transmission range and obstacle penetration [34].

Traditionally, governments through their respective agencies assign national licenses (usually at a fee) for users to operate in a particular frequency band exclusively. These assignments stay unchanged over the license validity period, typically 5-20 years. The cost of spectrum incurred by service providers is inevitably passed on to the consumer. Studies have shown that FSA results in inefficient spectrum utilisation [35, 36, 37]. White space can be found in any frequency band such as 4G (LTE) and Very High Frequency (VHF). However, the current emphasis is on the UHF television white space (TVWS) because this is where the most significant white space is found. In addition, TVWS is ideal spectrum for rural connectivity.

2.3.2 DSA regulatory approaches

The three main spectrum sharing approaches are Licensed Shared Access (LSA), Collective Use of Spectrum (CUS) and hierarchical model [38].

LSA is a regulatory approach where a limited number of users are authorised to use a frequency band that is already assigned to one or more incumbent users provided they do so in accordance with the applicable sharing rules agreed upon by the incumbents and the secondary users. Under LSA, secondary users are given individual licences and both secondary LSA licensees and primary users are guaranteed protection from interference.

CUS is a general authorisation where an unlimited number of independent users are allowed spectrum access in the same range of designated frequencies at the same time under a set of conditions. Under CUS class of usage, devices are allowed to use unused spectrum found through the device's own capability. Unlike LSA, the number of CUS users is not controlled, which implies QoS depends on the level of congestion.

Hierarchical model combines the operational principles of LSA and CUS. Similar to LSA, incumbents are given top priority to access spectrum at any point in time whereas, secondary licensees are given priority when spectrum is not in use by the primary user. Under the hierarchical model, there is a general authorisation similar to CUS when spectrum is not in use by neither primary nor secondary user. Unlike CUS, the hierarchical model general authorisation applies to the same band licensed to primary and secondary users. The term *light-license* is sometimes used to describe this type of general authorisation. Users may be required to register with the regulatory authority that might limit the number of authorisations or restrict registration to particular entities such as tertiary institutions for example.

2.3.3 Methods of detecting white space and accessing spectrum

The methods for identifying white space fall in one of three general categories namely *geolocation spectrum database* (GLSD), *pilot channel* and *spectrum sensing* used independently or one method combined with another [39].

GLSD involves establishing a regulator-approved central database that a device queries to get white space spectrum information at the device's location. There are two main schemes used for the GLSD to learn about spectrum availability at a particular location. The first is a *data-driven* approach that uses spectrum measurements for particular locations. The second is *model-driven* where spectrum availability at a given location is computed using radio frequency models [40]. The data-driven approach has the benefit of determining white space with precision however, widespread measurements are required, which could take a long time to accomplish. In addition, radio frequency spectrum scans have to be re-done whenever new transmitters are added or there are changes in transmission characteristics such as antenna height, transmission power or location of the primary transmitter. The model-driven approach is convenient but, the performance in terms of complexity and accuracy depends on the particular model used. Secondly, the method requires up-to-date information on primary transmitters.

Spectrum sensing requires the secondary device to continuously monitor its radio environment to detect the presence of incumbents, and determine the available channels. Conventionally, spectrum sensing refers to the measurement of the radio frequency energy on the channel. However, in the context of cognitive radio, sensing can be broadened to include other dimensions such as *code* and *angle* [41]. Sensing techniques fall into one of two main categories, *energy detection*, and *feature detection* based sensing [42]. Energy detection compares the energy detector output with a noise floor dependent threshold to determine presence of signal on a given channel. The feature detection method captures spectral signatures such as cyclostationarity, segment-synch, pilot, etc. depending on the type of signal under consideration.

Data fusion is a term used to describe an approach that combine GLSD with sensing. Spectrum database information is complemented by sensing to cater for dynamic incumbent usage patterns. Sensing could also be used for establishment of initial connection to the database or to obtain granular information on the available channels.

Beacons/Pilot channel is a centralised cellular-based implementation where coexistence information is shared over a known control channel [43]. A secondary user may transmit in white space if it receives a beacon signalling availability of a channel. Oppositely, a secondary user may continue transmission on a given channel until it receives a beacon declaring the channel unavailable.

Out of these three methods of identifying white space spectrum, GLSD is widely considered as the immediate viable solution largely because of its centralised nature, which eases implementation complexities. In addition, the GLSD method offers guaranteed levels of protection to incumbents. However, the current GLSD implementation is only concerned with protection of primary users and remains agnostic to secondary spectrum usage. Research has shown that the level of tolerable interference reduces as multiple devices access adjacent channels at the same time [44], but existing regulation is nonetheless mainly concerned with protection of primary users and has not stipulated methods of coexistence among multiple secondary users accessing white space simultaneously [45]. Therefore, more work remains to be done in developing spectrum etiquette protocols and managing coexistence among secondary spectrum users.

This research investigated GLSD performance for white space detection and found that as currently deployed, GLSD alone is inadequate in determining white space accurately (*see* section 7.2.2). The GLSD is prone to inaccuracies due to reasons ranging from limitations in propagation modelling to tending lack of up-to-date primary transmitter information. Furthermore, the GLSD may indicate a particular channel to be unoccupied based on primary transmitter (e.g. television broadcast) information, however the channel may be tainted by incumbent signals due to high decodability threshold [46], and unregistered sources in adjacent channels [47]. In view of the identified drawbacks of a GLSD when used independently, this dissertation recommends a hybrid approach i.e. GLSD coupled with localised spectrum scans.

2.4 Standards related to DSA

In comparison with fixed transmission medium, white space technology is still in its infancy. However several standards have already been drafted in alignment with the white space communication paradigm. The following sections provide a brief description of standards from the IEEE 802 groups [48], [49], [50], ECMA [51] and IETF [52] that are closely related to the emergence of white space based communication.

2.4.1 IEEE 802.22

The IEEE 802.22 standard specification covers the air interface, including the cognitive medium access control layer (MAC) and physical layer (PHY) of point-to-multipoint wireless regional area networks (WRAN) consisting of a fixed base station with fixed and portable end user devices operating in the VHF/UHF television broadcast bands from 54 MHz to 862 MHz. The principal assumption behind IEEE 802.22 is that communication devices share spectrum with primary users and as such, spectrum availability may vary from time to time and place to place. In addition to the 54 MHz - 862 MHz range, the spectrum may span 1300 MHz to 1750 MHz, and 2700 MHz to 3700 MHz. These bands may differ from country to country as they were specified by the FCC for the United States. However, the standard is intended to align emerging regulations with the current 802.22 technology and enable interoperability among WRAN products from different vendors.

2.4.2 IEEE 802.19

The IEEE 802.19 standard specifies radio technology independent methods for coexistence among dissimilar devices or independent networks of devices operating in television bands. Coexistence has been defined as the ability of multiple spectrum-dependent devices or networks to operate without harmful interference. Coexistence is viewed as a service rendered by the coexistence system to white space devices. This system consists of three logical entities that use TCP/IP in all the exposed interfaces as shown in figure 2.2.

The standard outlines two classes of coexistence algorithms: *coexistence discovery* and *coexistence decision algorithms*. Coexistence discovery algorithms are used by the coexistence discovery and information server (CDIS), and the coexistence manager (CM) to discover white space devices that might interfere with each other. The CM uses coexistence decision algorithms to reconfigure white space devices to avoid interference. The standard describes several algorithms for each class but, does not restrict implementation to any particular algorithm. In addition, the standard does not provide any specificity on the physical implementation. Therefore, the coexistence functionality may be built into a single device or the role of logical entities may be enabled in separate devices.

In addition to specifically addressing coexistence among IEEE 802 devices for effective use of TVWS, the IEEE 802.19 standard is also projected to be useful

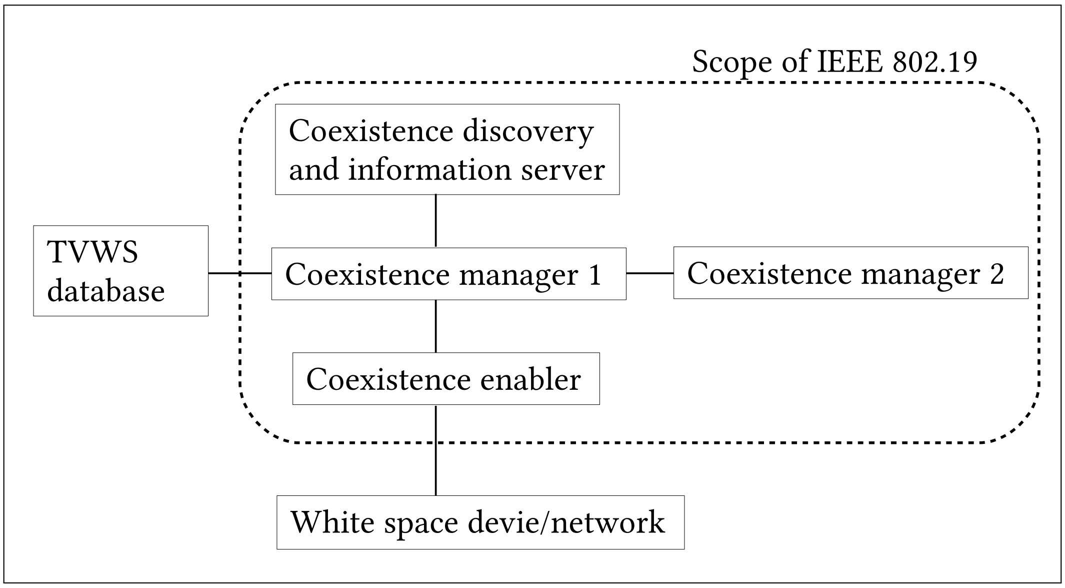


Figure 2.2: Coexistence system architecture.

for non IEEE 802 networks as well. Furthermore, though the standard specifies a TVWS database logical entity, the architecture can be generalised so much so that the system works with any method of white space detection e.g. sensing, and in other spectrum bands.

2.4.3 IEEE 802.11af

The IEEE 802.11af standard covers specific requirements for local and metropolitan area networks. It is an amended IEEE 802.11 physical layer (PHY) and medium access control (MAC) sub-layer enhanced to support operation in TVWS. The amendment adds a Television Very High Throughput (TVHT) PHY specification using orthogonal frequency division multiplexing (OFDM) based on the geolocation database control for TVWS detection and incumbent protection. The standard defines basic channel units (BCUs), namely 6 MHz, 7 MHz or 8 MHz depending on the regulatory domain. This implies that two contiguous BCUs provides 12 MHz, 14 MHz or 16 MHz, and four contiguous BCUs would provide 24 MHz, 28 MHz or 32 MHz. Single BCU transmission mode is mandatory whereas, use of multiple BCUs is optional.

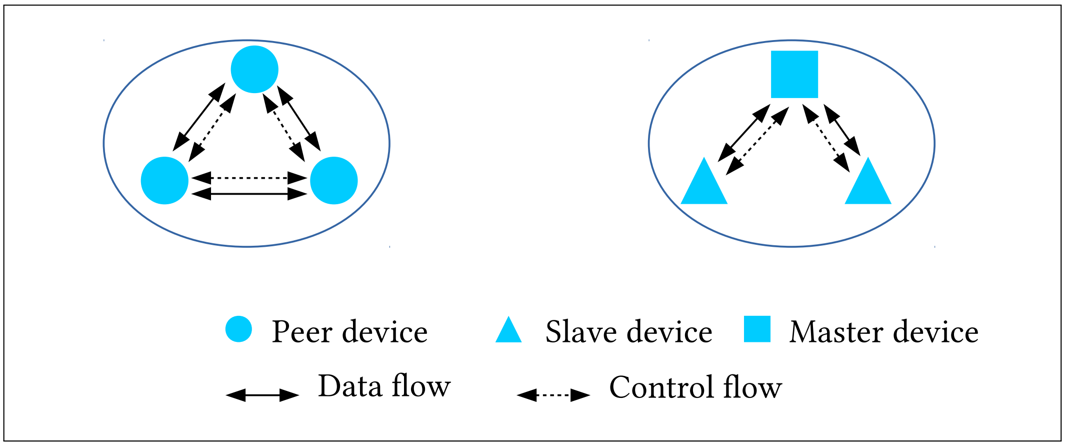


Figure 2.3: Basic network architectures.

2.4.4 ECMA 392

The standard specifies a MAC sub-layer and a PHY layer for personal/portable cognitive wireless networks operating in TVWS. Three device modes namely, master, slave, and peer are defined but, the standard does not support autonomous device mode transition. In a master-slave configuration, the master coordinates network formation, channel access, and communication between slave devices as illustrated in figure 2.3. On the other hand, in a peer-to-peer network, devices use distributed beaconing and channel reservation to coordinate channel access. A peer-to-peer network may also be described in this context as ad-hoc, self-organising, and self-healing. The standard also specifies a MAC client (MUX sub-layer) for higher protocols and several incumbent protection mechanisms that may be used to meet regulatory requirements. These mechanisms include protocols for detecting incumbents, coordinated channel measurement, dynamic channel selection, and transmit power control.

2.4.5 PAWS

The Protocol to Access White Space (PAWS) is a standard protocol defined by IETF to achieve interoperability between devices and databases of spectrum availability. Spectrum databases store information on spectrum availability and protection rules based on the guidelines of the regulatory domain. The centralised nature of the database approach provides two key benefits. Firstly, the approach relieves the device of the complexities associated with spectrum-policy conformance. Secondly, in the event of a policy change, updates are limited to database thereby simplifying adoption as opposed to updating numerous devices. PAWS is built on top of HTTP and Transport Layer Security (TLS) protocol, and allows a device with geolocation capability to query the database appropriate for the location and obtain spectrum availability information. The standard defines two types of devices i.e. a *master* that uses a URI (dynamically/statically obtained) to interact with the database directly and a *slave* that queries the database through the master device.

2.5 Peculiarities of mesh-networking with DSA

The advantages of DSA when combined with mesh networking not only build on the benefits of WMNs, but also compounds the challenges as well. This section discusses some of the challenges arising when DSA is applied to mesh networking.

2.5.1 Standardisation gap

To begin with, there are a number of WMN applicable standards, different DSA regulatory frameworks and several DSA related standards as described in sections 2.2, 2.3.2 and 2.4 respectively. However, at the time of writing this dissertation, a standard that bridges WMN and DSA requirements is yet to be drafted. For example, ICASA's draft TVWS regulation [53], [54] stipulates that a WSD must query a GLSD whenever the WSD's position changes by 100 m or more. This requirement is befittingly in anticipation of variations in the RF spectrum map potentially arising with every 100 m shift in location. However, the regulation provides little or no guidelines on how mesh nodes operating in ad-hoc mode (prospectively placed hundreds of metres apart) ought to access and coordinate spectrum usage. Therefore, running the WMN on a common optimal and clean DSA channel without interfering with primary transmissions at one corner of the network remains a significant challenge. In addition, WMNs with fixed spectrum operate on a set of fixed channels that remain fairly unchanged over time, whereas it is expected that the state of a WMN with DSA will be influenced by the activities of primary spectrum users.

2.5.2 Limitations of the layered approach

Communication between devices is often described with reference to the *layer model*. Protocol designers refer to the layer model as a tool for breaking down the complex communication process into simpler sub-processes. Using the typical layer model, individual layers communicate only with neighbouring layers i.e. layer k only communicates with layer $k-1$ and layer $k+1$. The layered approach has the advantage of breaking down the complex communication problem into a hierarchy of less-complex layers [55]. Each layer addresses a sub-communication problem and that allows the development of protocols on one layer to be done independent of protocols on other layers. This approach has worked well in the more static environments. However, in a DSA-based network the sub-problems on one layer do not interact with other layers in a strict hierarchical fashion, which makes it difficult to maintain total transparency in the layer functions. For example, when the best path is defined in terms of *channel width* availability, the routing protocol may need to interrogate the MAC layer and possibly the physical layer for such information. In light of this and other observed limitations of the layered model, there is a general consensus among researchers [56], [57], [58] that for optimal solutions in multi-hop wireless networks, it is imperative to adopt a *cross-layer* design approach. A cross-layer approach may be defined in two ways: firstly, as the interaction between non-adjacent layers and secondly, the spanning of a solution across multiple layers as illustrated in Figure 2.4. Several cross-layer design methodologies in the context of multi-hop wireless network have been proposed [59], [60], [61]. Characteristics of a DSA-enabled WMN add to the existing motivation for cross-layer design thinking in multi-hop wireless network environments.

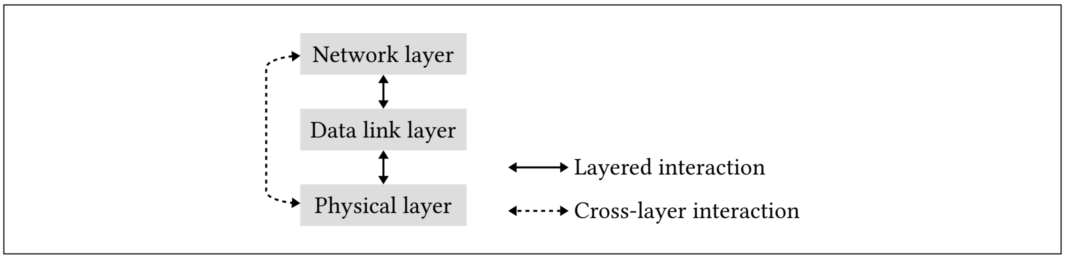


Figure 2.4: Cross-layer thinking with reference to the Open System Interconnect model.

2.6 Chapter summary

The chapter has given an overview of WMNs architectures and described typical characteristics of mesh networks. The chapter also gave an overview of DSA and outlined general potential benefits for both rural and urban communities. The different methods of detecting the spectrum opportunity and how these fit into the different DSA regulatory frameworks is also discussed. The chapter also highlighted the different DSA related standards applicable to different network types. Applying DSA to WMNs builds on the advantages that WMNs hold, but also compounds the challenges in the two fields. The chapter ended off with a discussion on some of the unique challenges faced in WMNs with DSA.

The next chapter presents prior work that is most closely related to this research.

Chapter 3

Related work

Wireless mesh networks create multiple possible paths between any sender/receiver pairs as already mentioned previously in the background chapter. *Routing* is the process of determining the best path between the source node and the target destination node. Literature abounds with numerous studies on routing in WMNs. This chapter presents a review of the work of other researchers around the thesis topic. The review was conducted with the intent of gaining insight and a better understanding of the subject matter. To guide the review and analysis, the following question was posed: how has the shift toward the DSA paradigm influenced routing in wireless networks?

3.1 Method

A pool of data comprising resources from online digital libraries as well as the institutional library were reviewed and analysed. The method draws on a method of *secondary analysis* of research by Glass [62] and a systematic qualitative *meta-analysis* procedure developed by Ke [63]. Secondary analysis refer to the re-analysis of data for reasons such as applying better statistical techniques in answering old research questions or using old data to tackle new questions. Meta-analysis on the other hand, is the analysis of analyses or the integration of findings from different individual studies by analysing a collection of analyses.

3.1.1 Sources of literature and search approaches

The studies reviewed were located by manually searching electronic records of publicly accessible publications that included, but not limited to the following databases: ACM digital library, Elsevier ScienceDirect, IEEE Xplore, Springer, UCT Primo and Wiley Science. The search strategy varied depending on the search tool used. Nevertheless, the general search terms used included "routing in wireless mesh networks", "cognitive radio networks", "wireless network with dynamic spectrum access", "cognitive radio in wireless mesh networks", "cognitive ad-hoc networks", "next generation wireless networks", "TVWS mesh network" and "TVWS network" coupled with backward and forward reference searching [1].

The search results underwent a series of parsing that initially involved a look at the title and a review of the abstract and entire content depending on the gleaned degree of relevance to the overarching topic under consideration. The studies considered in this chapter were selected using a subjective criteria guided by how relevant the source is to this dissertation or aspects of it. The degree of relevance was determined using the *theory of concentric circles* as depicted in Figure 3.1. The concentric circles theory approach was initially postulated by Ernest Burgess to explain the social structure of urban communities [64]. The method has since then been widely used in the field of political science to design and analyse foreign policy [65], [66] among other use cases. The concentric circles theory arranges items in the scheme of things in terms of concentric circles, which represent a higher order of priority as one moves inward from the outer circle. Extending this way of conceptualising complex issues, this dissertation applied the concentric circles theory to direct the criteria for inclusion/exclusion of sources. Articles that belonged to the centremost category were considered most applicable.

[1] Backward reference searching refers to the process of locating and reviewing the work cited in a publication. Forward reference searching refers to the practice of identifying and examining studies that have cited the original work. This helps to understand the evolution and expand knowledge on a given topic.

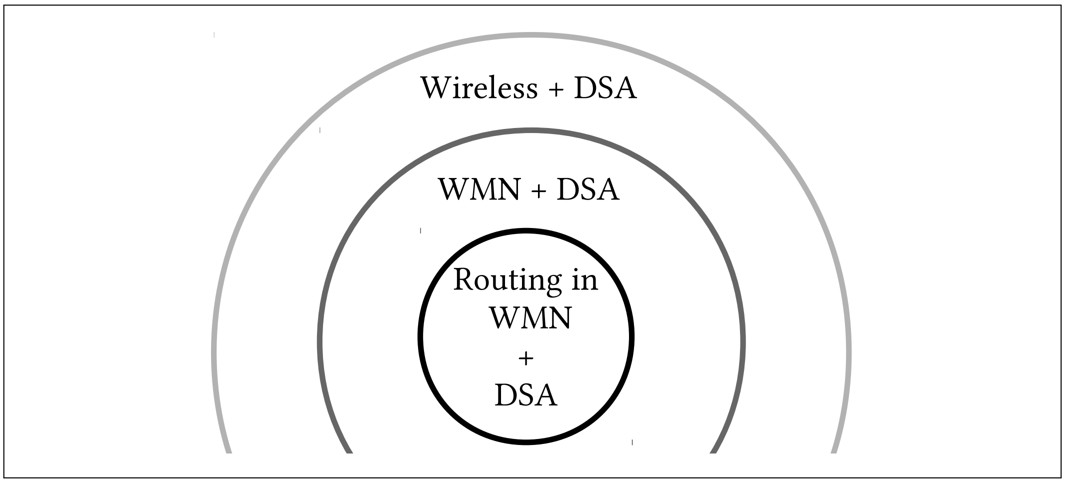


Figure 3.1: Using the theory of three concentric circles to determine the relevance of work.

3.2 Lessons learnt and inspiration drawn from related work

This dissertation draws from three interrelated fields, namely *routing*, *multi-channel/multi-radio systems*, and *cognitive radio networking* in the mesh networking context. The following sections discuss findings from studies situated at the intersection of the aforementioned research directions.

3.2.1 PU region avoidance

One of the (if not the most) critical requirement of any DSA based network is to avoid causing interference in and around the primary user (PU) region . From a WMN perspective, the solution needs to carry out two tasks, namely route discovery and route maintenance under the PU protection constraints. These tasks correspond to network formation and topology management functionalities of the mesh protocol.

Literature is replete with studies such as the enhanced dual diversity cognitive ad hoc routing protocol (E-D2CARP) [67] that identify the problem of network formation in DSA based ad-hoc networks, but fail to provide a clear solution that directly addresses regulation compliance in a multi-hop environment from network formation through the topology management stages. E-D2CARP is an on-demand protocol that attempts to establish a routing path in a manner that circumvents the

PU region(s). The E-D2CARP mechanism involves node(s) that happen to fall inside the PU region to set their status to "IN-PU-REGION" and change back to "OUT-PU-REGION" when there is no PU activity. By so doing, it is expected that the set of intermediate forwarding nodes between the sender and receiver will exclude the nodes inside the PU region. Besides the drawbacks of on-demand routing for WMNs, it is not clear from the authors' report how spectrum status information gets communicated among the nodes and how network-wide channel change transitions are effected, let alone coordinated.

Several other studies [68], [69], [70] attempting to address the problem of network formation in DSA based WMN presuppose devices have access to a common control channel (CCC). The design of CCC is a separate topic on its own [71], however with the CCC approach, nodes generally tune to the CCC initially at start-up and thereafter periodically at predetermined intervals to transmit and listen for control messages. The CCC approach undoubtedly eases the control and coordination complexities. However, there is compelling evidence pointing to the fact that the CCC approach may not be feasible in most deployment scenarios due to lack of uniformity in the distribution of other transmitters [72].

Given the arguments against the CCC applicability, several other prior related studies on network formation and topology management in DSA based mesh such as CogMesh [73], have appropriated *cluster* based methods. The cluster based approach groups the nodes in tandem with spectrum availability so much so that the scope of determining a suitable operating channel is reduced to individual clusters. The focus of work employing the cluster approach has been on the *selection of cluster heads* and optimisation of *cluster formation*. The major limitation in prior related work is that they assume a contiguous spectrum map, which is not typically applicable. On the other hand, work identifying the problem of fragmented spectrum [74] address other performance requirements and not the problems associated with mesh formation.

The other observation made from the literature surveyed is that meeting or improving end-user performance requirements is emphasised while overlooking regulation compliance. Prior related works have proposed algorithms that are based on full network topology information or a priori knowledge of primary users, which is a valid premise for FSA cases. However, the assumption does not hold for DSA-based WMNs because of the fragmentation that commonly characterises the spectrum space and the ad-hoc nature of WMN connectivity. It can be seen from the above analysis that there is a general lack of adequate detail on ensuring a regulation compliant network formation process. To back that claim, consider CogMesh for example, where it is mentioned that if a node fails to find a cluster to join, it randomly chooses a channel and starts a new cluster. The report went on to say that a cluster-head chooses gateway nodes and interconnects with other cluster-heads. As can be seen, there is insufficient clarity on how cluster-heads multiple-hops away get to establish connections. Similar sentiments can be expressed after analysing the distributed channel assignment algorithms proposed for DSA based WMN [75], as this also focuses on enhancing performance (assuming the network topology is formed completely) and does not show how that is achieved in a compliant manner.

Whilst prior related studies have unquestionably not addressed DSA regulation compliance at the mesh formation stage, the mechanisms used at the routing level to avoid interfering with incumbents can be placed in two generic groupings. The first approach aims to detect the PU transmission region and attempts to avoid forwarders (or relay nodes) that fall inside the PU region as explained in the earlier paragraph. This design assumes that there are other nodes outside the PU region than can forward packets between the sender and receiver, which may not always be the case. The second approach is where any node deemed next-best-hop can forward data traffic, but avoid interfering with the PU by reducing the transmission power to sufficiently low levels. The assertion is that secondary users can use the same frequency as primary users provided the secondary users' power spectral density is below that of the primary user [76]. The terms *overlay* and *underlay* are sometimes used to respectively refer to spectrum co-existence paradigms where the secondary user uses vacant channels only and in which the secondary user uses the same channel as the primary user, but at power levels low enough to eliminate interference with primary users [77].

The obvious drawback of lowering the transmission power is that it is only viable if the nodes are a short enough distance apart. To explain the relation between transmission power and transmission distance, consider the famous Friis' equation [78]:

$$P_r = P_t \left(\frac{\lambda}{4\pi d}\right)^2 \implies d = \frac{\lambda\sqrt{P_t}}{4\pi\sqrt{P_r}} \tag{3.1}$$

where P_r = remaining power of the wave at the receiver, P_t = transmission power of sender, λ = wavelength, d = distance between the receiver and the sender. It is evident based on equation 3.1 that effective transmission distance reduces when transmission power is reduced. Therefore, reducing the transmission power as a method of incumbent protection could potentially result in loss of connectivity among the nodes at long distances.

3.2.2 Routing metrics

It is worth noting upfront that variations in the way the metric is calculated (e.g considering efficiency, accuracy, amount of overhead and other aspects) and settings for parameters such as routing packet interval in a given protocol contribute substantially towards the overall performance. Therefore the performance of routing metrics (sometimes referred to as *path-weight functions*) should be analysed more wholistically.

Routing protocols that support multiple metrics facilitate the evaluation of routing metrics in that performance variation due to the protocol's internals is minimised and differences in performance can more confidently be attributed largely to the metric properties. Work meeting this criteria includes, Optimized Link State Routing (OLSR) [79], Dynamic Source Routing (DSR) [80], Multi-Radio Link Quality Source Routing (MR-LQSR) [81], BatMan-eXperimental Version 6 (BMX6) [82] as shown in Table 3.1.

A study conducted to compare standard hysteresis and the Expected Transmission Count (ETX) routing metrics using OLSR protocol showed that hysteresis

Table 3.1: Routing protocols supporting multiple routing metrics.

Protocol	Layer/ Type	Supported metrics
OLSR	2, link-state	Hysteresis, ETX
DSR	2, link-state	ETX, hop-count, per-hop RTT
MR-LQSR	2, link-state	WCETT, ETX, Hop-count
BMX6	2, distance-vector	Vector metric, Transmit quality, ETX, Hop-count

out-performs ETX on all accounts [23]. However, this holds for medium-to-large size networks (roughly 21 to 49 nodes). For a small to medium size network, ETX showed better performance.

ETX is generally considered as a superior routing metric to hop-count because it implicitly captures the hop-count and additionally takes the quality of the links into account by considering the packet delivery ratio. However, when there is mobility at the sender, hop-count performs better than ETX and Round Trip Time (RTT) link-quality metrics [80]. Earlier work on WMN routing metrics focused on accounting for the lossy nature of the wireless medium. As a result, the major limitation of basic metrics such as ETX and Expected Transmission Time (ETT) is that they only aim to increase the probability of packet delivery. They do not factor in interference and are based on the supposition that the links comprise uniform data-rates.

In response to the limitations of ETX and other basic metrics listed above, Weighted Cumulative ETT (WCETT) was developed for heterogeneous multi-radio environments. The report from the study comparing WCETT, ETX and hop-count implemented in MR-LQSR showed that WCETT provided the best performance while hop-count yielded the least performance. However, the study did not consider the impact of mobility, which leaves no evidence to support nor refute the suggestion that hop-count would outperform WCETT in a scenario involving mobility. In addition, there is a paucity of studies to collaborate the authors' claims on WCETT. Nonetheless, there is compelling evidence from analytical and simulation studies showing that WCETT itself lacks consideration for inter-flow interference and *isotonicity*[2] for efficient computation of the minimum weight path. Subsequently, in different comparative studies of WCETT with the Metric of Interference and Channel-switching (MIC), MIC performed superiorly to WCETT [83], [84]. While MIC improves on its predecessor in that it aims to achieve load-balancing by accounting for inter-flow as well as intra-flow interference interference, it does not explicitly account for possible variation in data-rates among the different link options.

The above snippet of collected studies on wireless network routing metrics albeit narrow, is a sufficient representative sample of the general pattern[3] prevailing in literature regarding the subject of routing metrics for wireless networks. Based on these and results from other related studies, it can be said with confidence that each metric typically has a scenario(s) or network condition(s) under which it either flourishes or fails. Following this line of enquiry, this dissertation drew out the concept matrix summarised in Table 3.2 to accentuate the core network strands and associated metrics. This research focused on WMNs comprising static nodes with no power constraints, however for completeness the concept matrix includes energy constrained and mobile environments.

While there is sufficient evidence to support the concept of *network classes* based on Table 3.2, there is still much to query and explore in the broader task of choosing the ideal metric. For a start, there is need to develop efficient methods of detecting network characteristics at the protocol level for purposes of determining the suitable routing metric. The other thing routing protocol architects need to consider is to develop highly *cohesive* metric calculation modules and institute loose *coupling* between the metric computation functionality and the rest of the routing mechanism. This will foster the much needed interchange of innovative outputs from work on routing and routing metrics among different studies. Furthermore, at present the points of transition for determining factor(s) i.e. where performance

[2]The isotonicity rule says that the order of the ranking on two paths should be preserved when a third path suffixes or prefixes the paths. See chapter 5 (Table 5.1) for an expanded definition of this and other metric properties.

[3]The observed pattern is that of this metric out-performing that metric, and that metric performing poorly under a given set of network characteristics or test conditions.

Table 3.2: Concept matrix of routing metrics. A dash (-) is used to indicate missing detail.

Name	**Target network/characteristics**									
	Energy constrained	Mobile nodes	Static nodes	Multi-radio	Single radio	Uniform data-rates	Diverse data-rates	Size		
								S	M	L
Hop-count		✓			✓			✓	-	-
Hysteresis			✓		✓					✓
EXT			✓		✓	✓		✓	✓	
ETT			✓		✓		✓	✓	✓	-
MIC			✓	✓				✓	-	-

of one metric begins to deteriorate and the other starts to get better are still only vaguely clear. All in all, the methods discussed in the previous section may be described as “best effort” approaches in that the routing protocol chooses a path deemed optimal for all data traffic.

Other approaches to assign link costs especially in mobile ad-hoc network (MANET) environments aim to explicitly support QoS for different classes of traffic priorities. One popular approach is to consider the network as an artificial neural network (ANN) and use link metrics to represent the weights of the ANN [85]. Learning techniques such as genetic algorithms can then be applied to determine the optimal path based on the optimisation function of the network. For this purpose, the use of *batch* based [86] and *online* based [87] machine learning algorithms to predict link quality have been proposed in prior related work. In these publications, the principle of link metric is expressed using the concept of “link quality predictors”. It is apparent that the usefulness of these machine learning based solutions depend entirely on the accuracy of the underlying prediction model. On one hand, batch machine learning methods cannot adapt once training is complete and as such accuracy may decline when the network conditions deviate significantly from the training data. Online based machine learning algorithms offer a better promise, but on the other hand, at the time of writing this dissertation, integration of online based machine learning with the routing module is still in its infancy. Therefore, it is unclear at this stage if the benefits that ANN promises will materialise because the aspects encouraging or inhibiting deployment are still unknown. There is a further dearth of test-bed based implementation and results, which raises concerns about the practicality of the solutions extending beyond the simulation environment.

There are other metrics highlighted in literature under the “cognitive radio network” umbrella. However, these are yet to be widely implemented and therefore, the findings are hard to substantiate let alone conduct comparative analyses at this stage. The other challenge affecting metric exploration is the degree and extent of coupling between the metric calculation component and the rest of the routing module. Tight coupling has hindered implementation of metrics in other routing protocols and eventual evaluation.

3.2.3 Multi-channel, Multi-radio systems

The current IEEE 802.11 based radios are said to be half-duplex i.e. the transmit and receive operations are not done simultaneously. This limits the network capacity in that throughput at relay nodes is halved as detailed already in the previous chapter (section 2.1.2). The capacity and performance of a network can be enhanced by using multiple channels at the same time. This requires multiple transceivers. Basic multi-channel capable nodes can be built using the following architectures [88]:

- *Multiple hardware platform* where two or more single-radio nodes are connected via Ethernet to form one logical multi-radio mesh router.
- *Single hardware platform* in which a single node has multiple transceivers fitted.
- *Single-chip multi-transceivers* where multiple transceivers are integrated into one wireless chipset on a router.

Enabling multi-radio capability can unarguably improve performance significantly, however mechanisms are still required to take advantage of the radios. Several routing protocols and metrics such as MR-LQSR protocol (introduced in section 3.2.2), *Weighted Expected End-to-End Delay* (WEED) [89] and *Generalized Partitioned Mesh network traffic and interference aware channeL Assignment* (G-PaMeLA) [90] to name but a few, have been proposed for routing in multi-radio scenarios. Other multi-radio network protocols such as Multi-radio Unification Protocol (MUP) [91] have been implemented at the link layer without modification to the upper layers. While these protocols are aimed at improving network capacity by making optimal use of multiple-radios, they are based on static channels and as such are ill-suited for the DSA environment.

Based on the survey conducted, there is a limited amount of literature on hybrid[4] back-haul link selection. The work most closely related to this dissertation worth pointing out are the schemes that have been developed for selecting the appropriate network for specific services given the integration of heterogeneous access technologies such as WLAN and cellular in 4^{th} generation (4G) communication systems . The approaches used include Fuzzy logic, Game Theory and mathematical techniques such as AHP and GRA [92], [93], [94], [95]. While these prior studies on network selection provide insight into the exploitation of multi-radio enabled devices for improved performance, the solutions proposed apply mostly to strict infrastructure based network environments that have some kind of centralised controller such as a base station. New mechanisms are needed to leverage hybrid links for back-haul WMN connectivity.

3.2.4 Routing in Cognitive Radio Networks

Routing protocols in Cognitive Radio Networks (CRNs) can be classified across multiple dimensions. Basic categorisation of routing in CRNs classifies the process as either *single-path* or *multi-path* routing [96]. Single-path routing refers to single-hop forwarding, whereas multi-path routing is where a network consists of redundant links between nodes to minimise the impact of interruption caused by primary user activity. A more comprehensive way uses three major taxonomies that are based on, extent of *spectrum awareness* [97], *diversity* [98], and *performance objective* [99].

[4]Multi-radios utilising different spectrum bands such as a combination of 5 GHz and TVWS.

Spectrum awareness based

Spectrum awareness based solutions may further be sub-classified as either *full spectrum knowledge based* or *partial/local spectrum knowledge based*. Spectrum awareness encompasses cognizance of both spectrum availability as well as spectrum quality. Full spectrum knowledge based solutions assume nodes know the full spectrum occupancy map through the spectrum database or the *master node*. Thus spectrum management is done via a centralised entity that may not necessarily be integrated with the routing process. On the other hand, partial or local spectrum knowledge based approaches rely on the spectrum information constructed locally at each node and through distributed protocols, shared among the nodes. Local spectrum knowledge based solutions are characterised by tight coupling between spectrum management and routing functionalities.

Several studies [100], [101] have identified the interdependence and shown that network performance is determined jointly by routing and channel assignment. For that reason several proposed routing algorithms such as ROSA [102], and CogWMN [103] have adopted the *cross-layer* [56] design approach to control the interaction between the routing and channel selection functionality. In CogWMN, the wireless mesh network is modelled as an undirected graph. The algorithm combines the channel allocation method with AODV routing protocol. ROSA and CogWMN respectively model the multi-hop wireless network as a directed connectivity graph and undirected graph. A time slotted CCC is assumed for spectrum control and coordination among the nodes. Both ROSA and CogWMN like many prior related work assume a pre-existing complete network graph and fail to address the graph formation part, which is an inevitable part of any WMN setup.

In other efforts, *Spectrum Aware Mesh Routing in Cognitive Radio Networks* (SAMER) [104] has been proposed for routing in CRNs. SAMER aims to find paths with the highest spectrum availability to maximise throughput. SAMER also attempts to balance the short-term opportunistic gains with associated switching overhead and the long-term optimality. The major shortcoming of SAMER and indeed other related studies is the premised mesh network operation or definition. For example, the authors mention that two communicating nodes have to contend for spectrum access using a control channel in the unlicensed bands. This view reduces spectrum requirements to two communicating nodes and completely ignores the multi-hop nature of mesh networks. The point at issue is that, if two nodes choose an operating channel that is orthogonal to the one used by its other neighbours, there is loss of connectivity with the other neighbouring nodes. SAMER could be a feasible solution if multi-frequency transmission capability among the nodes is enabled, but that would require a coordination scheme to be implemented, which is a non-trivial task. To add on, using multiple channels raises the chance of a node missing the RTS/CTS transaction on one channel while tuned to a different channel. For this and other reasons, IEEE 802.11 based single-radio mesh nodes have to be tuned to the same operating channel in order to maintain connectivity and for the routing protocol to maintain a correct routing table.

The other limitation observed in other related work such as Cognitive Routing Protocol (CRP) [105], is that they employ a method of ranking the next-best-hop based on the assumption that all links are symmetric, which is rarely the case in wireless environment. Therefore, on account of the issues pointed out, a lot remains to be done in ensuring that joint routing and channel assignment protocols address the concerns brought out in WMN environments.

Diversity based

Diversity based routing refers to a broad category of routing algorithms that aim to take advantage of peculiarities of the wireless space such as the inherent broadcast nature and spatial diversity of the wireless medium. Two of the main approaches include *opportunistic forwarding* and *network coding*.

Opportunistic forwarding itself is a wide class of routing schemes that leverage transmission opportunities instead of transmitting on a predetermined path. A wireless channel is inherently a single broadcast domain and with opportunistic routing, any node that "hears" the transmission can act as a relay candidate. The maximum end-to-end throughput with opportunistic forwarding is given by the solution to the objective function (3.2) given below:

$$\max \sum_{k=1}^{K} \sum_{l_{si}^{k} \in \mathbf{E}} \sum_{\alpha=1}^{M} \mu_{si}^{k\alpha} \tag{3.2}$$

where $\mathbf{E}$ = set of all the wireless links

$s_i =$ node operating on channel $k(1 \leq k \leq K)$

$\mu_{ij}^{k\alpha} =$ transmission rate on each link l_{si}^{k}

$\alpha = (1...M)$ denotes the times scheduled for concurrent transmissions.

Depending on the implementation, the *next forwarder(s)* can either be specified by the source or may require coordination among the candidate relay nodes to select the "best" forwarder. The advantages of opportunistic routing include dynamic selection of optimal path at the actual time of transmission and the ability (in principle) to combine multiple weak physical links into a single stronger logical link.

Network coding is a method of routing where multiple data packets are coded and delivered through a single transmission. Using this approach, a router can combine packets "over-heard" from different sources and send them out in one transmission. The destination then decodes to obtain the initial set of packets. Network coding increases efficiency by reducing the required number of transmissions. The improvement in efficiency realised through network coding is beneficial especially in multicast scenarios. Furthermore, retransmissions are inevitable due to the lossy nature of the wireless medium, therefore efficiency in transmission is valuable.

To overcome the limitations of individual diversity-based routing approaches such as opportunistic forwarding and network coding, an alternative approach is to appropriate a *hybrid* solution that combines the two methods in a complementary manner for added improvements.

Performance objective based

Irrespective of the extent of spectrum awareness and protocol diversity, routing protocols may be classified based on the performance objective, which could be link stability, throughput, localisation, energy based or multi-objective and so forth. Atomic metrics such as delay, hop-count, ETT, ETX, et al. are often combined as shown in equation 3.3 for improved performance trade-off.

$$\min_x \mathbf{F}(x) = [F_1(x), F_2(x), ..., F_n(x)] \tag{3.3}$$

where $\mathbf{F}(x)$ is a vector of performance objective functions $F_i(x)$ and n represents the number of objective functions or atomic metrics [106].

The optimal routing path is modelled by defining a global utility function M that is a combination of individual utility functions M_i where $1 \leq i \leq n$. Combining atomic metrics to form a global utility function is done using one of four main common methods namely, *weighted exponential sum or product, Lexicographic, weighted min-max* and *constraint-based* [96].

i **Weighted exponential sum** sums up the atomic metric exponentially as shown in equation 3.4 or multiplies as shown in equation 3.5 to form the global utility function.

$$M(r) = \sum_{i=1}^{n} w_i [M_i(r)]^p \tag{3.4}$$

where r is the routing path, $M(r)$ is the global performance objective function, which corresponds to F in equation 3.3, $w_i > 0$ is the weight of atomic metric i, $\forall 1 \leq i \leq n$, p is a constant parameter such that $1 \leq p \leq \inf$. The weight of the atomic elements w has to be decided, which renders the weighted sum method subjective depending on the choice of weights.

$$M(r) = \prod_{i=1}^{n} [M(r)]^{w_i} \tag{3.5}$$

ii **Lexicographic** global metric is where atomic metrics are ordered by level of importance and individual utility functions solved one at a time as shown in equation 3.7.

$$\min_r \quad M_i(r) \quad \text{such that} \tag{3.6}$$

$$M_j(r) \leq M_j(r^*) + \varepsilon, 1 \leq j \leq i-1 \tag{3.7}$$

where $M_j(r^*)$ is the optimum found in the j^{th} iteration and ε is a tolerance parameter.

iii **Weighted min-max** criteria aims to achieve fairness and balance among the atomic metrics.

$$M(r) = \max_{1 \leq i \leq n} \{w_i[M_i(r) - C_i]\} \tag{3.8}$$

where C_i for $i = 1, 2, ..., n$ are constraints.

iv **Constraint-based** approach does not weight the atomic metrics unlike the previously listed methods, but instead, one atomic metric is selected and regarded as the principal metric while the other metrics are considered constraints as shown below:

$$\max_{x} M_{i^*}(r) \tag{3.9}$$

$$A_i^{min} \leq M_i(r) \leq A_i^{max} \tag{3.10}$$

where i^* denotes the atomic metric considered as the global metric, A_i^{min} and A_i^{max} are the other atomic metrics' constraints.

Overall, individual objectives are often conflicting, which makes the solution unachievable. In such cases of contradistinction among performance objectives, it suffices to aim for a *pareto-optimal*[5] solution.

3.3 Summary of gaps in related work

Several studies have demonstrated the benefits of DSA. The topic of wireless networking with DSA has been studied more extensively in the context of cellular networks compared to the WMN context. The cellular environment possesses several characteristics that fundamentally differ from the WMN frame of reference. Therefore, the implementation of DSA in WMNs is expected to be different as already alluded to in section 2.5 of the previous chapter. National regulators in several

[5]The term Pareto-optimal has its roots in the field of economics. It is applied in this context to refer to a solution or set of solutions that cannot be improvement further in one dimension without worsening in some other aspect(s) [107].

countries including South Africa have recently passed regulation allowing the use of WSDs in the UHF band. Among the conditions is the requirement for WSDs to query a GLSD for spectrum availability. There are two possible repercussions to regulation coming into effect: (i) a number of solutions proposed prior, may be rendered invalid depending on the extent to which assumptions initially premised deviate from regulatory requirements; and (ii) the complexities of prior solutions with the associated overhead resulting from the assumed degree of spectrum dynamicity and the need to balance between the gains and the cost of switching spectrum may be less justifiable. The rest of this section discusses challenges central to the implementation of DSA in WMNs that still need to be addressed.

To reiterate, the problem of network formation[6] is yet to be addressed. For example, COMNET [75] proposes an algorithmic framework for frequency shifting. COMNET focusses on frequency shifting for a given cluster or set of clusters i.e. grouping of a wireless mesh router with its connected mesh clients. The study assumes a completely formed WMN in which each node location is known to all the other nodes. The aspect of coordination among the nodes in a self-organising mesh network is not clear. This dissertation in chapter 4 addresses the problem of WMN formation in relation to TVWS regulation compliance.

Furthermore, DSA-based networks are expected to operate on a wider range of frequencies (*see* section 5.2.4 of chapter 5). The wider frequency range hints at a substantial degree of variation in transmission radius and other propagation properties across the range of operating frequencies. Therefore, the potential implications of the choice of operating frequency need to be addressed as it can either establish a link or break a link. On the other hand, from a spectrum usage standpoint, short transmission range and long transmission range, poor obstacle penetration and superior obstacle penetration are both opportunities and challenges at the same time. For instance, while the objective of back-haul links is to maximise transmission range, radio frequencies with shorter transmission radius can be said to have a higher spatial spectrum re-use factor in that interference with other nearby trans-

[6] A mesh network is formed when peer links are established among neighbouring nodes such that every mesh node is able to send and receive packets from any other node on the network.

mitters is minimised. Furthermore, while superior obstacle penetration is desired to extend connectivity, poor obstacle penetration is advantageous in the sense that spectrum with poor obstacle penetration characteristics can be used inside buildings without worrying about interfering with external networks. Thus the concept of "suitable spectrum" should always be qualified with adequate specificity of context.

By comparison, wireless links are more often than not, of an asymmetric nature for a variety of reasons (see section 6.3.2 of chapter 6). For this reason, methods of ranking the next-best-hop that assume symmetric links in prior related work, will result in bad routing decisions. The process of determining the optimal path is a joint task of the routing algorithm and its accompanying metric computation function. What is needed are methods of ranking links for routing purposes that put the asymmetric nature of links into account for optimal path selection. This study in chapter 5 addresses the link metric aspect of routing in WMNs using DSA.

On a final note, several works have looked at the problem of *network selection* in the context of cellular networks, which is more straightforward in that a client can decide to connect/disconnect from the base station. For WMNs that use ad-hoc mode type of nodes, the choice of connectivity requires synchronisation on both ends of a link. In addition, given multi-radio enabled nodes, related work assumes uniform radios. The particular problem of efficient multi-link utilisation involving non-uniform radios has not been adequately addressed. Chapter 6 analyses the performance of 5 GHz WiFi and UHF-TVWS hybrid radios and discusses multi-link utilisation approaches.

Chapter 4

Towards DSA for TVWS regulation compliant WMN

Single-radio nodes provide a relatively low-cost way of mesh-networking for ubiquitous coverage. However, the current MAC mechanism defined for single-radios does not support multi-channel operation. Therefore, a WMN consisting of single-radio nodes has to use the same channel for all the nodes on the network in order to maintain connectivity, which makes it challenging to meet DSA requirements in a WMN environment. The current DSA authorisation is for TVWS and for this reason, this chapter focuses specifically on the challenge of TVWS regulation compliance in a multi-hop environment with ad-hoc connectivity.

4.1 Problem description

ICASA's TVWS regulation [53], [54] requires the WSD to query a GLSD when it starts up to access TVWS as already pointed out in chapter 2 section 2.5.1. To ensure that the operating parameters remain valid at all times, the regulation stipulates that after starting up, the WSD must thereafter query the GLSD periodically (every 12 hours) and whenever the device repositions by 100 m or more.

The requirement to query the GLSD whenever the WSD relocates suggests that the Regulator anticipates the spectrum map to potentially vary with every 100 m change in position, which is justifiable considering the degree of variation in path-loss as illustrated in Figure 4.1.

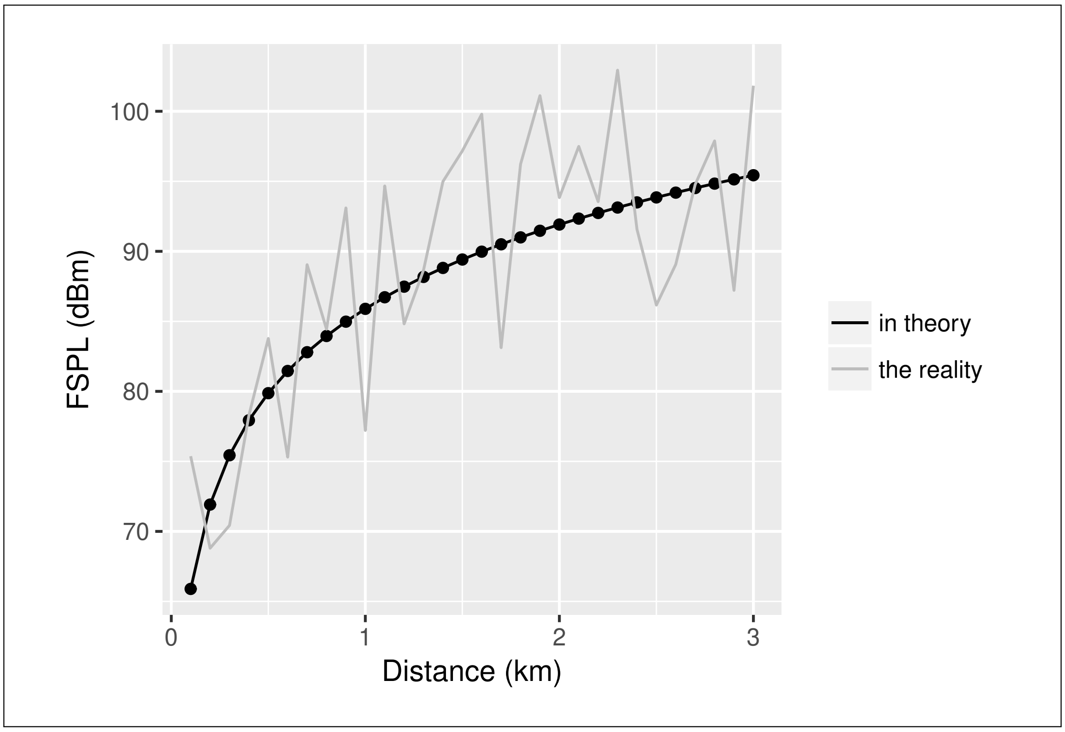


Figure 4.1: Path-loss calculated using the Free Space Path Loss (FSPL) model plotted against distance for a 470 MHz signal varies smoothly as marked by the "*in theory*" curve. Based on the observation of radio frequency spectrum scans, in reality the signal varies more widely due to a range of factors such as terrain and multipath fading as illustrated by "*the reality*" curve.

For a mesh network with nodes deployed within a 100 m radius, it suffices to have one node (so called master node) query the spectrum database, pick an operating channel based on the query results and initialise the network. However, for a network deployment spanning a couple square kilometres, the individual nodes' operating channel availability can be expected to vary significantly as Figure 4.2 illustrates. Therefore, the overarching question is, how should a self-configuring mesh network stay compliant in a multi-hop environment? In the best case scenario there is a set of clear channel(s) for the entire network, whereas in the worst case event, there is no single non-interfering channel across the mesh. With reference to Figure 4.2, this research explored the following question: if channel 1 is optimal, can we use it when G-E-B is the optimal path between nodes C & H?

There are two major parts to the problem, or rather the compliance objective can be met through two separate but related tasks, which are *network formation* and,

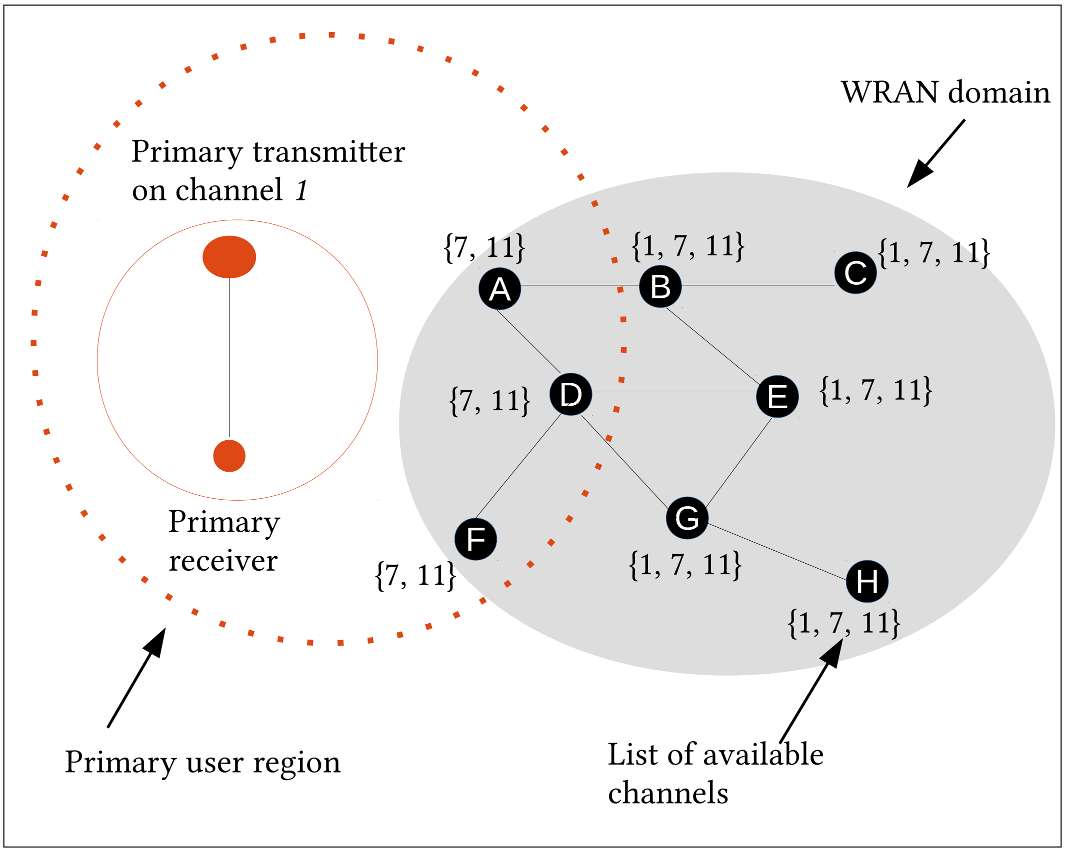


Figure 4.2: Route on optimal path based on spatial/temporal spectrum availability. In this example, channel 11 is the common control channel.

topology control and management. Network formation encompasses neighbour discovery and node peering processes to form a mesh. Topology control and management refers to post network formation operations performed for purposes such as minimisation of interference caused/suffered. This dissertation builds on ideas around exchanging control and channel coordination information via distributed mechanisms based on the assertion that there may be no common control channel known a priori.

Considering the framework for dynamic and opportunistic spectrum management, the Regulator's position is that primary licensees should be adequately protected from interference through regulation. For that reason, the Authority encourages technological research, development and innovation that enables efficient as well as opportunistic utilisation of available radio spectrum to wireless communications devices. Motivated by the benefits that DSA promises, the research community has presented overwhelming evidence supporting the application of DSA especially in the television broadcasting band. However, some stakeholders, mainly primary licensees such as television broadcasters and mobile operators alike, have expressed scepticism and argued that applying DSA in UHF-TVWS has the potential to introduce interference and render the services ancillary to broadcasting unusable.

In view of the aforementioned arguments, it is critical at present for the research community to innovate protocols that will ensure total compliance to regulation and adequately demonstrate how the solution is used to address the concerns raised. Influenced by the regulatory Authority's position and other stakeholders' view point, this research developed a principle of *comply-first-then-optimise* as visualised in Figure 4.3 to underscore the imminent order of priority.

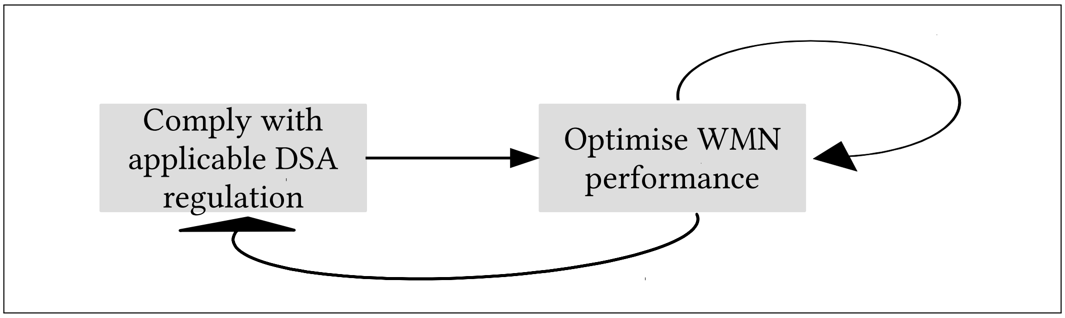


Figure 4.3: Comply with regulation first, then optimise performance

The focus of prior related work has been on two other associated functional components of the MAC, namely spectrum sensing and spectrum access. Related works have sufficiently dwelt on the wireless network performance improvements accompanying the application of DSA. However, ensuring compliance in a multi-hop mesh environment has not been addressed adequately. The nature of the mesh network's physical and logical topology makes it more challenging to maintain TVWS regulation compliance compared to single-hop wireless networks or networks with centralised management such as cellular or infrastructure based WLANs. This study contributes effort towards realising a TVWS regulation compliant WMN.

4.1.1 Existing MAC protocols for DSA enabled nodes

Though mesh networking may be realised as a function of routing protocols operating at layer 2 or layer 3, *network formation* alone is typically implemented as a functional component of the MAC protocol. One category of MAC protocols proposed for DSA enabled nodes relies on a central entity to manage and coordinate network activities among the nodes [108]. The other class of MAC protocols does not require centralisation of network operations, which is specially meant for adhoc networks [109]. These protocols may further be classified as random access, time slotted or a hybrid of the two. The major limitation of prior work is that they assume a separate CCC. Besides intermittency in feasibility, some scholars have labelled the CCC approach in itself as a wastage of spectrum. In place of the CCC, some studies have employed the idea of a *rendezvous channel* (RC) for control and coordination purposes [110]. Other studies have recognised the *hidden incumbent problem* [111], however these solutions are still inadequate to address the compliance problem in a multi-hop mesh environment described in the previous section.

4.2 Keeping the TVWS WMN regulation compliant

Radio frequency spectrum scans were conducted as part of this research to check TVWS channel availability at different locations around the area earmarked for a trial TVWS network deployment. Using information from the spectrum analysis, it was possible to determine TVWS channels available at each location and manually set the nodes' operating channel. To adhere to the WMN's "self-organising" and "self-healing" characteristic goals, what is lacking currently is a standard means for the WMN nodes to automatically select and assign operating channel parameters without manual intervention. The challenge faced in WMN with DSA is that current mesh standards such as 802.11s do not afford dynamic channel switching to a significant extent, while TVWS related standards such as 802.22 provide limited support for mesh networking. For example, the standard specifies an *infrastructure-based* point-to-multi-point network topology and defines coexistence mechanisms aimed at resolving contention among multiple base stations if they happen to be in

Table 4.1: Properties of a TVWS based WMN that need to be maintained while ensuring regulatory compliance and the extent to which the 802.22 and 802.11s standards support these features.

	Standard	
TVWS WMN feature	**802.22**	**802.11s**
Ad-hoc connectivity, Self-organising, self-healing	-	✓
Distributed in nature	-	✓
Multi-hoping	-	✓
Dynamic channel assignment	✓	-

the same space/time/frequency. The standard does not adequately cover the multi-point-to-multipoint connectivity requirements of a typical WMN. This conundrum poses two interim lines of enquiry, which are to either extend the mesh standard to support compliance with DSA standards or add mesh support to the applicable DSA standard. Table 4.1 summarises some of the key features that a TVWS WMN needs to maintain while ensuring regulatory compliance. As observed from the table, the major gap currently arises from the fact that applicable TVWS standards (802.22 for example) do not support mesh networking, whereas the mesh standard (e.g. 802.11s) provides limited support for TVWS based WMN key features such as dynamic channel assignment (see Appendix A for details on key 802.11s features). The 802.22 standard specifies a point-to-multipoint topology whereas a WMN is essentially multipoint-to-multipoint. Thus the standard seems to assume communicating devices share the same spectral map, which may not be the case for WMNs characterised by multi-hoping. The 802.22 architecture further assumes base stations are connected to the main network by some “means”. As such, methods of coexistence among WRANs are provided, but a possible multi-hop communication scenario among base stations is unspecified. Therefore, even if TVWS WMN routers were thought of as “base stations”, the standard is unclear on communication and coordination among a collection of base stations constituting a single WRAN to autonomously determine a network-wide operating channel. On the other hand, 802.11s devices’ IBSS mode connection provides for ad-hoc connectivity, but is based on fixed channel assignment.

Table 4.2: Key regulatory requirements and their implication for WMNs.

Regulatory requirement	Implication for WMNs
Query the GLSD periodically (e.g every 12 hours) or whenever position changes by 100 m or more.	The location of each node and transmission characteristics (e.g antenna height) should be considered when determining operational parameters.
Master WSD must provide operational parameters to the associated client WSDs.	From this viewpoint, unless the master WSD has the geo-coordinates of all the other nodes, the operational parameters may only be valid for its single-hop neighbours.
Client WSDs may only operate on frequencies determined by the master WSD.	Since the operational parameters provided by the GLSD are only valid within a specific geographical area, this raises concern about the validity of the operating parameters issued to client WSDs multiple hops aways from the master WSD.
Client WDS must cease operation immediately if it does not receive a contact verification signal from the associated master WSD.	The peer-connections and cooperation in the forwarding of packets among the nodes is what gives WMNs the resilience, self-healing and self-organising capabilities needed whenever one of the nodes goes down. Therefore, the requirement for client WDS to cease operation is in conflict with the strength of a WMN that lies in its distributed nature.

The Authority's position is that primary licensees must be adequately protected from interference through regulation and considers the GLSD the best method for interference management. Table 4.2 highlights key regulatory requirements and their implication for WMNs. In preference to re-framing the whole MAC layer, this dissertation proposes extending the 802.11s MAC protocol to include features necessary to support TVWS regulation compliance. These features include mechanisms to utilise white space spectrum without interfering with primary users as well as mechanisms for transitioning to new channels (i.e. inband channel change propagation) and network-wide unification of operating channel.

Note: the terms channel *selection*, channel *allocation* and channel *assignment* are often used interchangeably throughout literature. This dissertation makes a distinction between these terms to accentuate the significance of inherent subtasks and subprocesses. Channel selection is used in this context to describe the activity encompassing low-level analysis of frequencies to determine clean channel, whereas channel allocation/assignment refers to the task of taking the lists of usable channels available at each node to determine the network-wide optimal channel.

4.2.1 Traditional network formation

A WMN creates a single broadcast domain where each node is configured with a Basic Service Set Identifier (BSSID). In a traditional network, the operating channel is configured on all the nodes and is not subject to frequent change. When nodes boot-up, they detect each other through *passive scanning* and *active scanning*. Passive scanning describes the observation of beacon frames across a given spectrum band, whereas active scanning refers to the transmission and scanning of probe frames. The beacon and probe frames contain the mesh BSSID and through passive and active scanning mechanisms, nodes with the same BSSID are able to associate [26]. A detailed description of 802.11s neighbour discovery and topology formation procedures is provided in Appendix A.

The 802.11s standard specifies a simple channel unification protocol and a simple channel graph switching protocol [27]. However, the channel switching protocol assumes simple scenarios with infrequently changing radio frequency environment. For example, when one of the nodes detects the need to change the channel (e.g. in order to avoid radar), it sends out a *channel switch announcement* indicating the number of the channel it intends to switch to. Thus the existing channel assignment criteria ensures a unified channel graph, but the standard does not specify any algorithm necessary for mesh routers to determine the channel to use. Consequently, the DSA regulatory compliance requirements such as the location dependency in channel availability are unmet in the current 802.11s WMN deployments. A TVWS based network for example, is fundamentally different in that the channel to establish a connection on cannot be predefined in that WSDs share the band with licensed television broadcast transmitters. If operating channels were to be predetermined, that could potentially result in interference to incumbents at some locations, which must be avoided totally.

Potential workaround

The GLSD proposed standard RFC 7545 [52], specifies several message types including *AVAIL_SPECTRUM_BATCH_REQ*. The batch request allows the WSD to specify multiple locations, which might be relevant to the problem presented in this chapter. For example, the initiating node can leverage this feature to query the GLSD with all the nodes' locations included in the request and then determine common channels from the GLSD response. However, this feature is currently intended for a non-stationary master device to acquire spectrum to use at different anticipated locations in one request and as such is inadequate to meet the WMN requirements. The other alternative is to leverage the *location* parameter itself and design data structures that allow the location to be specified as a region instead of a single point. The challenge with either option is that firstly the GLSD must support the query types. Secondly, the querying device has to know the area covered by the network in its entirety, which can only be achieved once the network is fully connected.

4.2.2 Proposed network formation to comply with regulation

Building on the existing 802.11 standard, this section presents an improved network formation algorithm to comply with TVWS regulation. The solution puts into consideration two key WMN properties, namely multi-hopping and the absence of a centralised network coordinator. To explain how the algorithm works, consider the WMN layout depicted in Figure 4.4: the proposed solution employs a procedure similar to the well known *listen before talk* based protocols. After powering up, all nodes initially enter into passive scanning mode i.e. listening for beacon frames, but not transmitting any. While in passive scanning mode, there are three possible cases: (i) beacon received, (ii) no beacon detected or (iii) gain access to the GLSD. Active beacon requests are disallowed until a node obtains spectrum information by querying the GLSD for example, and/or whatever the regulation demands. The passive scanning method is shown in Algorithm 1 (page 58). To simplify the analysis, the assumption at this stage is that while at this phase, only one node will be first to gain Internet access, query the GLSD and start beaconing. In this illustration it is assumed that regulation requires querying a GLSD for spectrum access. Thus the process of network formation is initiated by the first node to gain access to spectrum information and all the other nodes receive the beacons in due course and use the initiating node as gateway to the GLSD. The proposed solution further uses a TCP-like *three-way handshake* between node pairs as illustrated in Figure 4.5 to reach consensus and assign a suitable operating channel network-wide. The input in the problem formulation is the set of channels each node is allowed to use at its location. The parameter to be found is the intersection set.

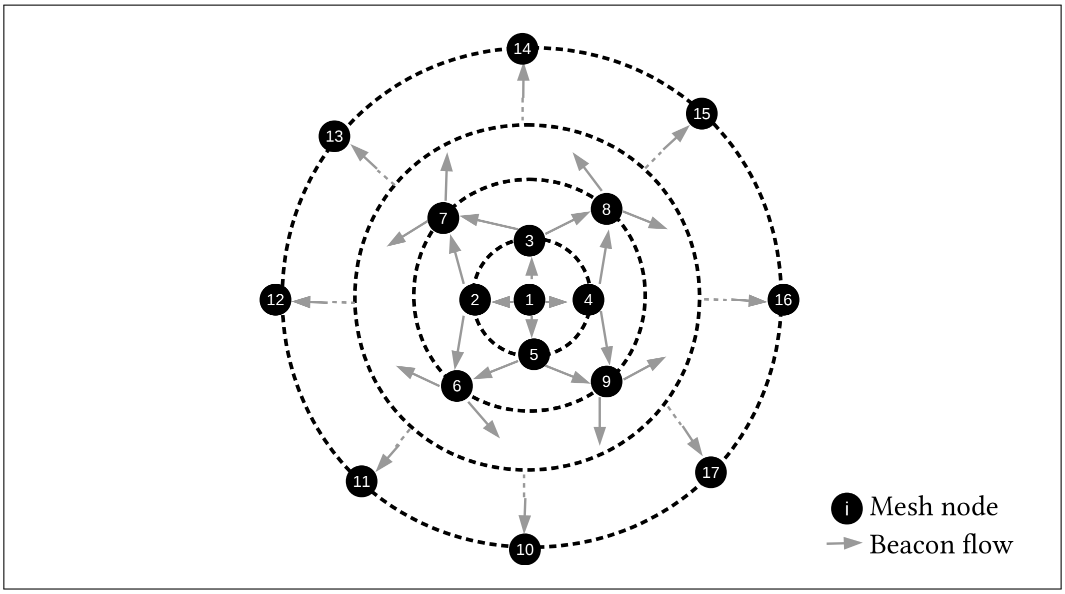


Figure 4.4: Realising a WMN compliant with TVWS regulation.

The three-way handshake works as follows:

i The first node to gain Internet access queries the GLSD, picks a channel to use and broadcasts a beacon frame. The beacon contains information such as channel and channel width to operate on, and an ordered list of alternative channels. At the start, the initiating node lacks network-wide information and so the starting operating channel is picked based on the node's local spectral information;

ii Upon receipt of the beacon frame, the one-hop neighbouring nodes tune to the channel specified in the beacon frame or the channel on which the beacon was detected and query the GLSD. If the channel selected earlier is among the GLSD query results, the node sends a beacon response signalling intention to join the mesh using the suggested channel. If the operating channel selected by the beacon frame originator is not among the receiving node's GLSD query results, the node selects a channel from the list of alternatives and sends a beacon response signalling intention to join the mesh using an alternative channel. The beacon response contains the selected channel and the list of alternative channels. This list of alternative channels is an intersection set of the beacon frame originator's list and the receiving node's list;

iii Upon receipt of the beacon response, the beacon originator switches to an alternative channel if indicated in the beacon response received and sends a response acknowledgement. Once the node receives an acknowledgement to the beacon response sent earlier, it can now start broadcasting its own beacon frames.

Thus under the proposed scheme, a mesh node broadcasts beacon frames containing mesh information only when it has access to regulatory spectrum information or after receiving a beacon response acknowledgement from the beacon frame originator. After the three-way handshake described above, node pairs with matching mesh profiles begin to associate.

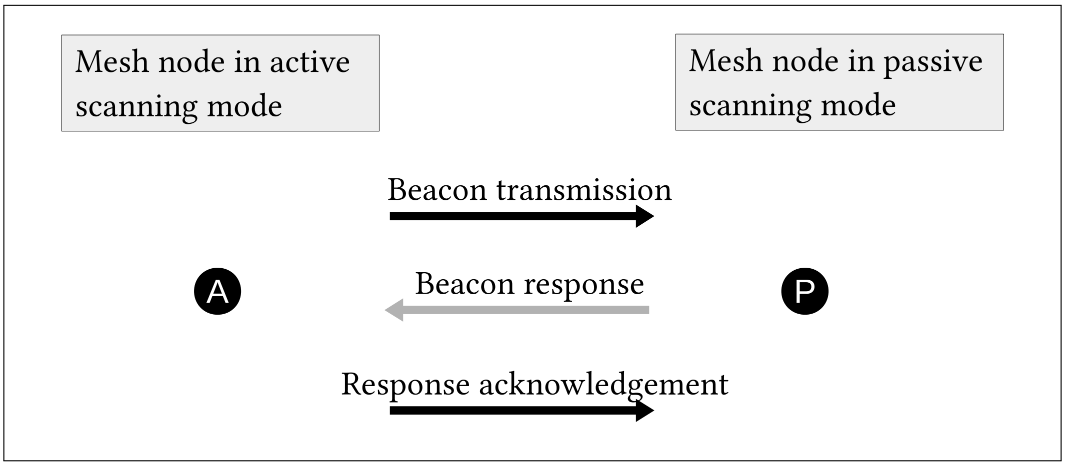


Figure 4.5: Three-way handshake for regulation-compliant network formation and operating channel unanimisation.

Algorithm 1 : Passive scanning procedure.

C: list of channels in the band.
R: radios detected.

```
for radio r in R
    run scanning (r) instances concurrently;
end for
start scanning ( r )
    listen on current channel setting;
    if beacon detected;
        break 1;
    else
        while beacon not detected and no GLSD access do
            for channel c in C
                listen on channel c for t time units;
                if beacon detected:
                    set operating channel = c;
                    break 2;
                end if
            end for
        end while
    end else
end scanning
```

Note: During the passive scanning phase, while the operating channel can be inferred based on the channel on which the beacon was observed, it might be better to explicitly indicated this in the beacon frame. That is because during the network formation phase, the beacon may sometimes be broadcast over a non-preferred channel.

Scenario 1: when there is a common optimal channel, no need for reconciliation

Referring back to Figure 4.4 on page 56, assuming node 1 is the first to gain Internet connection and that the GLSD is accessible via the Internet, the protocol works as follows: node 1 queries the GLSD and receives a list of channels its allowed to use based on its GPS coordinates and transmitter characteristics such as height. Node 1 picks a channel x to use and starts broadcasting beacon frames. In addition to information such as the *mesh ID*, the beacon frame includes the suggested operating channel x as well as a list of alternative channels. This can be referred to as the *first ripple*. At this stage, all the other nodes are in passive scanning mode (i.e.

listening for beacons, but not transmitting any) except node 1. The passive scanning procedure (*see* Algorithm 1 on page 58) is very similar to the mechanism used by 802.11 WiFi clients to detect Access Points. While passive scanning, node 1's single-hop neighbours (i.e. nodes 2-5) detect and decode node 1's beacon frame and switch to channel x. After that, using node 1 as the gateway, nodes 2-5 are also now connected to the Internet and are now able to query the GLSD. Assuming the query result has channel x on the list, nodes 2-5 transmit a beacon response back to node 1 signalling intention to join the mesh and accept to use channel x. When node 1 receives this beacon response, it sends an acknowledgement as illustrated in Figure 4.5. When nodes 2-5 receive this acknowledgement, they now have the leeway to broadcast beacon frames specifying x as the operating channel. At this stage nodes 6-9 observe the beacon frames and switch to channel x. This can be referred to as the *second ripple* of the network formation process. Thus the initiating node acts as a sink during the network formation phase.

This ripple pattern and three-way handshake processes carries on through the third, fourth, up until the n^{th} ripple, which is the outermost set of nodes. By so doing, WMN TVWS regulation compliance is ensured in terms of the operating channel used by nodes at different locations. The above scenario is a simplistic case in that it assumes channel x suggested by the initiating node incidentally turns out to be common in all the nodes' subsequent GLSD query results.

Scenario 2: when there is a common optimal channel, reconciliation required

Building on the procedure described in scenario 1, this section addresses the question of, "what if during the second or third ripple it turns out that the outward nodes are not allowed to use channel x?"

Assuming that node 1 is the first to have Internet connection again: node 1 queries the GLSD and receives a list of channels allowed to use. Node 1 picks a channel w to use and includes this in the beacon frames broadcast to the neighbouring nodes. The beacon frame contains the selected operating channel w as well as a list of alternative channels x, y, z.

In this first ripple node 1's single-hop neighbours (nodes 2-5) decode node 1's beacon frame and switch to channel w. After that, nodes 2-5 are also now connected to the Internet and are able to query the GLSD. Assuming the query result has channel w on the list, nodes 2-5 go through the three-way handshake process and thereafter transmit beacon frames that include w as the operating channel as well as an intersection set of alternative channels i.e alternative channels available to nodes 1-5. At this stage nodes 6-9 observe the beacon frames and switch to channel w. At this second ripple of network formation, nodes 6-9 also acquire Internet connection and query the GLSD. If the GLSD indicates that channel w is not allowed for nodes 6-9, the nodes through the iterative three-way handshake process signal to nodes 1-5 to switch to channel y and broadcast beacon frames specifying channel y as the operating channel. The beacon frame includes the selected operating channel and a list of alternative channels that is an intersection set of the nodes' allowed channels.

This ripple action of beacon transmission and iterative three-way handshakes carries on forward and back depending on GLSD query results at each stage until the n^{th} ripple, which is the furthermost set of nodes. Through this series of network formation steps, the WMN maintains TVWS regulation compliance by utilising channels that are allowed at all node locations.

Note : using the GLSD combined with sensing approach, the list of alternative channels could be arranged in order of preference. Furthermore, in cases where the GLSD provides a long list of available channels, the beacon frame could contain only a subset to minimise the frame size.

Scenario 3: when there is no common optimal channel

Scenarios 1 and 2 assume that if the lists of allowed channels are constructed for each node, the intersection set is not empty i.e. there is at least one channel in common that is available. This section describes a scenario when the intersection set is empty. To make the problem tractable, it is assumed that if the network is split across the lines reflecting the spectrum map, the resulting network segments or clusters would have common optimal channels among the nodes on that network segment or within the cluster. Therefore each segment operates on a channel that is suitable for the segment, though potentially different from the rest of the network. To prevent the network from splitting, the virtual interface technique is applied to maintain connectivity among segments or clusters.

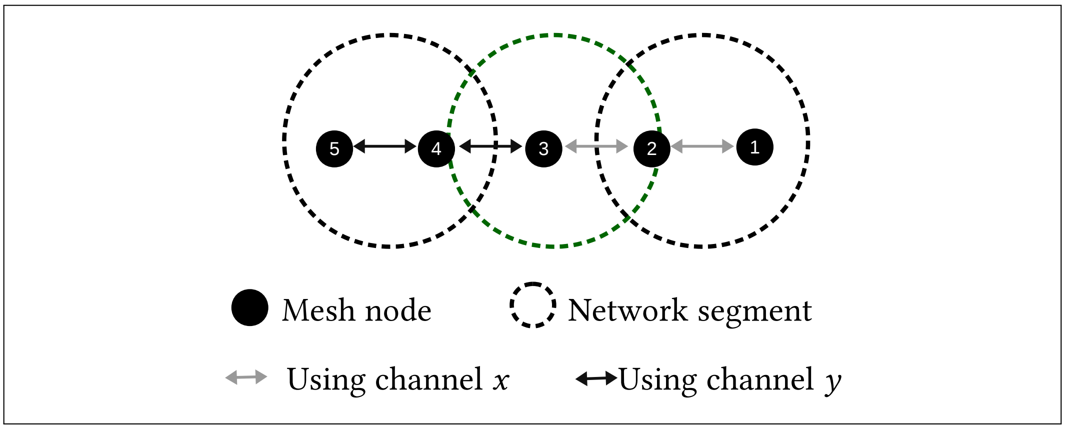


Figure 4.6: Making WMN regulation compliant amid fragmented spectrum.

Consider the lack of contiguous spectrum depicted in Figure 4.6 where node 1 and node 2 are able to operate on channel x, while node 4 and node 5 operate on channel y because channel x is unavailable. Despite the shortage of network-wide common channels, by cause of the unbounded nature of the wireless medium, single-hop neighbours will typically still have several channels in common -an observation that Zhao et al [72] also makes.

Thus node 3 is able to use either channel x or channel y and so node 3 connects to node 2 and node 3 on channels x and y respectively and by so doing bridges the two segments in what would otherwise have been a split network. If this condition was known a priori, it could easily be solved by equipping node 3 with two radios. However, the spectrum state depicted in Figure 4.6 may not be known beforehand and may not be a permanent state. Secondly, equipping nodes with additional radios inevitably pushes the cost of mesh nodes and overall network complexity upwards. Therefore, while multi-radio node capability would undoubtedly ease the task, this work tackles the problem from the perspective of single-radio mesh nodes, which is what most CWMNs typically use. To that end, this dissertation proposes 1 to n virtualisation of the candidate node's radio. With reference to Figure 4.6, node 3 is a good example of a suitable candidate to employ virtualisation[1].

To give an example, consider the node layout in Figure 4.4: node 1 queries the GLSD and announces to its immediate neighbours that they can switch to channel x; the neighbours (nodes 2-5) connect to the Internet, query the GLSD and channel x is on the list, so they announce this in the second ripple to their neighbours (nodes 6-9). Upon querying the GLSD, it turns out that channel y is the optimal channel for nodes 6-9 and all the outer nodes. Luckily nodes 2-5 are allowed to use both channel x and channel y and so these nodes virtualise the radio and connect the inner nodes on channel x and the outward nodes on channel y.

Just to emphasise, in a multi-hop WMN environment, the notion of a master node as spelled out in the regulatory framework is of minimal relevance with the current GLSD implementation. This is because the GLSD serves spectrum information based on the querying device's location and yet a WMN has nodes placed at several other different locations that are only reachable via multi-hop forwarding capability. Algorithm 2 on page 63 summarises the proposed network formation procedure.

Scenario 4: when there is no TVWS available

The three scenarios presented above describe cases where each node upon querying the GLSD acquires a set of channels that may be used. However, TVWS is not guaranteed at all locations at all times. For a TVWS-based network, there is a possibility of a node querying the GLSD and based on the node's location and transmission characteristics, the GLSD indicating that there are no TVWS channels available. In that case the node will have to use alternative spectrum such as 5 GHz WiFi because there is no workaround within the TVWS regulatory framework.

Note: the above principle can be applied to WMNs that use other methods of accessing spectrum information such as spectrum sensing. Additionally, channel probing techniques can be incorporated in the ordering and selection of channels.

[1] Virtualisation comes in different forms depending on the objective. 1 to n is the kind of virtualisation where a single physical entity is mapped to multiple virtual instances. There is also n to 1 virtualisation in which multiple physical resources get functionally mapped to a single logical entity. The intuitive reader would realise by now that virtualisation can also take the form of m to n.

Algorithm 2 : Network formation

C	:	Possible channels in the band
C_a	:	Set of channels available network-wide
C_{a_i}	:	Set of channels node i is allowed to use, $C_{a_i} \subseteq C$
j	:	Next-hop node
C_{a_j}	:	Set of channels node j is allowed to use, $C_{a_j} \subseteq C$
c	:	Operating channel across the network, $c \in C_a$
c^i	:	Passive scanning channel by node i, $c^i \in C$
c_o^i	:	Operating channel by node i, $c_o^i \in C_{a_i}$

Pre-processing condition: disjoint network graph.
Post-processing condition: unified network graph.

start $\rightarrow$ passiveScanning();
if access to GLSD:
    populate C_{a_i} the list of allowed channels;
    set operating channel c where $c \in C_{a_i}$;
    broadcast *beacon frame* (c, C_{a_i});
end if
if *beacon frame* detected:
    query GLSD: $\rightarrow C_{a_j}$;
    construct common set of allowed channels $C_a = C_{a_i} \cap C_{a_j}$;
    if $c \in C_{a_i} \cap C_{a_j}$
        set operating channel c;
        transmit *beacon response* (c, C_a);
    Else if $c \notin C_{a_i} \cap C_{a_j}$ and $C_{a_i} \cap C_{a_j} \neq \emptyset$
        select alternative channel $c_j \in C_a$
        transmit *beacon response* (c_j, C_a);
    Else if $c \notin C_{a_i} \cap C_{a_j}$ and $C_{a_i} \cap C_{a_j} = \emptyset$
        instantiate virtual interface v_o; set operating channel on $v_o : c = c_j$
        appropriately package and send beacon response;
    end if
end if
if *beacon response* (c, C_a) detected:
    send *beacon response ack*; send updated beacon frames with new c and C_{a_i};
Else if *beacon response* (c_j, C_a) detected:
    send *beacon response ack*;
    set operating channel: $c = c_j$;
    update channel list: $C_{a_i} = C_a$;
    send updated beacon frames with new c and C_{a_i};
end if
if *beacon response acknowledgement* received:
    appropriately package and send beacon frame;
    broadcast *beacon frame*;
end if

What if nodes have list of preferred channels ordered differently?

The choice of network-wide operating channel can be resolved using a weighted matrix approach. The weighted matrix is structured as shown in Table 4.3. To explain, let c_1, c_2,..., c_j represent the channel values. Assuming the list of common channels is w elements long, let w, $w-1$, $w-2$, $w-3$, ..., 1 be the possible channel ranking where w is the highest weight a node can assign to a channel (i.e. best channel) based on its local spectrum analysis. Further let w_1^i, w_2^i, ..., w_n^i denote node 1, node 2, ... and node n's ranking of channel i. Thus to generalise, the total network weighting of channel i can be represented as $w_1^i + w_2^i + w_3^i + ... + w_n^i$ where n is the node count. The channel with the highest aggregate weight can be considered as the suitable channel for the network. This computation can be done centrally by the node that initiated the network formation. Alternatively, once all the nodes join the network, the calculation can be carried out distributively at each node. The nodes will arrive at the same answer since they all have the same input. In the event that multiple channels are weighted equally, the assignment scheme can simply consider the ascendency of channels for example.

Table 4.3: Using individual nodes' channel ordering to determine network-wide operating channel.

Channel	**Weight**
c_1	$w_1^1 + w_2^1 + w_3^1 + ... + w_n^1$
c_2	$w_1^2 + w_2^2 + w_3^2 + ... + w_n^2$
c_3	$w_1^3 + w_2^3 + w_3^3 + ... + w_n^3$
...	...
c_j	$w_1^j + w_2^j + w_3^j + ... + w_n^j$

In short the global weighting W_i of channel i can be expressed succinctly as

$$W_i = \sum_{j=1}^{n} w_j^i \tag{4.1}$$

Assuming perfect neighbour discovery, the proposed network formation scheme with dynamic channel assignment achieves a fully connected network. The method is expected to yield near optimal performance on the basis that it results in a network operating channel that favours the majority of nodes. However, one drawback of taking the channel with the *highest aggregate weight* as suitable channel for the network is that, a path through the network is only as good as the weakest link. Thus, considering the *largest common denominator* may be an alternative approach. The important thing to note is that a mesh network will have an underlying routing protocol that attempts to use the "best" forwarders between any two sending/receiving repairs. For this reason, whether the largest common denominator approach performs better or not depends on the routing protocol's handling of traffic.

4.3 Formalisation

To formalise, the node's state transition is modelled as shown in Figure 4.7, while the notation used in modelling the node states is described in Table 4.4 (pages 67 & 68). Each node maintains a spectrum map that is a tuple $\mathcal{M} = (C_{a_i}, Q)$ where C_{a_i} is a set of allowed channels and Q indicates the estimated channel quality. There are several computational methods and metrics that can be adopted for estimating channel quality such as signal-to-interference plus noise ratio (SINR) [112], and other channel sounding techniques [113]. Details of actual low-level calculation of channel quality is outside the scope of this study. In this research, channel quality is estimated from radio frequency spectrum scan results by considering the incident power on the channel. Channel ranking = 0 (zero) can be used if the channel quality is unknown or if the node has no spectrum analysing capability [2]. Spectrum scanning is done periodically or in response to deterioration in link quality on a current channel. Thus a channel change/selection is triggered initially when a node boots up and latterly by a change in GLSD query results or spectrum scan output.

The following scenario is assumed: a DSA based WMN comprises a set of nodes $\mathcal{N}$. The nodes are located in a d_1 x d_2 grid structure such that d_1 x d_2 = $|\mathcal{N}|$. There exists node i's associated set $N_i \subset \mathcal{N}$ of its one-hop neighbours. Links are modelled as ordered pairs such that $n_i n_j$ represents transmission from node i to node j and $n_i \forall N_i$ represents a broadcast from node i to all its one-hop neighbours. Node i

[2]For practical considerations, ideally each node should be equipped with a dedicated spectrum analyser. In the absence of a dedicated RF analyser, the node's WNIC itself can be used to measure noise induced by external interference on a given channel.

has a set C_{ai} of channels that may be used. Node i's operating channel is denoted by c_o^i. The distance between node pairs equals d such that $d \leq r$ where r denotes the transmission radius. Half-duplex communication is assumed and communication between node pairs $n_i n_j$ is successful iff message transmission and reception is done on the same channel i.e. when $c_o^i == c_o^j$. The WMN back-haul tier is modelled as an undirected diagram $G = (\mathcal{N}, E)$, where E is the set of links. The problem of TVWS regulation compliance in a WMN can be expressed as follows:

$$\begin{aligned}
&\textbf{Find} \\
&\qquad c \\
&\textbf{Maximise} \\
&\qquad \textit{network size} \\
&\textbf{Minimise} \\
&\qquad \textit{convergence time} \\
&\textbf{Subject to} \\
&\qquad c \in C_a, C_a = (C_{a1} \cap C_{a2} \cap \ ... \ \cap C_{an}) \\
&\qquad c_o^i = c_o^j, \forall n_i n_j \in \mathcal{N} \\
&\qquad t_j^{c^i} \leq \alpha, \forall c^i \notin C_{ai}
\end{aligned} \tag{4.2}$$

where C_{a1}, C_{a2}, ..., C_{an} are the sets of channels permitted at respective locations of node 1, node 2, ..., node n, c^i is the channel used by node i while in passive scanning mode, $t_j^{c^i}$ denotes the amount of time that node j occupies channel c^i, α equals the time within which secondary users should vacate the channel when primary users become active. The above formulation is similar to a consensus problem. Performance of consensus algorithms is typically measured in terms of the agents' ability to reach agreement and the speed of convergence. However, applications of "straight-through" distributed consensus algorithms assume pre-existence of a means of communication that is independent of the state variables the consensus pertains to. The problem of regulatory compliance in TVWS WMNS detailed herein has an added dimension in that the establishment of communication among the nodes is in itself dependent on the very consensus the nodes need to arrive at.

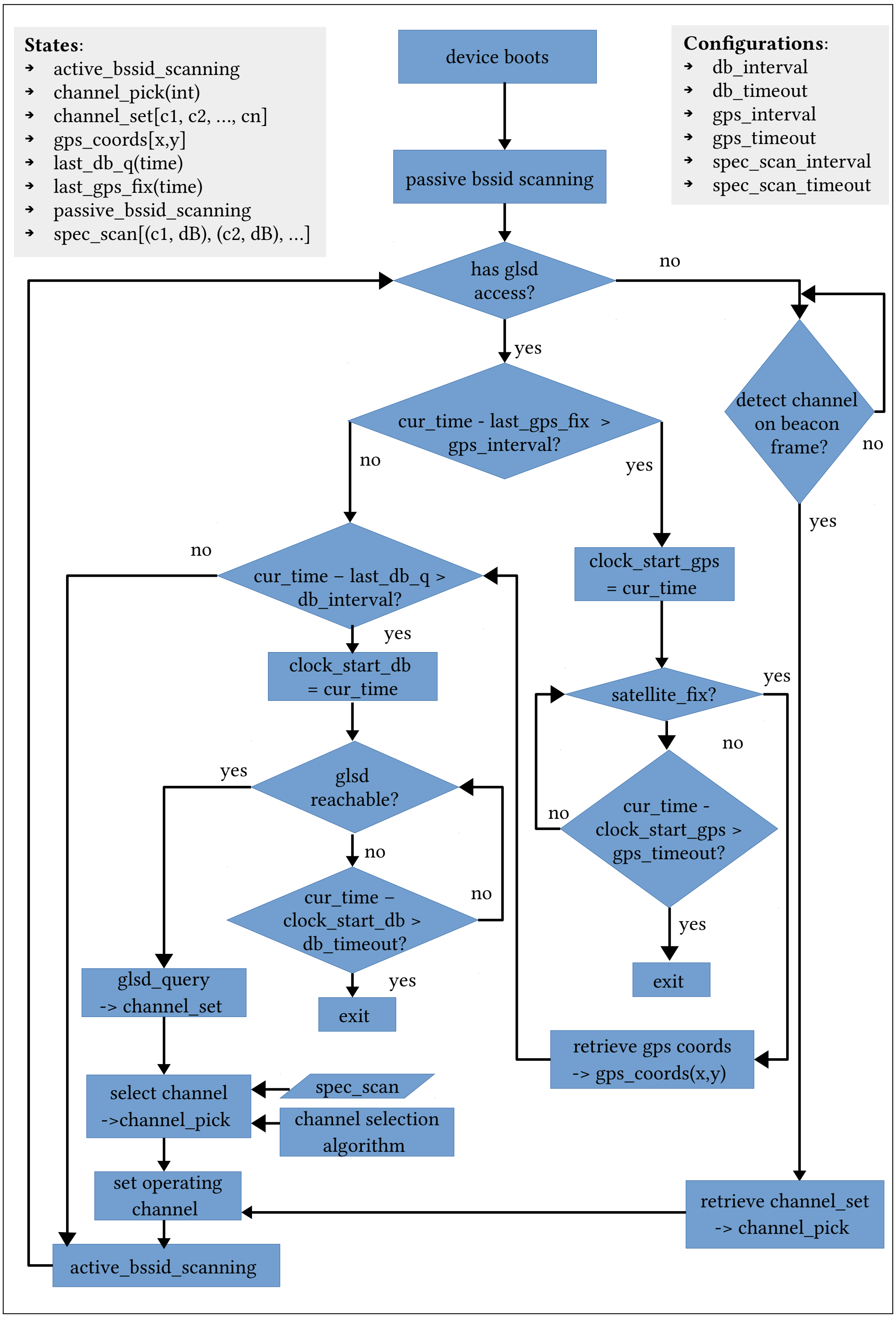


Figure 4.7: DSA-enabled mesh node state machine.

Table 4.4: Description of terms used in Figure 4.7.

Term	**Description**
active_bssid_scanning	This is a state where a node listens for beacons and is also able to transmit beacons.
channel_pick	Given a set of channels that a node is allowed to use, *channel_pick* refers to the channel selected for use.
channel_set	*channel_set* refers to the list of channels a node is allowed to use. This is constructed from the GLSD query results and/or via message exchanges among the nodes.
db_interval	The db_interval indicates the frequency with which GLSD queries are made.
db_timeout	When a node queries the GLSD, *db_timeout* shows how long a node waits for a response. Thus a node may get the query results or it may terminate the query if the GLSD server does not respond within the *db_timeout* period.
gps_coords	This is the satellite-based global positioning system (GPS) coordinates used to identify the node's location.
gps_interval	Similar to db_interval, the gps_interval defines how often the node interrogates the GPS satellite signal to determine its location.
gps_timeout	The GPS satellite signal can get blocked by obstructions such as mountains and buildings, *gps_timeout* indicates how long a node is going to attempt to establish it's GPS coordinates.
last_db_q	This corresponds to the last time a GLSD query was made.
last_gps_fix	This shows the last time the node established its location (GPS coordinates).
passive_bssid_scanning	The refers to the initial state the node goes through before acquiring spectrum information. While waiting to acquire spectrum information (e.g. via GLSD query), the node in *passive_bssid_scanning* mode listens for beacons, but does not transmit anything.
spec_scan	This refers to the process of RF radio spectrum scanning.
spec_scan_interval	Spectrum scan periodicity.
spec_scan_timeout	This is the amount of time allotted for spectrum scanning or the period the node waits for response from the spectrum scanner.

4.4 Evaluation of the proposed solution

Seeing the problem of regulation compliance in a multi-hop environment highlighted in section 4.1, the purpose of this part of the research was to design a mesh formation and dynamic channel assignment protocol towards realising a regulation compliant TVWS based WMN. This section details the evaluation of the proposed solution that was carried out using a combination of prototypical experiments and simulations. Performance evaluation metrics were derived from South Africa's regulatory framework as far as possible. For critical aspects that the regulation is not specific about, assumptions were made drawing from OFCOM [114], [115] and FCC [116], [117] guidelines. This section attempts to:

- show the correctness of the solution in forming a WMN that complies with TVWS regulation without the notion of a master node;
- shed light on the running time as the TVWS requirements for ad-hoc nodes induces additional control messages to complete mesh formation;
- prove that the channel selection and assignment algorithm adapts well to changes in channel availability.

4.4.1 Delimiters of the study

The research was conducted in the Western Cape region of South Africa because firstly, this is the region with the most number of used TV channels in the country and represents a worst case environment. Secondly, it was more convenient to situate the study in this area for easy access to spectrum information and corroboration of GLSD information with ground truth. Nonetheless, the issues addressed are typical and therefore, the findings are expected to have broader relevance. The study focused on network formation and topology management for a TVWS based WMN specifically. However, lessons on distribution of channel information and coordination of channel transition can be appropriated for other mesh network contexts. Sections 4.5 and 4.6 discuss the nominal solution adaptations necessary to suit variation in regulation requirements. To add on, this work takes the clean optimal channel as a given. Low-level channel state analysis and methods of determining optimal channel are outside the scope of this study.

4.4.2 Simulation description

The proposed solution was evaluated through simulation using *Network Simulator* version three (NS-3). Table 4.5 shows a summary of the simulation settings used. The mesh module was adapted and used together with other supporting ns-3 modules. The NS-3 simulation environment uses the *MobilityModel* mechanism to implement the concept of node positioning on an *x, y, z* plane. This was leveraged to model the nodes' latitude and longitude coordinates, and the height. Two topologies were used for evaluation. In the first layout, the nodes were uniformly distribution in an $n \times n$ grid layout. The grid topology is included because it is able to form a totally connected mesh network that can easily be transformed in several other topologies by judiciously switching some nodes off. Furthermore, the grid formation is covered because the number of alternative routes among distant node pairs creates a worst-case complexity problem for the routing protocol [23], which is of particular interest from a research perspective. The other leg of simulations consisted of nodes laid-out in a chain topology. These two topologies were considered because they represent two extreme ends of network connectivity i.e. highly connected and poorly connected. The connectivity of real-world deployments is expected to fall somewhere in between the two extremes. TVWS regulation allows for adaptation of transmission power to meet the co-channel and adjacent channel interference suppression requirements. From the ICASA regulatory standpoint, the maximum permitted EIRP and EIRP spectral density is 36 dBm and 17 dBm respectively for urban locations and 41.2 dBm and 22.2 dBm for rural areas. For purposes of evaluating the proposed solution, the transmission power was kept at a constant 20 dBm. The primary concern in the simulation setup was to ensure the transmission power is high enough to enable connectivity between adjacent nodes, but not too high as to annul multi-hopping. Therefore, it was assumed that the distance between the nodes is indicative of the nodes' transmission radius and that each node's beacons are detectable by all its single-hop neighbours.

Table 4.5: Simulation settings. Code snippet of key functionality is provide in section D.2 of Appendix D, whereas the complete source code and further simulation environment specific settings is accessible online [118].

Parameter	**Value**
Node spacing	100 m
Node mobility	static
Antenna	Omni-directional
Transmission power	20
Beacon interval	0.5
Topology	chain & n x n grid layout
Modules	mesh and other supporting modules
Simulation time	variable
Simulator version	ns-3.25

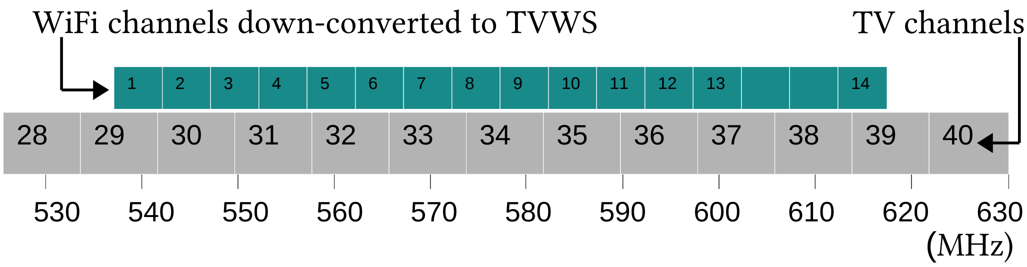
Channel availability at each node location was modelled such that it mimicked information obtained from the GLSD. Table 4.6 gives a snippet of actual GLSD results used to construct the spectrum map. Compliance can be evaluated in terms of adherence to or violation of regulatory terms and conditions. The principal concern is that WSDs should ensure a low causal effect of harmful interference to other services in and adjacent to the licensed band. Some of the other ancillary requirements include: (i) the master WSD must query the GLSD every twelve hours, may continue up to forty eight hours after last GLSD query [ICASA]; (ii) the client WSD must establish contact with the master WSD every 900 seconds [ICASA]; and (iii) the WSD must vacate or reduce power within two seconds of incumbent becoming active [IEEE 802.22 standard].

4.4.3 Correctness of the procedure

For a WMN with ad-hoc connectivity, there are several possible scenarios as already alluded to in previous sections. The simplest case is when there is only one instance of network formation. Considering the premised deployment scenario, it is also possible that multiple nodes initiate network formation. Multiple simultaneous network formation instances is not a problem if they happen to start on the same channel. But if they happen to emerge on different channels, then a method of unification becomes necessary to achieve a single fully connected mesh network.

Table 4.6: Channel availability at selected locations.

Node	Name	Longitude	Latitude	Channels
1	Cape Town city centre	18.4146937	-33.923142	{22, 26, 30, 32, 33, 34, 46, 61, 66, 67}
2	Cape Town train station	18.4228739	-33.9221506	{30, 32, 33, 46, 61, 66, 67}
NB. The correspondence of television broadcast channels to TVWS radio channels is given below.				



Down-converted WiFi mapping to UHF-TVWS channels. Though the GLSD provides a list of vacant channels, the hardware implementation places further restrictions on the choice of operating channels. For example, the TVWS radio available for this study only supports TV channels ≈ 29 - 39. In this case the set of common channels that are also supported by the hardware is a much smaller set (30, 32, 33), which is still overly optimistic because that is assuming there are no other secondary users utilising these channels in the area.

However, for a community-owned network, nodes are typically installed one then the other, which eliminates the chances of multiple network formation instances occurring. In a nutshell, the correctness of the solution can be established by checking that the dynamic channel assignment for ad-hoc nodes meets the following three key requirements:

i) Each node operates on a channel that it is allowed to use as determined by the GLSD based on the node's location;

ii) Timeous vacation of non-permitted channels;

iii) Realising a complete and unified network graph through distributed coordination as opposed to centralised control.

(a) Interference avoidance

Let $(C_{a1}, C_{a2}, ..., C_{an})$ be the set of sets of channels permitted at node 1, node 2, ... and node n's location respectively as determined by the GLSD. Line #8 of Algorithm 2 on page 63, shows that every node queries the GLSD and constructs the list of allowed channels C_{ai}. From lines #4 and #11, it can be seen that each nodes sets the operating channel to $c_o^i \in C_{ai}$. By doing so, each node meets the TVWS requirement of operating on permitted channels.

(b) Correction of potentially harmful interference

The major potential risk of causing harmful interference exists to such an extent as the chance of a node detecting a beacon on channel c, connecting to the gateway on c, querying the GSLD and then the GLSD response indicating that c is not permitted at the node's location. Considering the clause in the regulation that says the secondary user must vacate a channel within α seconds of a primary transmitter coming active on the channel, it goes without saying that the risk is always there, but the impact is negligible if corrective action is taken swiftly. To assess the proposed solution in terms of its capability to mitigate the identified potential risk, let $t_j^{c^i}$ denote the time in seconds that node j occupies channel c^i. With the GLSD approach, the task of compliance can be reduced down to ensuring that each node operates only on channels that are allowed at the node's location. In other words, a WMN can be said to be compliant if all nodes satisfy the following constraint:

$$t_j^{c^i} \leq \alpha, \forall c^i \notin C_{a_i} \tag{4.3}$$

In the event that a node peers with a remote node on a channel that may not be allowed at the node's location, ignoring the server-side delays, the minimum Internet connection speed required to take corrective action with negligible interference must be

$$\geq \frac{q + h_q + r + h_r + l}{\alpha} \text{ [bits/sec]} \tag{4.4}$$

where q, h_q, r and h_r are the message sizes in bits of the GLSD query message, query overhead, GLSD response, and response overhead respectively; l is the sum of delay caused by other factors such as a broken link and the time required to re-establish the connection, whereas α is the period within which a secondary user is required to vacate an active incumbent's channel.

To illustrate, suppose node i is connected to the gateway on a channel chosen arbitrarily, taking $\alpha = 3s$ and neglecting server response and other delays, Table 4.7 shows the link speed needed for the node to query the GLSD in no more than α seconds. The minimum message size was estimated based on the mandatory parameters specified in PAWS. The ideal link speed will vary depending on the number and type of optional parameters turned on. Refer to Table E.1 and E.2 in appendix E for the listing of required and optional PAWS-based GLSD query and response parameters.

Table 4.7: GLSD query/response size and minimum link speed required. The required link speeds were calculated based on minimalistic TCP/IP and HTTP header lengths of 40 and 26 bytes respectively.

GLSD query size (bytes)		**Link speed needed to transmit in $\ngtr \alpha$**	
Minimum	Options on	Minimum	Ideal
26	± 148	245.33 bits/sec	570.67 bits/sec

GLSD response size (bytes)		**Link speed needed to receive in $\ngtr \alpha$**	
Minimum	Options on	Minimum	Ideal
48	± 164	304 bits/sec	613.33 bits/sec

Besides asserting the feasibility of achieving TVWS regulation compliance in a multi-hop mesh environment, this enquiry into the nodes' capability to correct the potential risk of causing interference raises two important points. Firstly, assuming the GLSD is reachable via the Internet only, the Regulator can impose a "minimum Internet link capacity" TVWS mesh requirement as an additional measure to address compliance concerns. This minimum link capacity requirement can be enforced quite easily, for example by leveraging an already existing PAWS parameter such as the *rulesetId* to identify multi-hop TVWS use cases and then analysing the difference between the timestamp on the GLSD query message and its time of arrival. Secondly, spectrum database protocol design should factor in this requirement by building capability into the protocol to automatically turn optional features on/off based on link quality and supplementary apply efficient encoding techniques to minimise the message size. In addition, the nature of authentication methods, the length of API keys (if in place) are bound to increase overhead and influence the transaction time.

(c) Convergence analysis

In the previous paragraph it has been shown that the proposed mesh formation protocol ensures that each node operates on a channel that is permitted at its location as determined by the GLSD. This section aims to verify that using the proposed algorithm, the nodes reach a steady state. Steady state is hereby defined in this context as the status when the nodes form a network i.e. when every node is able to communicate with every other node, which happens once the nodes are tuned to the same operating channel. Since the topology of the WMN at the formation phase undergoes time-varying changes due to nodes joining the mesh and links getting created, the network can and should be modelled as a dynamic graph $G_{p(t)}$ where $p(t) : \mathbb{R} \rightarrow L$, $L = \{1,2,...,m\}$ is the transformation parameter. The network graph at different stages can be represented as a set of network topologies $T = \{G_1, G_2, ..., G_m\}$. Overall the nodes attempt to reach consensus on the operating channel by implementation the function, which is of the form:

$$y = algorithm(x) \tag{4.5}$$

where the input x is node i and node j's set of allowed channels C_{ai}, C_{aj} and the algorithm attempts to determine the operating channel $C_{ij} \in C_{ai} \cap C_{aj}$ between node pairs. Thus the algorithm converges given the set of universally allowed channels $\{C_{a1} \cap C_{a2} \cap C_{a3} \cap \ ... \ \cap C_{an}\} \neq \emptyset$.

Furthermore, the set of neighbours of node i is N_i, which in graph theory terms is defined as $N_i = \{j \in N : n_{ij} \neq 0\}$; $N = 1, ..., n$ where n_{ij} are elements of the adjacency matrix. A graph is fully connected if either a direct link or a path exists between any arbitrary node pairs. A direct link exists between node i and node d if $d \in N_i$ while a path exists between node i and node d' for $d' \notin N_i$ if there is a finite non-null sequence $P = n_0e_1, n_1e_2, ..., e_kn_k$ whose terms are alternately distinct vertices and edges. The necessary condition for single-hop neighbouring nodes to establish a link is for them to be on the same operating channel. Looking at lines #7-20 in Algorithm 2 on page 63, the protocol ensures that adjacent nodes converge on a common operating channel.

With the exception of the initiating node, the network formation algorithm works in such a way that nodes switch to active scanning mode upon receipt of beacon frames from neighbouring nodes. Therefore, we can say that the degree of each vertex of G is at least 1. Considering node i and node d's neighbourhoods:

$$N_i = \{i \in N(G) | n_i \in E(G)\}$$
$$N_d = \{d \in N(G) | n_d \in E(G)\}$$

Taking any $P \in N_i \cap N_d$:

$$\begin{aligned}
|N_i \cup N_d| &= |N_i| + |N_d| - |N_i \cap N_d| \\
|N_i \cap N_d| &= |N_i| + |N_d| - |N_i \cup N_d| \\
&= degree(n_i) + degree(n_d) - |N_i \cup N_d| \\
&\geq 1 + 1 - 1
\end{aligned}$$

Therefore, since $|N_i \cap N_d| > 0$, it is concluded that $N_i \cap N_d \neq \emptyset$. This means that the neighbourhoods overlap with other neighbourhoods that in turn overlap with others, which is sufficient indication that a path exists between any arbitrary source/destination node pairs.

4.4.4 Time to complete mesh formation

Computational efficiency is of prime concern as community mesh networking routers are typically low-cost and not renowned for high computational capabilities. Generally, the time to complete mesh formation is direct proportional to $|E|$, the total number of edges. If we let m and m' denote the number of messages required to access spectrum information and the number of control messages exchanged between a node and its one-hop neighbour(s), the total time τ required to complete network formation is directly proportional to the number of control message exchanges required and the number of nodes i.e.

$$\tau \propto (m+m')|E| \tag{4.6}$$

Best case scenario: when $c_o^1 \in (C_{a1} \cap C_{a2} \cap \ ... \ \cap C_{an})$
Considering the three-way way handshake procedure described in section 4.2.2, the best case is when the channel assigned by the initiating node turns out to be a globally permitted channel. In this case, $m \rightarrow 3$ and with the GLSD approach, $a \rightarrow 3$ (i.e. initialisation + query + response). Assuming perfect neighbour discovery and that all GLSD queries, control messages, and ACKs are always sent/received successfully,

$$\tau \propto (3|E|+3|\mathcal{N}|). \tag{4.7}$$

Figure 4.8 shows the best case performance of the proposed network formation algorithm obtained from ns-3 simulation. The results confirm the analytical expectation concerning the topology effect on convergence speed. Generally, the convergence time for a chain topology is much higher than that of a grid layout. This is because the grid network layout can be said to have a higher *connectivity* compared to a chain topology. A more detailed explanation on that is given on page 80. But basically, in a chain topology, node i is only able to join the network upon receiving a beacon frame from node $i-1$, whereas in a grid layout, each node has multiple sources of beacons. Node i inside an $n \times n$ grid for example, can receive beacons from nodes $i-1$, $i-(n-1)$, $i-n$ and $i-(n+1)$. Comparatively, the regular mesh network on the other hand, convergences much faster as the plot shows, whereas the proposed network formation algorithm ensures TVWS regulation compliance, which is the primary focus. The best case scenario is further based on the assumption that the candidate channel is in the best position relative to the channel search space as explained on page 81. Considering the difference in convergence speeds between a regular mesh and TVWS mesh shown in Figure 4.8, the results also indicate that for a highly connected multi-hop network, TVWS regulation compliance

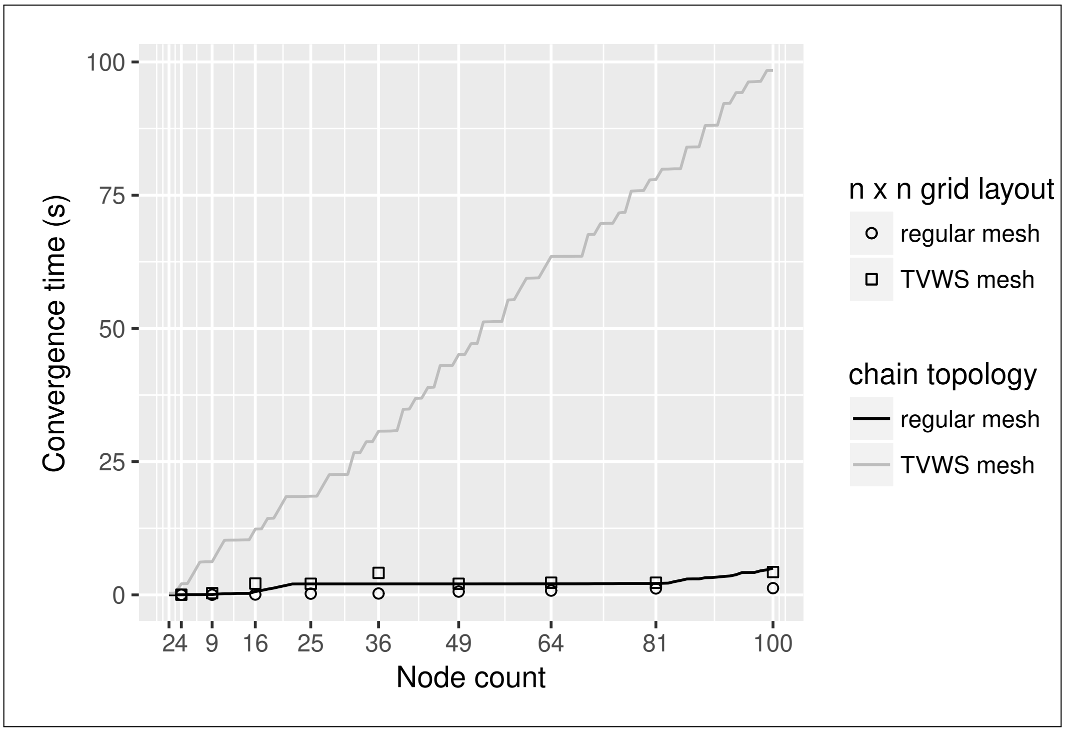


Figure 4.8: Best case convergence time. TVWS mesh simulation assumed negligible GLSD query/response times.

can be achieved without incurring significant additional delay in network formation.

Worst case scenario: when $c_o^i \notin (C_{aj} \cap C_{j+1} \cap \ldots \cap C_{an})$

The worst case is defined in this context as when node i's initial operating channel is not permitted at node j's location where j is node i's single-hop neighbour. Thus in its beacon response, node j indicates to node i to switch to an alternative channel. In this case, $a \to 3$ still, but an increased number of control messages is required for nodes to reach consensus on the choice of operating channel. Therefore,

$$\tau \propto (3|E| + 3|E'| + 3|\mathcal{N}|). \tag{4.8}$$

where $E' \subset E$ is the number of links on which an inband channel change is triggered. For evaluation purposes, it is assumed that $C_{a1} \cap C_{a2} \ldots \cap C_{an} \neq \emptyset$ to keep the problem tractable. Figure 4.9 shows the performance of the proposed network formation algorithm in a worst case scenario. The irregularity in the convergence

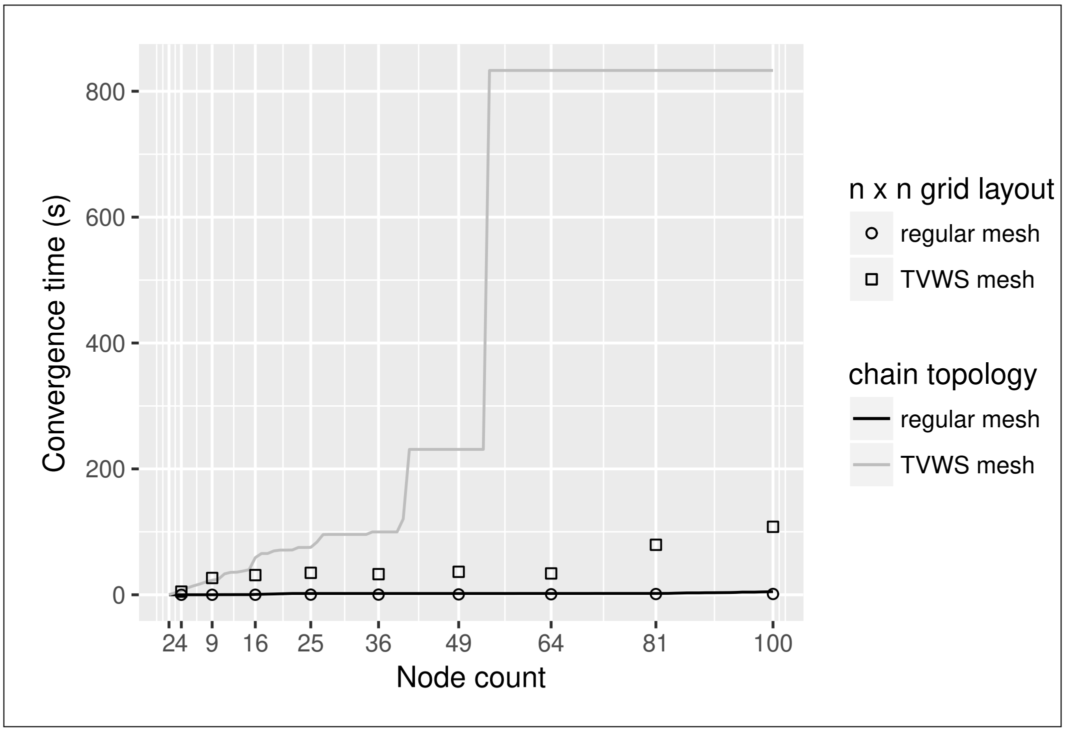


Figure 4.9: Worst case convergence time. Neither the chain topology nor the n x n grid layout represent typical community wireless networks, however the two extreme cases provide a good indication of the effect that node placement has on convergence time.

speed of the chain topology observed in Figure 4.9 might have been caused by the beacon scanning and beacon transmission cycles periodically going out-of-sync between neighbouring nodes, which may also hint at a need to improve on the implementation. All in all, the simulation results confirm that provided the universal intersection set of allowed channels is not empty, the nodes converge on a common allowed channel. There is a significant difference in convergence time between a chain topology and a grid layout, which points more generally at the impact that the physical arrangement of nodes has on convergence. Most mesh networks avoid multiple hops beyond four to five where the throughput begins to be less than the capacity of the gateway. For that reason, the chain topology of more than five nodes will probably never be used without another gateway being inserted. The next paragraph discusses the effect of topology on convergence in more detail.

Topology effect on convergence speed

The previous paragraphs discussed the best and worst case scenarios existing within a given physical topology depending on the choice of initial channel assignment and network-wide channel availability. This subsection aims to provide additional clarity on how the speed of convergence is further impacted by the underlying logical connectivity. To explain, assuming the nodes boot-up at the same time, the process of network formation requires the nodes to distributively determine the operating channel that is favourable for all the nodes. The speed with which the nodes "reach an agreement" is proportional to the degree of connectivity. Considering the WMN graph modelling described previously in section 4.3, the graph is strongly connected if a direct path exists that connects any two arbitrary nodes. *Algebraic connectivity* is given by the second smallest eigenvalue of the Laplacian matrix of the topology graph.

The $h \times h$ matrix of G on h vertices is constructed as follows:

For elements along the diagonal: $l_{ii} = \sum_{i \neq j} a_{ij}$

For all the other elements : $l_{ij} = -a_{ij}$

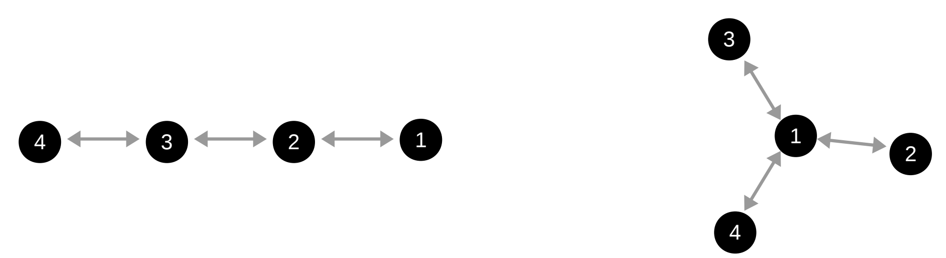
where the non-diagonal element a_{ij} is the number of edges from vertex i to vertex j. The resulting adjacency matrix equals

$$\begin{bmatrix} a_{11} & a_{21} & a_{31} & a_{41} \\ a_{12} & a_{22} & a_{32} & a_{42} \\ a_{13} & a_{23} & a_{33} & a_{43} \\ a_{14} & a_{24} & a_{34} & a_{44} \end{bmatrix}$$

Using the above method, the Laplacian matrices for the topologies in Figure 4.10 (a) and (b) are

$$L(a) = \begin{bmatrix} 1 & -1 & 0 & 0 \\ -1 & 2 & -1 & 0 \\ 0 & -1 & 2 & -1 \\ 0 & 0 & -1 & 1 \end{bmatrix} \qquad L(b) = \begin{bmatrix} 3 & -1 & -1 & -1 \\ -1 & 1 & 0 & 0 \\ -1 & 0 & 1 & 0 \\ -1 & 0 & 0 & 1 \end{bmatrix}$$

The algebraic connectivities of (a) and (b) are 0.586 and 1 respectively. Therefore convergence is expected to happen faster in network (b), which has a higher algebraic connectivity. An algebraic connectivity = 0, would mean that the graph has two disconnected components. For more background and further reading on the concept of convergence and connectivity, refer to work on *consensus algorithms* [119], [120].



(a) **(b)**

Figure 4.10: Simple example to explain topology effect on convergence speed.

Other factors affecting convergence speed

Firstly, the position of the seed channel in relation to the global channel space affects convergence speed. For example, given {36, 40, 44, 48} as the channel space. Considering the sequential nature of passive scanning, the beacons are detected significantly quicker if the initiating node starts transmitting beacons on channel 36 than if it was beaconing on channel 48 for example. Thus assuming a linear search of the channel space to detect beacons, shifting the candidate channel to the right extends convergence time by a factor. Secondly, the beacon generation interval also has a bearing on the speed of convergence. Logically, if the beacons are too far apart, detection is bound to take longer as the nodes have to wait longer to receive one. Tied to the beacon generation interval is the aspect of channel *listening* duration (denoted as t in Algorithm 1) i.e. how much time a node lingers on a channel for incoming beacons. A shorter listening duration quickens the channel space search completion time, but counter-intuitively does not necessarily result in quicker beacon detection. To explain, consider an initiating node sending beacons every 2 seconds. If the next-hop node has a channel listen duration of 1 second, there is a high chance of missing the beacons in between transitions from one channel to the other. From the simulation setup, it was observed that for a beacon interval of 0.5, channel listening duration of between 3 and 3.5 yielded the best results.

WiFi beacon intervals vary from one equipment manufacturer to the other, but routers typically generate beacons every 100 ms. WiFi clients on the other hand employ a shorter beacon listening duration such as 30 ms to avoid affecting the data link, but do it in regular intervals of 1, 5 or 60 seconds (depending on scanning mode) to detect SSIDs quickly.

4.4.5 Adapting to changes in inband channel availability

The frequency with which nodes need to switch to a different channel depends on the spectral environment. The spectrum opportunity is currently defined in terms of *frequency*, *time* and *location*. Since the focus is on UHF-TVWS[3], the dominant dimensions are 'frequency' and 'location'. For a network with static or immobile nodes, which is what this research considers, 'frequency' stems out as the major aspect. To gauge the readiness of the mesh nodes for the DSA paradigm, Table 4.8 gives an indication of performance capability of the devices used in this study.

Table 4.8: Execution completion times observed on the *Mikrotik RB433* based node. Changing settings like channel, channel-width, et al. can be done in a fraction of a second and can be done simultaneously. The 5 seconds indicated above is the amount of time the node requires to apply the settings triggered by a *user space* process i.e. load the settings in the kernel's running memory.

Task	**Time** (seconds)	
	Best case	*Worst case*
Channel change	5	variable
Change channel-width	5	variable
Detect signal	5	variable

Figure 4.11 shows the radio frequency spectrum scans of the environment this

[3]Compared to other spectrum bands, the television broadcast band is fairly static. When the white space being considered is the unused television channels over a given area, generally the white space is defined more in terms of frequency than the time dimension because of the relatively static nature of the television broadcast band.

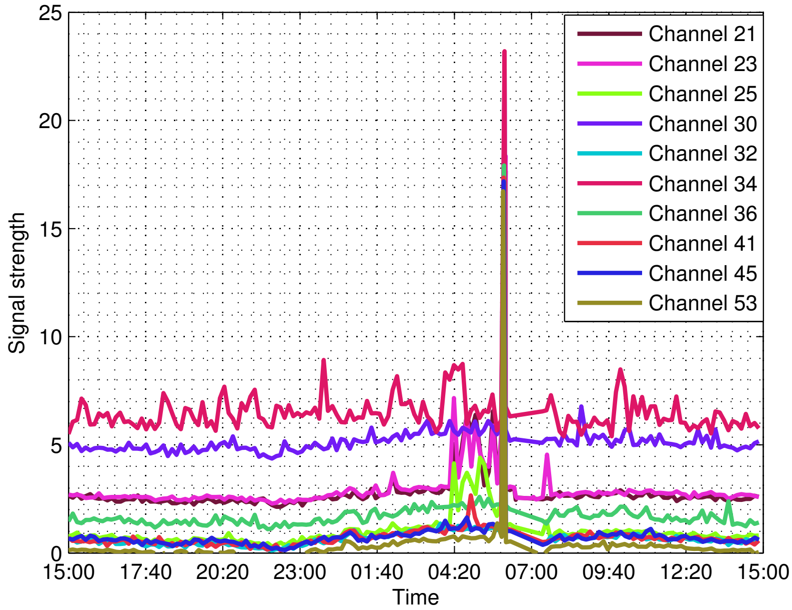


Figure 4.11: Radio frequency spectrum scan over a 24 hour period. The plot shows fairly stable spectral activity across the frequency band, experiencing a significant spike only once over the course of measurement.

dissertation is situated in. The current TVWS regulatory framework is such that a user is only liable for interference caused based on what is known from the GLSD. Therefore, the spectrum scan information is only helpful for the TVWS mesh device in selecting a good operating channel. Based on this set of spectrum scan results collected over a 24 hour period, for practical considerations, this study asserts that changes in the spectrum map will occur with a periodicity in the order of hours or days, and not seconds or minutes as envisaged in some prior related work [121], [122]. Thus the impact of overhead traffic associated with channel information exchanges among the nodes can be minimised by widening the generation interval.

4.4.6 Limitations of the solution

Firstly, the node to first gain access to spectrum information picks a channel and advertises this channel to the network. The initial channel assignment decision lacks a global network view and as such the initial operating channel may not be globally optimal. However, this is mitigated by the fact that further advertising of the nominated channel past the one-hop neighbours is subject to the three-way handshake described in section 4.2.2. Through this three-way handshake at each instance of network formation, the final operating channel is unanimously picked by the mesh nodes.

Secondly, the method of reaching consensus on the operating channel among the nodes assumes uniform traffic demands across the links. In practice, nodes in a large WMN may have conflicting choices of optimal channel. But as described in section 4.3, spectrum analysis is triggered by the fixed time interval or in response to deterioration in performance on the current channel. Therefore, through the channel selection and consensus processes described throughout this chapter, the nodes gradually converge on a *pareto-optimal* choice of operating channel. Furthermore, it is also expected that once network formation is complete, the mesh routing protocol of choice (implemented at either MAC or network layer) will work towards finding the optimal path through the mesh between source/destination node pairs.

So far the solution has been considered correct provided the nodes do not occupy a disallowed channel for more than α seconds. But if a few nodes spend β seconds vacating an active incumbent's channel such that $\beta < \alpha$, it is unclear whether evaluation should consider the time as a sum or focus on single β vacation time instances. The current assumption is that nodes are spaced such that each node is surrounded by its own set of incumbents. Based on that assumption, it suffices to evaluate the solution based on individual nodes' time on the channel.

Furthermore, node placement in real-world deployments is dictated by a combination of factors such as connectivity requirements and topographic elements, and hardly follows a uniform pattern. Node organisation is generally going to significantly affect the process of network formation. Nonetheless, the uniform node layout modelled in this study provides adequate abstraction sufficient to study the regulation compliance problem in a multi-hop environment.

4.5 Discussion

The best case convergence speed was found to be in the order of $(3|E|+3|\mathcal{N}|)$ while the worst is $(3|E|+3|E'|+3|\mathcal{N}|)$. The best case refers to cases where the channel the initiating node starts with turns out to be common to all nodes. The worst case refers to a situation where the initiating node picks an initial operating channel and later propagates a channel change to suit other nodes' channel requirements or availability. Thus in practice, between the best case and worst case lies a continuum of convergence speed variations depending on how many times the channel changes are triggered and propagated before the network converges on a common operating channel.

The worst case scenario might be inevitable when the network starts up for the very first time, but avoidable thereafter. The best case convergence speed can be achieved by a simple re-collection function in the nodes i.e. learning from previous network formation processes. To explain more clearly, this research introduces the concept of *seed channel*, which is the initial starting channel. Once the network converges on a common channel using the iterative process described earlier, the initiating node can make note of this channel. If the network is later restarted, the node can use the previously known common channel as the seed channel. If a different node initiates the mesh formation, it can equally use the previous operating channel as the seed channel. By so doing, the network may experience the worst case scenario only once when the network map is initially unknown and the initial channel selected arbitrarily, but thereafter achieve converges with best case time complexity. The success of this approach rests on the presumed constancy in node location, height and other factors influencing the availability of TVWS channels.

From the description given above, by virtue of being the first node to access the GLSD, it is appropriate to consider the node that initiates network formation as the network gateway. The position of the gateway relative to the network topology has a significant bearing on overall network performance. In view of this fact, some researchers have explored the problem of mesh router placement as well as placement of gateway(s) in WMNs and proposed solutions for working out optimal locations for these functional WMN components [123], [124], [125]. However, in practice one would expect that the choice of location for WMN nodes and gateway will be minimally guided by optimisation theories, but dictated much more by factors such as the intended application, organisation of the target community, geographical elements. physical security concerns and alike. Therefore, the onus should be placed on the mesh protocol to exploit the underlying physical connectivity and find optimal routing paths.

4.6 Chapter summary and future work

Considering the Regulator's position as well as other stakeholders' views around the application of DSA allowing unlicensed users to operate in the licensed bands, it goes without saying that the establishment of a WMN that is compliant with TVWS regulation in all dimensions should be of topmost priority. Once compliance is realised, follow-on work can then focus on optimising various performance aspects i.e. optimising performance of a compliant WMN. This chapter presented an algorithm that extends the existing mesh MAC mechanism to enforce compliance in terms of the nodes' operating channel.

The proposed solution has been evaluated analytically and through simulation using NS-3. For anybody interested in extending the work, the key code snippet for the NS-3 implementation is provided in Appendix D section D.2. The study considered two network topologies, a grid layout and a chain topology. In keeping with TVWS regulation, the operating channel is not pre-configured unlike fixed spectrum access. Instead, when the nodes start-up they initially passively scan the channel space supported by the radio to try and detect beacons from neighbouring nodes. The first node to get spectrum information by querying the GLSD over the Internet through a wired connection for example, initiates network formation by starting to actively transmit beacons. Nearby nodes on a given BSSID eventually detect the beacons, establish a connection on the active channel and query the GLSD using the initiating node as gateway. To mimic the GLSD based spectrum access mechanism, upon joining the mesh, each node retrieves spectrum information from a file-based store populated with available channels based on actual GLSD query results. Once the nodes gain access to spectrum information they are then able to switch to active scanning mode and continue beacon propagation for network formation. Thus nodes are able to autonomously converge on a common channel to form a fully connected network. Analysis of the nodes' capability to correct the potential risk of interfering with incumbents based on the current PAWS specification in section 4.4.3(b), revealed that the Internet connection serving GLSD queries needs to meet a certain minimum capacity enabling the nodes to initiate and complete the transaction within a time period that is sufficiently small to render the potential impact of interference negligible. This is something the Regulator can impose as an additional TVWS requirement for ad-hoc multi-hop environments.

Feasibility was demonstrated using a proof-of-concept prototype that was developed to address the aspect of auto channel configuration for network nodes in ad-hoc mode (refer to Appendix D for the code snippet). By so doing, the research extended the mesh nodes' self-configuring capabilities to include channel assignment. Additionally, the prototypical setup included a node with a single radio connected to two other nodes operating on different channels. This was to test the workability of the radio virtualisation concept as a technique for mitigating shortages in network-wide common channels for single-radio nodes. To simplify the initial analysis, this work considered a case where only one node is first to establish a connection with the GLSD. Future work could explore more complex cases involving multiple nodes establishing connections with the GLSD resulting in multiple network formation instances. In summary, based on the analytical and simulation performance results, this research confirms that DSA for TVWS can be applied to WMNs within the context of the existing regulatory framework. However, careful consideration in the implementation of network formation and topology management protocols is required to ensure compliance in multi-hop environments.

Chapter 5

A-link-metric

WMNs are characterised by multiple possible routes between any two communicating nodes. The logical topology formation and determination of best path between the source and destination is usually implemented as a function of the underlying mesh protocol. The inherent multi-hop and multi-path nature of WMNs renders the routing aspect more relevant in WMNs than other network environments. However, as currently deployed, the link metrics used by routing protocols to weigh the links are inadequate for optimal path selection in DSA based WMNs. This is because the DSA opportunity introduces additional sources of variability that affect link performance and therefore need to be factored in the metric. Over and above, performance is dependent on the design of the routing algorithm and protocol implementation. The link metric employed by the routing protocol is a key component as it forms the basis for the protocol's selection criteria.

The bulk of early research on DSA focused on characterising spectrum usage patterns and quantifying the available *white space* (i.e. parts of the licensed spectrum that are vacant either spatially or temporally), highlighted the drawbacks of FSA and motivated the shift towards DSA [28, 29]. Being able to dynamically access spectrum is only the first step. Issues surrounding optimal utilisation of the spectrum opportunity are yet to be fully addressed.

This chapter focuses on the link metric aspect of routing in WMNs using DSA. The hypothesis is that augmenting existing link metrics can leverage existing routing protocols and improve performance. I refer to the resulting link metric as *A-link-*

metric (Augmented Link Metric). Using A-link-metric, DSA characteristics can be factored in to reinforce current link metrics and reuse existing routing protocols thereby quickening the deployment of WMN with DSA. The observation is that performance improvement is achieved, for a given network scenario(s). Building on this observation, this study introduces *dynamic path metric selection* (DPMeS). Simulation results show that with DPMeS, the routing protocol achieves better performance consistently across a range of scenarios compared to routing with a fixed link metric.

5.1 Notes on metric composition guidelines

Although the routing metric's value may provide a true reflection of link and path quality, it is essential to additionally ensure that the chosen metric is efficiently calculable. Different on-demand and proactive algorithms require the metric to meet certain criteria in order for the protocol to compute the path metric efficiently and avoid routing loops [84]. For example, Bellman-Ford and Dijkstra's algorithms, which have been widely used in the implementation of routing protocols require the metric to be isotonic in order to find paths with minimum weight. Therefore, as a general principle the augmentation process should aim to maintain or realise the routing metric property required by the underlying computing algorithm as highlighted in Table 5.1. The properties presented here are an extension of ideas adapted from guidelines for designing efficient composite routing metrics for low-power and lossy networks (LLN) routing protocol [126]. A *composite* metric is a metric derived from several basic metrics such as hop-count, ETX, delay, and others.

Key differentiator of this work

Specific metric implementations such as [127, 128, 129] et al. share this research's goal of enhancing link metrics to improve network performance. This study makes two key contributions. Firstly, a general framework for augmenting existing metrics for added improvement is introduced (*see* section 5.3). Secondly, the study introduces DPMeS (*see* section 5.3.5). Besides the fresh insight into the topic of routing metric, these contributions aim to unify prior work by utilising several preferred

Table 5.1: Ideal properties of composite routing metrics

Property	**Formal definition**	**Description/comment**
Continuity	Given an interval of [i, j] as the domain of factors, the metric M is continuous iff $$\lim_{i \to j} M(i) = M(j)$$ and thus can take values within the interval between $M(i)$ and $M(j)$	When augmenting, the resulting composite metric should vary proportionately with the factors i.e. small variations in values should result in small variations in the composite metric. Continuity is necessary to avoid instabilities or inconsistencies.
Orthogonality	Metric M composed of variable set S is orthogonal if $\text{cov}(x_1, x_2) = 0, \forall_x \in S$	In this context, orthogonal simply means "uncorrelated". An augmented metric is orthogonal if its constituent independent variables are uncorrelated. In other words, redundant information should not be carried. See section 5.5.2, (i) for a discussion on what constitutes redundant information.
Scalability	$F'(N) \geq F(N)$ where F' and F is the scalability in terms of a given performance objective for the augmented and its corresponding base metric respectively.	The augmented metric should scale medium-to-large sized WMN, taking into account specific computational characteristics of the application scenario. See Appendix B for a discussion on scalability analysis.
Isotonicity	A metric M is isotonic if $M(A) \leq M(B) \rightarrow M(A\&C) \leq M(B\&C)$ and $M(C\&A) \leq M(C\&B)$ for all paths *A, B, C*	The order of the ranking on two paths should be preserved when a third path suffixes or prefixes the paths
Monotonicity	A metric M is monotonic if $M(A) < M(A\&B)$ and $M(A) < M(C\&A)$	The path cost increases appended when added to another path or link. Monotonicity is essential for convergent and loop-free routing.
Lopsided	Given an asymmetric link ij, let M_{ij} be the link metric from $node_i$ to $node_j$ and M_{ji} the metric from $node_j$ to $node_i$, a metric is lopsided if $M_{ij} \neq M_{ji}$	NB. the routing algorithm needs to factor in this property when computing path metric.

Property	Formal definition	Description/comment
Load sensitivity	Given a path capacity of C and load W. As $f(W) \to C$, a metric is load sensitive if the aggregate metric M satisfies the following condition: $\Delta M \propto \Delta W$	As the number of flows on path P increases due to multiple nodes selecting the same set of forwarders at time t, the metric should gradually change to reflect path quality deterioration due to traffic load to allow the routing protocol choose alternative optimal forwarder(s). If this property is not built into the metric, the optimal path may momentarily become the network bottle-neck as the number of flows and traffic load increases.

metrics that have been developed in recent years.

5.2 Why do we need another routing metric?

The progression of routing metrics can be traced through the following stages of network evolution: wired, wireless single-radio, wireless multi-radio. The shift towards DSA marks a landmark phase in the evolution of networking, which necessitates a re-adaptation of routing solutions, similar to the modifications needed when routing protocols from wired networks were ported to wireless environments as illustrated in Figure 5.1. Historically, advancements in routing protocols and associated metrics have been triggered by developments in network media and access types. For example, it was found that routing protocols from wired networks such as OSPF fail to work optimally in wireless networks because they are not tailored to handle a non-static topology or lossy link. At the time of writing, there is yet to emerge a clear industry-standard routing protocol and metric for DSA based environments. The current proposals are still in their infancy, existing only within the research environment, hence the question mark (?). Furthermore, the topmost question mark in Figure 5.1 is to acknowledge that DSA itself may just be a precursor to what is yet to emerge.

This section discusses four important reasons why we need new routing metrics. The arguments presented in this section are not meant to suggest that a new routing metric alone will eliminate the issues completely but rather to touch on the broader question of, what is the implication on routing.

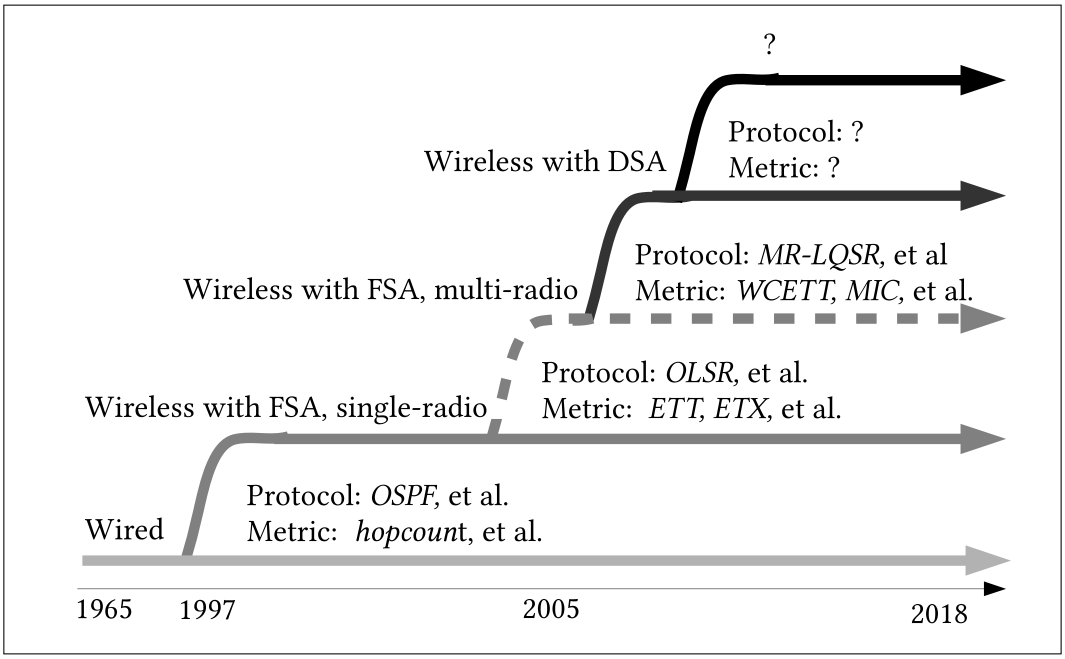


Figure 5.1: Networking evolution and progression of routing protocols and metrics.

5.2.1 Variable channel settings

Traditional wireless routing metrics such as ETX are agnostic to DSA peculiarities. For instance, link throughput varies proportionally with the allowable channel width, but without a change in the packet delivery ratio, the ETX value for example, stays constant as shown in Table 5.2. This was measured on Doodle labs DL509-78 Broadband Radio Transceiver for the 470 - 784 MHz television band [130]. Other metrics that infer link quality based on upper layer parameters are expected to exhibit similar shortcomings.

Table 5.2: Sensitivity of routing metrics to factors affecting link throughput.

Channel width (MHz)	Throughput (Mbits/sec)	ETX	Hop-count	Airtime
5	4.2	1	1	55
10	9.8	1	1	55
20	20	1	1	55

Furthermore, traditional 802.11 wireless networks use a predetermined fixed channel width value such as 20 MHz and for communication to take place, all nodes have to be on the same channel and with the same channel width. However, techniques such as SIFT [131], have been developed that allow variable channel width communication. There are several reasons why variable channel width might be desirable. These include the need to meet regulatory requirements concerning spectrum availability, which is location dependent, and at the same time integrate heterogeneous hardware with varying channel-width support. Another reason is for purposes of adapting the channel-width to optimise the nodes' *filter* performance and reduce *leakages*. The term leakage is used in this context to describe out-of-band and in-band emissions. Out-of-band emission refers to noise or unwanted RF signals. In-band emission is the signal produced in the channel used by communicating devices that affects adjacent channels. Analysis of spectrum masks shows that given a constant transmission power, spectral leakage increases with an increase in channel width [132], though the extent and severity depends highly on the underlying RF frontend hardware. Based on these observations, the next generation of DSA based WMNs are envisaged to comprise links with variable channel settings. Therefore, new routing metrics and techniques are needed that are capable of selecting links with optimal channel settings.

5.2.2 Spectrum availability

White space availability is not guaranteed at all node locations at all times therefore, the nodes require access to some fixed spectrum such as the 5 GHz band in order to maintain connectivity during periods of white space unavailability. Depending on spectrum availability, this implies that DSA based mesh nodes will consist of multi-radios operating in different spectrum bands. These links will perform differently under different environmental conditions as discussed in chapter 6. For example, there are conditions under which a 5 GHz link might perform better than a link operating in the UHF band and vice versa [133]. Therefore, given two possible links such as 5 GHz and UHF, there is need for a standard of comparison between these two links so traffic can be routed over the optimal link. The current metrics such as ETX are inadequate in making a fair comparison of such links as they assume a uniform data-rate across all links, which is less likely in multi-band multi-radio environments.

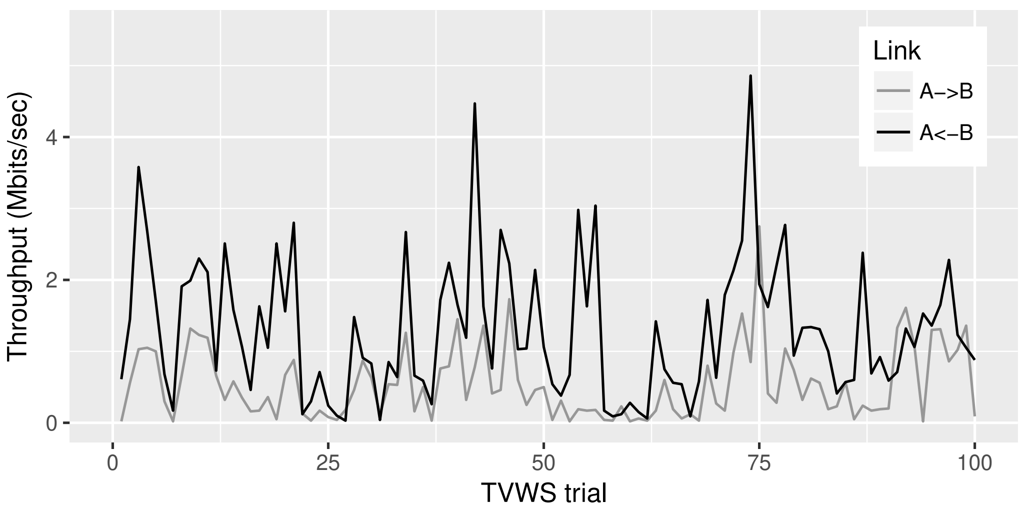
5.2.3 Interference and link asymmetry

Methods of ranking the next best hop used in related work tend to assume *symmetric* links. Given A and B as two source and destination node pairs, a symmetric link is where the link quality from A to B is approximately equal to the link quality from B to A. However, it was observed from the outdoor test-bed deployment comprising nodes equipped with both 5 GHz and UHF-TVWS radios that primary transmitters and other sources of strong RF signals tend to desensitise or interfere with nodes close by. This results in links that are *asymmetric* to a significant extent i.e. the quality of the link in the forward direction is rarely equal to the link quality in the reverse direction as Figure 5.2 shows. Link asymmetry is largely caused by interference, but can also be induced by traffic patterns, faulty hardware and other causes. This link asymmetry presents both a challenge and an opportunity. The opportunity stems from the fact that interference occurs at the receiver. Using multi-band-multi-radio nodes, radios that are "interference-plagued" can be used for data transmission while radios utilising "cleaner" spectrum can be set to receive data as described more detailedly in section 6.3.2 of chapter 6. The imminent challenge is that suitable link metrics are required that factor in necessary link characteristics in both directions to enable the routing protocol to forward traffic via the optimal interface, 'optimal' from the point of view of the sender as well as the receiver.

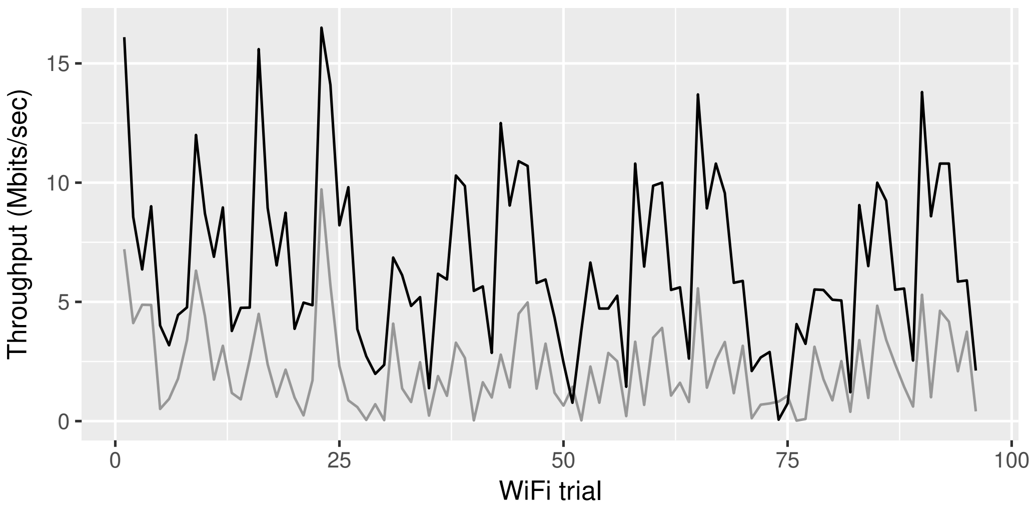
5.2.4 Wider frequency range

Traditional wireless networks operate using a set of fixed channels that stays fairly unchanged over the course of deployment. Networks using either 2.4 GHz or 5 GHz WiFi only for example, operate in a band with relatively low *frequency range*. DSA-based networks on the other hand, are envisaged to operate on a wider range of frequencies that potentially change frequently and have varying propagation properties. Frequency range is calculated as

$$D_{dB} = 20\log_{10}(\frac{f_1}{f_2}) \tag{5.1}$$



(a) UHF-TVWS radio.



(b) 5 GHz WiFi.

Figure 5.2: Multiple forward and reverse throughput samples taken over a period of time on both UHF-TVWS and 5 GHz WiFi radios.

where f_1 and f_2 respectively denote the highest and lowest frequency in the band, gives an indication of variation in free-space loss across the band [134]. For example, the dynamic range for WiFi (5 GHz) $= 20\log_{10} \times (5700/5170) = 0.848$ dB whereas UHF-TVWS for example, has a frequency range of $20\log_{10}(862/470) =$ 5.27 dB. It has been shown that metric performance varies depending on the operating channel [135]. This variation is anticipated to be even more pronounced as the frequency range increases. Therefore, new metrics are needed that enable routing protocols to factor spectrum characteristics in routing decisions.

5.3 Design philosophy

The two main operations of a WMN routing protocol are (i) maintaining connectivity; and (ii) determining the next best-hop such that traffic is ultimately routed over an optimal path. The link metric comes into play in the latter function. In response to the motivation presented in section 5.2, how then should the routing metric look? What characteristics of a DSA channel should be factored into a link metric for optimal route selection in WMN with DSA? Following these guiding questions, the augmented metric is formulated as

$$\textit{(base metric)}\ \Phi\ Z \tag{5.2}$$

where $\Phi \in \{+,-,\div,*\}$ is the specific metric aggregation operator. The choice of operator depends on two things namely, the base metric's path metric concatenation rules as well as the order relation. The metric order relation generally takes one of three forms: (i) the-larger-the-better, (ii) the-smaller-the-better, or (iii) nominal-the-better. A 'nominal' value implies that there is a set condition that has to be met in line with a set reference value. Z is the augmentation factor defined as

$$Z = \frac{(\mathit{penalty\ parameters})(1-\alpha)}{(\mathit{reward\ parameters})(1-\beta)} \tag{5.3}$$

where $0 \leq \alpha, \beta < 1$ are scaling constants. The scaling constants serve two purposes: (i) normalise raw data; (ii) scale the reward/penalty values. For example, when a link with high data rate and high Rx/Tr noise gets rewarded for the data rate and penalised for the noise, the scaling constants regulate the proportions. Examples of base metric candidates include, Hop-count, ETT, ETX, et al. Using these metrics provides a good measure of basic connectivity. Augmentation is deemed necessary to support the routing protocol in selecting superior paths.

Table 5.3: Example definition of the augmentation factor

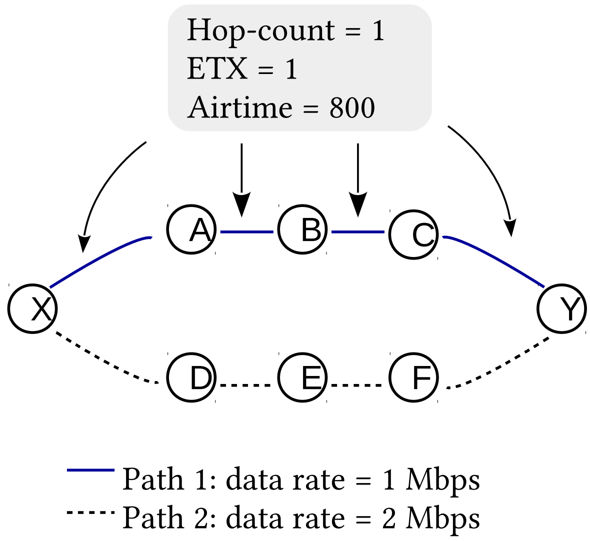
Base metric	Possible Z (augment factor) definition	Augmented metric along the path
Hop-count	$Z = R$, where R_i is the priority that is based on data-rate at Hop_i	a_Hop-count = $\sum_{i=1}^{n}\left[\frac{i}{R_i} * \frac{(1-\alpha)}{(1-\beta)}\right]$, where n is the path hop-count.
ETX $= \frac{1}{(d1*d2)}$, where $d1$ and $d2$ are the forward and reverse packet delivery ratios.	$Z = R$	a_ETX = $\sum_{i=1}^{n}\left[\frac{ETX_i}{R_i} * \frac{(1-\alpha)}{(1-\beta)}\right]$
Airtime = $\left[O_{ca} + O_p + \frac{B_t}{r}\right]\left[\frac{1}{1-e_f}\right]$, where O_{ca}, O_p and B_t are constants for channel access overhead, MAC protocol overhead and the bit count in a test frame respectively, r is the bit rate in Mbit/s and e_f is the frame error rate.	$Z = \frac{n_f}{s_f}$, where s_f and n_f are the signal strength and noise at operating frequency f. Here, Z is being used to penalise forwarders with a low signal to noise ratio.	*See note 1*
Note: a_Airtime $= \left[O_{ca} + O_p + \left(\frac{B_t}{r}\right)\right]\left[\frac{1}{1-e_f}\right]\left[\frac{n}{s} * \frac{(1-\alpha)}{(1-\beta)}\right]$		

5.3.1 Path metric calculation

Consider the well known metrics hop-count, ETX, and Airtime as base metrics. Table 5.3 gives an example application of the augmentation factor Z for each of the base-metrics. The resulting augmented variants of the link metrics are henceforth referred to as *a_Hop-count*, *a_ETX*, and *a_Airtime* respectively. The path metric is defined as the sum of link metrics along the path. Considering Figure 5.3 for example, there are two possible paths between X and Y, which are $A - B - C$ or $D - E - F$. Assuming 100 % packet delivery ratio, using Hop-count or ETX the cost on either path is 4. But when augmented as shown in Table 5.3, the path with a higher data rate is favoured as exemplified in Figure 5.3. The main improvement of a_Airtime is that it factors in the signal to noise ratio in the ranking of the links.

5.3.2 Reward and penalty parameter data

The major weakness of many existing routing metrics is that they are based on implicit measurements, 'implicit' in the sense that they use network layer parameters



a_Hop-count ($\alpha = 0.9, \beta = 0$)	a_ETX ($\alpha = 0.9, \beta = 0$)	a_Airtime ($\alpha = 0.9, \beta = 0$)
A-B-C: 0.4 D-E-F: 0.2	A-B-C: 0.4 D-E-F: 0.2	A-B-C: 80 D-E-F: 40

Figure 5.3: Path metric calculation between nodes X and Y.

to infer link layer status. Seeing that such approaches lead to suboptimal solutions, this study hypothesises that augmenting link metrics with data based on direct interrogation of the *wireless network interface card* (WNIC) can yield a more accurate assessment of link quality for purposes of optimal path selection. The readily accessible data depends on the node's firmware and NIC driver. On a Linux based platform for example, wireless tools such as *iw <interface> info, iw <interface> station dump* can be used to query the WNIC. Some of the possible raw data obtainable from the WNIC include *channel, channel-width, tx bitrate, rx bitrate, MCS, signal level, tx power* and *noise*, which are all well known parameters of an 802.11 device. The obvious candidates to factor into the routing metric are those characteristics that vary from node to node and have an impact on performance. Section 5.3.4 and section 5.5 discuss the inclusion of factors that are uniform across the network such as channel or MCS into the routing process.

5.3.3 Choice of scaling constants

Section 5.3 introduced scaling factors α and β that may be applied when using raw data from the WNIC to standardise the values that might be driver dependent. The other purpose of the scaling factors is to bring the reward parameter and penalty parameters to even ground as illustrated in Figure 5.4. The ratio of impact on performance of a set of reward parameters to that of penalty parameters may not be 1:1 therefore, a method of correlating specific rewards to penalties and vice versa is required for well-rounded link comparisons.

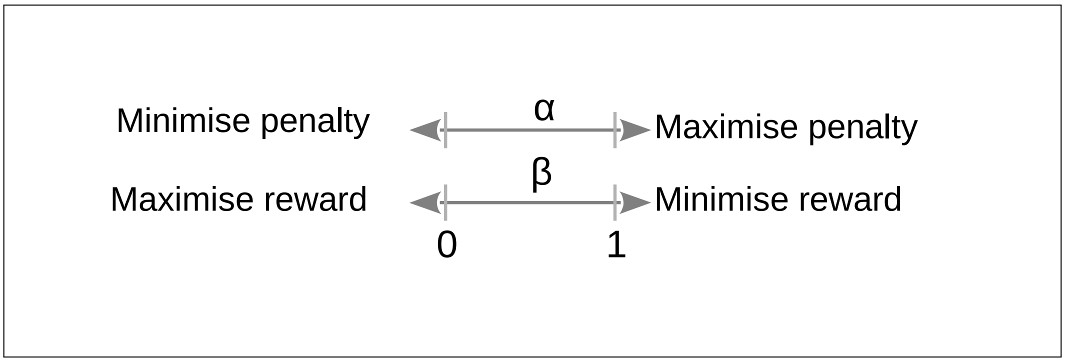


Figure 5.4: Scaling constants

5.3.4 A case for cross-layering

Prior related work on wireless network management framework approaches such as Antler [136], outlines a multi-tiered approach in collecting metrics. The framework allows the network administrator to take action when certain thresholds are reached. In keeping with the WMN's *self-organising* and *self-healing* properties, this study proposes building the administrator actions such as changing the channel, into the node's capability. To this end, in addition to establishing/dropping a routing table entry when the metric value reaches a certain level, nodes can be designed to change to a different channel when the quality of the operating channel deteriorates to a set threshold. Furthermore, based on the assertion that the quality of a link is impacted by the quality of the operating channel, it follows that the choice of operating channel conversely influences the routing decision as illustrated in Figure 5.5. Switching to a different operating channel yields one of three performance outcomes: (i) improvement; (ii) deterioration; or (iii) no significant change.

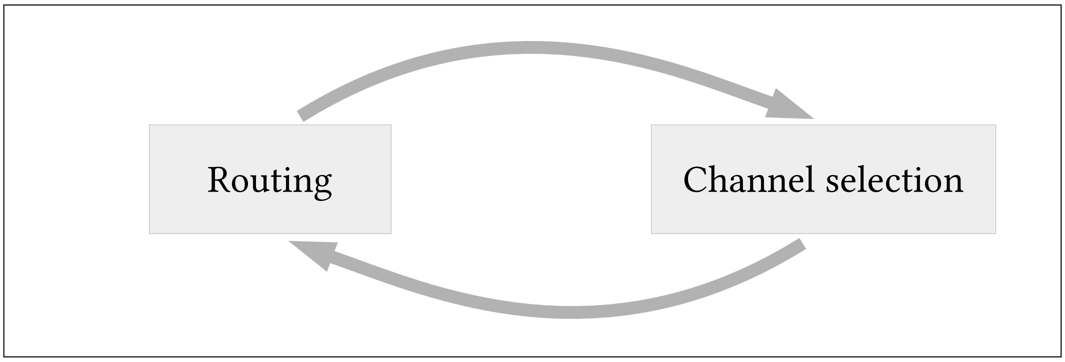
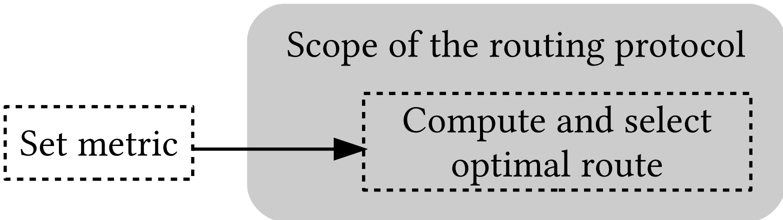


Figure 5.5: Traffic patterns induced by routing decisions impacts the channel performance. Conversely, the choice of operating channel affects the routing decisions.

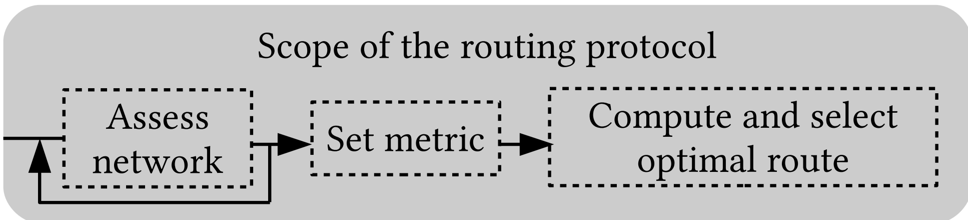
A proactive routing table can be represented as an *n-tuple*, typically a 4-tuple $T = (d,h,i,m)$ where d is the destination address, h is the address of the next-hop, i is the interface to forward through, and m is the metric value computed. This research embraces the idea of including an additional dimension to the routing information so as to consider DSA characteristics in the routing decision. Thus ideal routing with DSA may be symbolised as $T^{'} = (d,h,i,m,y)$ where y is the channel consideration. For simplicity, the assumption is that all the nodes have a common set of usable channels. Adding the spectrum dimension to the routing table is aimed at guiding the channel switching decision. The challenge for WMN consisting of ad-hoc nodes in a multi-hop environment is two-fold. Firstly, the globally optimal channel has to be determined. Secondly, the decision to transition to the new operating channel needs to be coordinated. For this reason, $T^{'}$ is the preferred approach because channel information and other control messages can be shared among the nodes by piggy-backing on the routing protocol's *hello packets*, which helps to keep overhead traffic to a minimum.

5.3.5 Link metric selection

Traditionally, a routing protocol is statically configured with a routing metric such as ETX, ETT, WCETT [127], et al. Evidence from pre-existing work on link metrics point to the fact that "one size fits all" does not apply because the suitability of link metrics seems to depend on the application or service scenario of the network and usage pattern among other things. Newer versions of OLSR for example, can make use of two types of routing metrics, namely hysteresis and ETX. However, once the metric is set at start-up, it remains unchanged until the administrator decides to make changes. The approach proposed in this dissertation is to aggrandise the scope of the mesh routing protocol by including a *pre-routing phase*. The pre-routing phase is initially a start-up process and latterly a periodic process where the protocol carries out an assessment of the network to determine the suitable link metric as illustrated in Figure 5.6.



(a) Traditional routing



(b) Enhanced routing strategy

Figure 5.6: Dynamic link metric setting. Refer to Table 3.2 (page 37) for the concept matrix serving as a guide for dynamic path metric selection from known/pre-determined sets of metrics for a given scenario.

In response to the question of which one is the ideal metric, this research introduces the concept of *dynamic path metric selection* (DPMeS). Empirical findings from this study collaborated with meta-analysis results led to the assertion that routing protocols should have inbuilt capability to determine the suitable link metric. DPMeS is an extension of the functionality of the routing protocol to encompass mechanisms and criteria for determining a suitable routing metric for the network. To achieve this, a routing protocol requires a mechanism of assessing the network and determine best performing metric as illustrated in Figure 5.6.

Implementing DPMeS introduces two sub-problems: firstly, how to carry out the network assessment; and secondly, determining how frequent to do the assessment. The dynamic link metric selection mechanism consists of the following key components:

i *Network assessment.* Per neighbour assessment requires time of $\mathcal{O}(n^2)$, whereas the broadcast method requires $\mathcal{O}(n)$ where n is the node count. For this reason, the broadcast method, which has a lower time complexity is preferred. To simplify coordination, a node designated as *master node* probes the network via *link class request* (LCRQ) broadcast messages. The other nodes in turn respond to the broadcast message and send a *link class reply* (LCR) back to the master node. Compared to route updates, these messages are exchanged much less frequently, which minimises overhead.

ii *Network classification.* The master node collects the probe responses and uses the data to classify the network based on the dominant network characteristics. Possible network profiling criteria include, number of radios, network size, degree and extent of external RF interference, node mobility, data-rate pattern, etc, similar to the conceptualisation in Table 3.2 (chapter 3).

iii *Link metric selection.* The master node applies rules set before hand to map the network class to a suitable link metric. Thereafter, depending on the network class, the master node broadcasts a message directing the nodes on what metric to use. At this stage of the work, the rules for network classification and link metric mapping were arrived at based on link metric tendencies that have been derived from a combination of simulation results and literature survey of prior work on link metrics [23, 84, 137, 135, 138, 127].

5.3.6 DPMeS formalisation

To formalise the system, the network is modelled as a bipartite graph $G = (N, C, E)$ where N is a set of nodes deployed over an area, E is a set of node pair links and C is a set of link classes for one-hop node pairs $(u, v) \in E$. Additionally, let $r \in N$ = master node and M = set of link metrics. The overall network class c is defined as

$$c = \max \sum_{i=1}^{n} [c_i = c] \tag{5.4}$$

For a network classified as c, the metric to use is denoted by

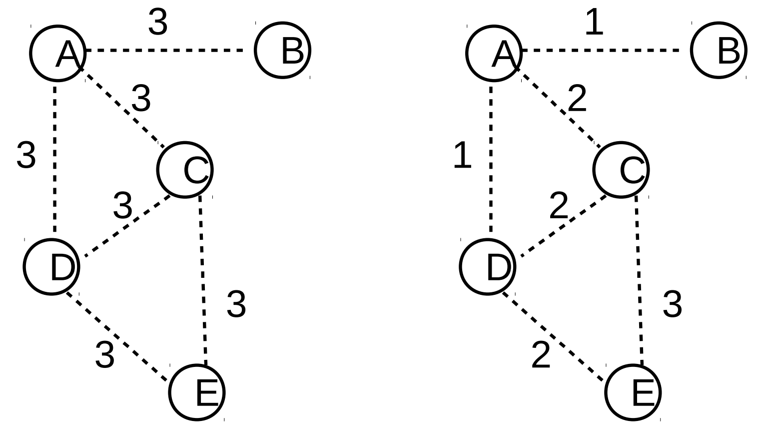
$$f : C \to M, \text{ for } \forall c \in C \tag{5.5}$$

Algorithm: there are three key message types transacted namely (i) *link class request* (LCRQ), (ii) *link class reply* (LCR), and (iii) *link metric directive* (LMD). LCRQ is the probe sent out by the master node, LCR is the message sent to the master node in response to a LCRQ, and LMD is the directive sent by the master node to all the other nodes. LMD dictates when to switch the link metric and which metric to switch to.

Algorithm 3 : Dynamic link metric selection procedure at the master node.

1: At start-up:
2: Master node r sends LCRQ to $\forall i \in N$
3: For all LCRs received from nodes u and v:
4: assign c_i the class of the edge (u,v), $\forall (u,v) \in E$.
5: Count each of the link classes in the graph.
6: Determine c the network class.
7: If the network class $c \neq$ previously computed class:
8: send LMD.
9: Repeat steps 2 - 8 every t time units.

To illustrate, consider Figure 5.7: the numbers *1, 2, ..., n* on the edges correspond to network classes *class 1, class 2, ..., class n.* Figure 5.7a shows the simplest case where all the links possess the same characteristics such as node type, and data rate. This puts all the links in the same class, *class 3* in this example, and on that basis, the network in Figure 5.7a is easily classified as *class 3*. Figure 5.7b on the other hand, represents a network exhibiting heterogeneity in link characteristics e.g. a mix of single-radio and multi-radio nodes, low and high data rates. As an example, the links (A, B), (A, C), (A, D), (D, C), (D, E) and (C, E) have been categorised as *class 1, class 2, class 1, class 2, class 2* and *class 3* respectively. There is one *class 3* link (C, E), two class 1 links (A, B) and (A, D), and three class 2 links (A, C), (C, D) and (D, E). Using simple majority rule for example, overall the network can be



(a) Scenario A: homogeneous links **(b)** Scenario B: heterogeneous links

Figure 5.7: Conceptual depiction of network classification based on node and link characteristics.

classified as *class 2*. Alternatively, a weighted sum approach can be integrated in the decision making process.

5.4 Performance evaluation

To demonstrate how the augmentation approach works with a given base-metric, this study considers *hopcount* and *ETX*, which are common link metrics used in WMNs routing. In addition, *Airtime*, which is the default routing metric used in Hybrid Wireless Mesh Protocol (HWMP) is also included. Besides their widespread adoption, attention is drawn to these three metrics because they have the same *aggregation operator*, which is addition (+). Additionally, they also use the same *order relation* i.e. in all three cases, the metric value i is better than j iff $i < j$.

To test the dynamic link selection concept, a modified version of HWMP was developed that included a component that assesses the network and sets the link metric based on network characteristics as described in section 5.3.5. The network assessment process runs at start-up and thereafter periodically. The modified protocol version is hereafter referred to as m_HWMP. The presupposition made in this study is that changes in network conditions necessitating a switch in the set link metric will occur at long intervals and as such, it is expected that the gains of switching metrics will outweigh the cost.

5.4.1 PHY layer modelling

The PHY model comprise channel loss and delay model based on the model detailed in YANS [139].

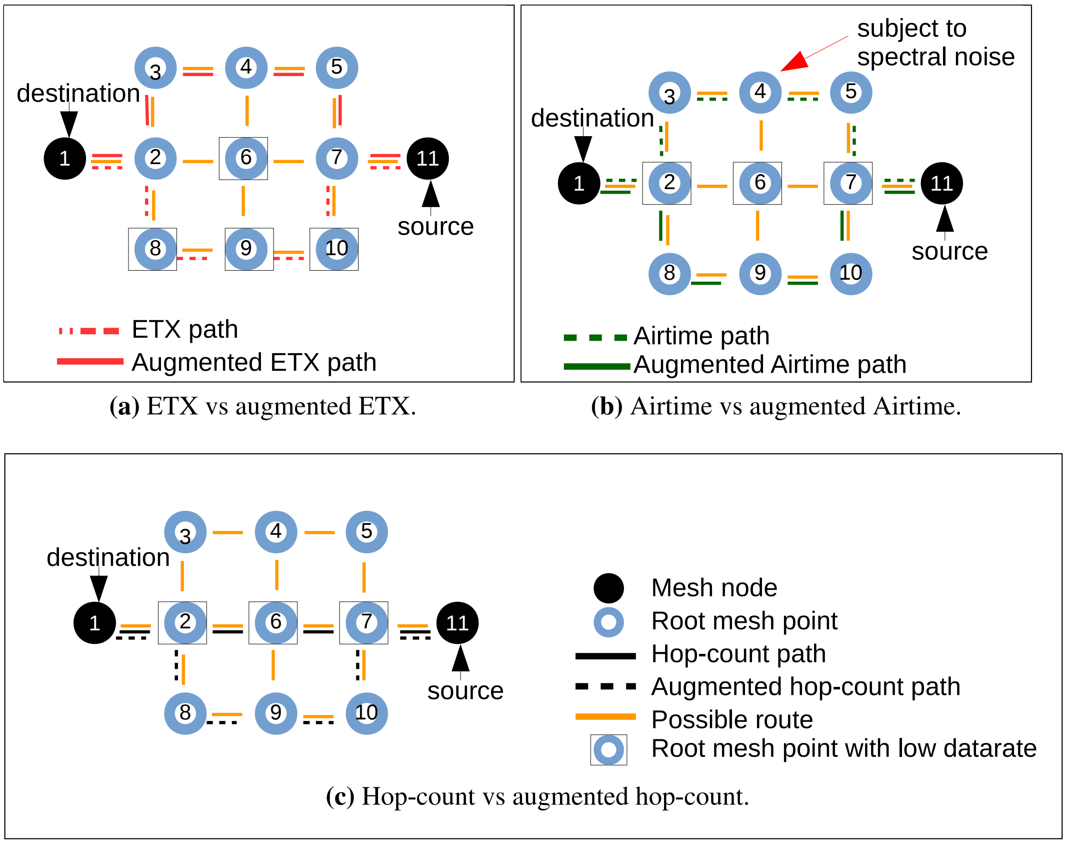
5.4.2 Routing protocol description

For evaluation purposes, HWMP [137], which is the default protocol for IEEE 802.11s WMN was used. HWMP supports *on-demand* and *proactive* modes of operation depending on the configuration.

5.4.3 Simulation scenarios and setup description

Evaluation was conducted in a simulation environment using *Network Simulator version 3* (NS-3) [140]. NS-3 is a *Discrete-event simulator* (DES) that can be configured to produce deterministic results or stochastic output based on an inbuilt pseudo random number generator. The default fixed *deterministic seed* value was used throughout the simulations, while *run numbers* 1, 2, ..., 23 were used to get a broader sense of results . The output of a deterministic model is determined by the set of parameter values, which implies that the output of each run is the same unless there is a change in parameter values. This is on the contrary to *stochastic models* that are characterised by elements of chance and probability. As such, the output of a stochastic model may vary given the same parameter values. The deterministic approach was chosen in this study because it fosters reproducibility of results, which helps with further research. The style of reporting used in this section and subsequently other parts of this dissertation makes use of *Strengthening The Reporting of Empirical Simulation Studies* (STRESS) guidelines [141] and the references therein. STRESS guidelines are aimed at providing a standardised approach for reporting on discrete-event simulation-based operational research. The guidelines emphasise providing adequate detail of the modelling as well as software/hardware specifics to foster reproducibility of studies.

Figures 5.8a - 5.8c show the general layout of nodes used to compare performance of base link metrics with the augmented variant. The setup shows clearly



(a) ETX vs augmented ETX.

(b) Airtime vs augmented Airtime.

(c) Hop-count vs augmented hop-count.

Figure 5.8: Overview of network scenarios used to compare base metric with augmented metric.

marked sender and receiver node pairs and the path selected by the routing protocol using the base metric and its augmented variant. The topologies are intentionally simple to facilitate rigorous analysis. The network was simulated initially with uniform data-rate to trace the packets and establish the path chosen by the protocol based on the metric as illustrated in the Figure. In latter simulations the sensitivity of the metric to changes along the path was studied by varying the data-rate and introducing spectral noise at the *root* mesh point along the protocol's preferred path as indicated in Figure 5.8b. To achieve multiple data-rates, the *DataMode* node attribute setting in ns-3 was varied to mimic low and high data-rates. Using augmented hop-count and augmented ETX metric, links with higher data-rate got a higher priority while nodes with lower data-rate got a lower priority as discussed in the next section. This concept can easily be extended to support several data-rates by defining intermediate levels of priority between the lowest and highest priority.

Table 5.4: Simulation configuration

Parameter	Setting
Node spacing	100 m
Node mobility	static
PHY specification	802.11
Antenna	Omni-directional
Routing protocol	HWMP (proactive mode)
Transport protocol	UDP
Packet size	1024 bytes
Number of flows	variable
Simulation time	100 s
Seed value	1
Run numbers	1, 2, ..., 23
Simulator version	ns-3.25

Table 5.4 shows a summary of the simulation settings used. The complete source code and further simulation environment specific settings is accessible online [142].

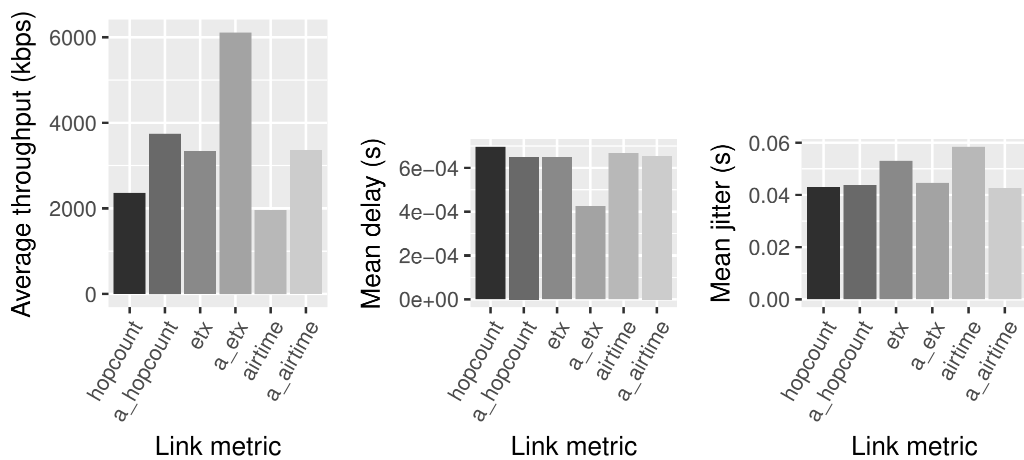
5.5 Discussion of findings

Figures 5.9a, 5.9b and 5.9c show the performance in terms of throughput, mean delay and jitter respectively, yielded by the routing protocol using the metrics under consideration. The augmented metric variant exhibited performance improvement in terms of throughput and delay. Hop-count on the other hand, outperformed all the other metrics in terms of jitter.

When hop-count metric was tested in the network scenario depicted in Figure 5.8c, the protocol yielded lower throughput. This is because the protocol chooses the path with least hop-count, whereas the augmented version of hop-count prioritises the path with a higher data-rate thereby producing higher throughput. Similarly, when ETX was tested in the network layout shown in Figure 5.8a, the protocol selected the path with minimal *path* ETX. Whereas using the augmented ETX variant, the protocol was able to consider path ETX and additionally favour links with a higher data-rate. As a result, the augmented metric variant exhibited performance improvement in terms of throughput and delay. Equivalently, the basic Airtime metric failed to appropriately rank the optimal path under the set-up depicted in

Figure 5.8b because of its agnosticity to spectral noise. By augmenting Airtime metric to factor in noise, the routing protocol was able to select the path comprising links with higher data-rates and low noise. Subsequently, a_Airtime returned better performance compared to Airtime metric.

Proactive mesh protocols send *hello* packets at intervals in the order of seconds, which is useful in quickly establishing alternative routes when a preferred link goes down. One obvious drawback to the augmented approach is that it inevitably increases the size of hello packets to include the additional information. However, DSA-induced link factors do not change significantly every couple seconds. Therefore, at the routing protocol level, we can rip the benefits of carrying out accurate link ranking by *active probing* or mathematical *predictive analysis* at longer time intervals to lessen the overall impact of probing or computational costs. This research proposes an *n-tiered* approach in setting the update interval i.e. using different intervals for different factors. For example, channel information changes less frequently and so, the hello packet only needs to include channel information at intervals in the order of hours or days. Alternatively, these control messages can be scheduled to occur at fixed off-peak times to minimise the impact of overhead traffic.



(a) Average throughput **(b)** Mean delay **(c)** Mean jitter

Figure 5.9: Performance results.

Furthermore, the metric calculation process makes use of a *measurement window* i.e. a period over which probes are received. Reducing the window size results in routing decisions that are more responsive to rapid fluctuations in link quality. The advantage of high responsiveness is that at a given instance, the protocol is able to find high throughput paths. However, the heightened sensitivity to changes in link quality also causes more *route flapping*. Excessive route flapping can significantly increase packet loss. Therefore, this study recommends a moving measurement window similar to TCP's sliding window.

Besides choosing the best forwarder based on the metric value received or calculated, the routing protocol design has to put into account the trade-off between global and local optima. For instance, data-rate, which is a possible reward parameter to factor into a metric is inversely related to transmission range. Conversely, Modulation and Coding Schemes (MCS) typically employ rate adaptation techniques based for example, on signal strength to maintain optimal "goodput". The transmission speed listed by the driver indicates the wireless device's modulation rate, which may not necessarily be equal to the usable throughput. However, it provides a good indication of the device's throughput capability. All in all, further investigation is needed to thoroughly understand the interrelation among reward and penalty parameters, global and local optima.

5.5.1 Scalability

One of the major concerns regarding A-link-metric is scalability. To address such concerns, analysis of scalability defined in terms of network convergence was carried out. The method and findings are presented in *Appendix B*. The results show no significant difference in scalability between the augmented metric solution and the corresponding base metric. This confirms the expectation that scalability has little to do with the metric component and more to do with the routing protocol as a whole.

5.5.2 Implication of the findings

i *Explicit factoring.* Thorough experimentation may be required in some instances to establish whether or not a piece of information is redundant. For example, in most MCS implementations, the data-rate is regulated based on the signal to noise ratio (SNR). Hence at first glance, combining data-rate and SNR into the metric might appear redundant because the two may be seen as capturing the same link characteristic. However, simulation results show an observable performance boost when SNR and data-rate are explicitly factored into the metric. Furthermore, while variables may be highly correlated in principle, they may not in practice correlate as highly due to a range of issues such as driver and hardware limitations. Therefore, explicitly factoring the variable(s) into the metric is essential for effective routing.

ii *No all-round ideal metric*. Metrics perform differently under different scenarios. As new routing protocols are developed to harness DSA dividends, support for multiple metrics and easy integration of new ones should be a core design objective.

iii *Dynamic metric selection.* Once there is support for multiple metrics as well as metric calculation algorithms, the next step is to in-build the routing protocol with the "intelligence" to dynamically select the suitable metric based on the prevailing network status.

5.5.3 Limitations of the study

i The enormous complexity associated with modelling a wireless channel suggests that results obtained from a simulation environment only give an approximation of performance, but serve well as a guide nonetheless.

ii The characterisation of the network for purposes of determining suitable link metric employed in dynamic link metric selection was to an extent influenced by the test results obtained through this ns-3 simulation setup. The results obtained from other simulation environments may be different due to lack of consistency in simulator package implementations.

iii Network performance does not depend on the sufficiency of the link metric alone, but also on the routing algorithm and protocol implementation. The results presented herein are specific to the routing protocol considered. Follow on work will include an extension of the study to cover other protocols.

5.6 Chapter summary and future work

This study confirms that base metrics are inadequate and that augmented alternatives would be better for DSA. This research makes no claim about a single suitable routing metric, but instead provides a framework for taking a desired existing metric and adapting it for DSA.

The study has demonstrated basic scenarios under which a routing protocol might fail to compute the optimal path using the metrics considered. Suffice to say that for every scenario under which a routing protocol with its associated metric thrives, there is always another set-up or network state under which it performs poorly. Based on this observation, it is evident that routing protocols should always be designed to support multiple routing metrics and dynamically toggle the link/-path valuation scheme for optimal performance in different deployment scenarios. The discussion on routing is going to remain relevant for as long as there is demand for higher QoS for various wireless network services. It is difficult to maximise performance in all desired terms because several performance objectives such as transmission rate and transmission range are antagonistic. Consequently, courses of action taken to maximise one objective tends to minimise the other. More research is required to resolve the ensuing conflict graph.

Although wireless network routing metrics have been studied for a long time, there is yet to emerge a single agreed upon routing metric. This goes to show that the choice of routing metric in a multi-path environment is not a settled matter yet. There is still plenty of room for improvement, and thus further inquiry should continue to challenge the current ideal. As we prepare for the adoption of the dynamic link metric selection concept in emerging and existing routing protocols, future work will include the following further investigations:

i *Criteria/techniques for network assessment and classification.* Suppose metric A is suitable for a network with static nodes and metric B is ideal for a network with mobile nodes. Now posit the network consists of some nodes that are static and nodes that are mobile, there is a question of which metric the routing protocol should use between A or B. The current DPMeS strategy uses simple majority rule to classify the network, which means that if there are more static nodes than the ones that are mobile, then the network will be classified as static. This may lead to a suboptimal solution, therefore further research is required in that direction.

ii *The frequency with which to assess the network and fine-tune the assessment process for practical purposes.* There is ample evidence to support the proposed assessment criteria, however the points of transition for determining factor(s) i.e. exact points where performance using one metric begins to deteriorate and the performance of the other metric starts to get better are still only vaguely clear. For example, the question of "what extent and degree of mobility is required for hop-count to outperform ETX?" still needs further investigation.

iii *The inter-play among the link metric, routing protocol and the choice of values for the tuning parameters α and β.* The relationship among the aforementioned aspects is not adequately understood at the moment. One possible line of enquiry worth exploring is to investigates trends (if any) in the validity of these scaling constants and explore the option of dynamically sizing the values.

iv *Test-bed implementation to confirm the simulation results.* There is a lack of standardisation across network simulation packages. In addition, several wireless network aspects such as channel quality and interference are hard to model realistically. Therefore, a test-bed implementation is imminent to promote further adoption and refinement of this work.

Chapter 6

Characterisation of 5 GHz WiFi and UHF-TVWS hybrid links

Network capacity and performance can be improved by using multiple channels simultaneously, which requires multiple transceivers. Basic multi-channel capable nodes can be built using one of the following architectures: (i) *multiple hardware platform* where two or more single-radio nodes are connected via Ethernet to form one logical multi-radio mesh router; (ii) *single hardware platform* where a single node has multiple transceivers fitted; or (iii) *single-chip multi-transceivers* where multiple transceivers are integrated into one wireless chipset on a router [88]. This study considers the single hardware platform fitted with multiple transceivers approach. The focus is on mesh routers fitted with 5 GHz WiFi and UHF-TVWS transceivers to realise multi-band-multi-radio mesh routers. Spectrum availability varies from location to location, but is generally inversely proportional to the population density. WiFi is suitable for densely populated urban areas, whereas UHF-TVWS is ideal for sparsely populated rural areas, which also happen to have significantly more TVWS compared to urban communities.

When confronted with diverse population densities, there exists a grey region (sometimes referred to as peri-urban) that is characteristically a cross between rural and urban regions from a spectrum requirement standpoint as shown in Figure 6.1. A combination of WiFi and TVWS is appropriate in this region of intersection. Research [143] has shown that in such scenarios, the gains of using a combination of

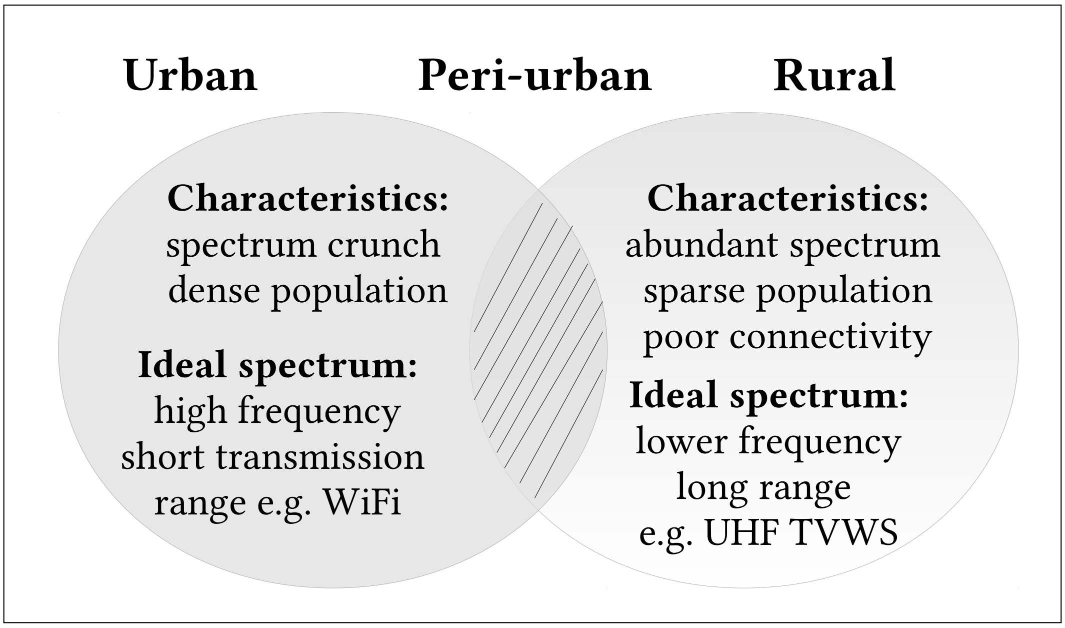


Figure 6.1: Spectrum requirements by region.

TVWS and WiFi are much larger compared to WiFi-only or TVWS-only spectrum band usage.

Applications of WiFi and TVWS can be categorised coarsely into *access-tier* and *back-haul-tier* network architectural components. For a combination of technical and economic reasons, several reports from literature have shown deployment scenarios where any single operating band is inadequate, which points to the fact that an optimal solution requires a mixture of operating bands at the access as well as the back-haul tier. Notable examples of proposals made by the research community include, a combination of WiFi and LTE [144], and a combination of TVWS and LTE-A [145]. The problem of optimal use of TVWS and WiFi bands for back-haul connectivity amid diverse population densities is highlighted in WhiteMesh [143]. WhiteMesh introduces a Band-based Path Selection algorithm designed for optimal channel assignment of both TVWS and WiFi. The WhiteMesh solution is analysed in terms of traffic served putting the population density into account, but does not consider environmental factors that affect link performance. Other researchers have proposed combining TVWS with 5G infrastructure for rural coverage where traditional cellular coverage models are less economically viable due to low user density and subsequent revenue [146]. The work on TVWS with 5G considers the cost and analyses the feasibility of using TVWS for rural Internet access using 5G, but does not provide any test results of TVWS performance for the proposed architecture. Overall, there is limited experimental studies comparing the performance of links operating in 5 GHz and UHF-TVWS radio frequency bands.

Regarding the performance of WiFi-like access points operating in TVWS, the benefits of larger coverage area and better obstacle penetration are challenged when inter-access point interference is considered [147]. The lower operating frequency of TVWS results in larger cell sizes and the overlap in contention domains among interfering access points significantly reduces the link rate. Therefore, it may be said that the wider coverage range provided by TVWS is considered best suited to rural settings because degradation due to inter-access point interference is minimal because of low access point density as a result of sparsity in population. However, a few judiciously well placed TVWS radios spaced far apart in urban areas can offer lower data rate coverage filling and better building penetration, which is useful in bridging the gaps among clusters of high frequency WiFi radios as illustrated in Figure 6.2.

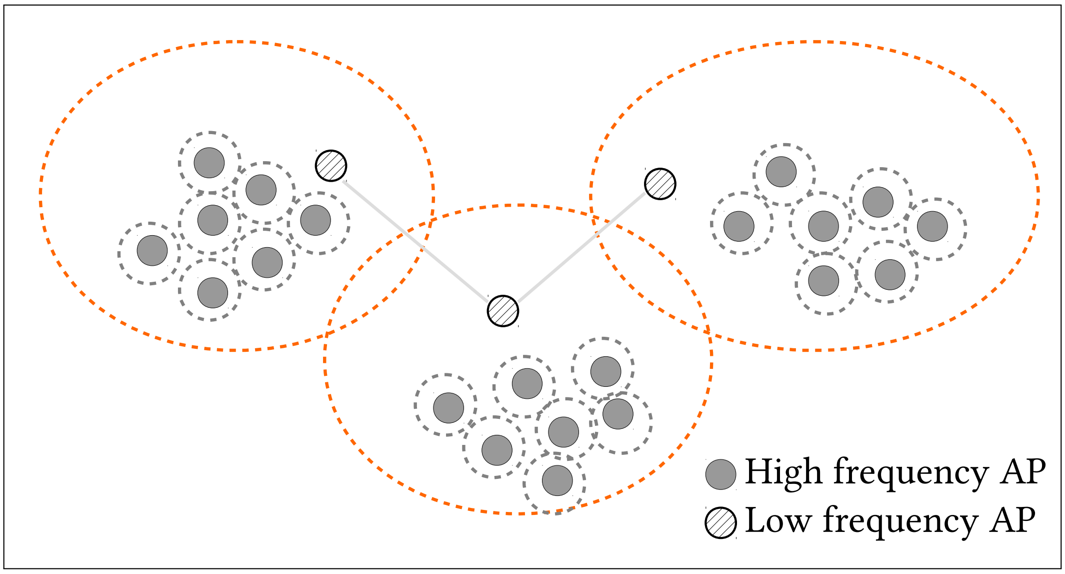


Figure 6.2: Densely spaced high-frequency (e.g 2.4/5 GHz) access points combined with judiciously placed low-frequency (e.g. UHF-TVWS) access points at the access layer in urban communities.

6.1 Envisaged application scenario

One of the biggest challenges facing rural communities is the extension of connectivity from the nearest point-of-presence (POP) to the houses. These areas are typically characterised by sparse population and rugged terrain, which makes it economically and technically impractical to lay down copper or optical fibre cables. Moreover, vegetation and other obstacles along the signal propagation path results in obstructed line-of-sight.

Owing to the known advantages and drawbacks of *high* and *low* operating radio frequencies, this work considers using a combination of WiFi operating in 5 GHz and TVWS for *first-mile* connectivity. The term "first-mile" is hereby defined as the stretch from the location of the remotest user to the closest POP. Figure 6.3 illustrates the envisioned application scenario. The architecture comprises nodes with 2.4 GHz WiFi, 5 GHz WiFi and UHF-TVWS radios strategically deployed at key community sites such as schools, clinics, libraries, office parks and houses. The 2.4 GHz radio serves the access-tier whereas the 5 GHz WiFi/UHF-TVWS radios interconnect the nodes in mesh mode to form the back-haul-tier.

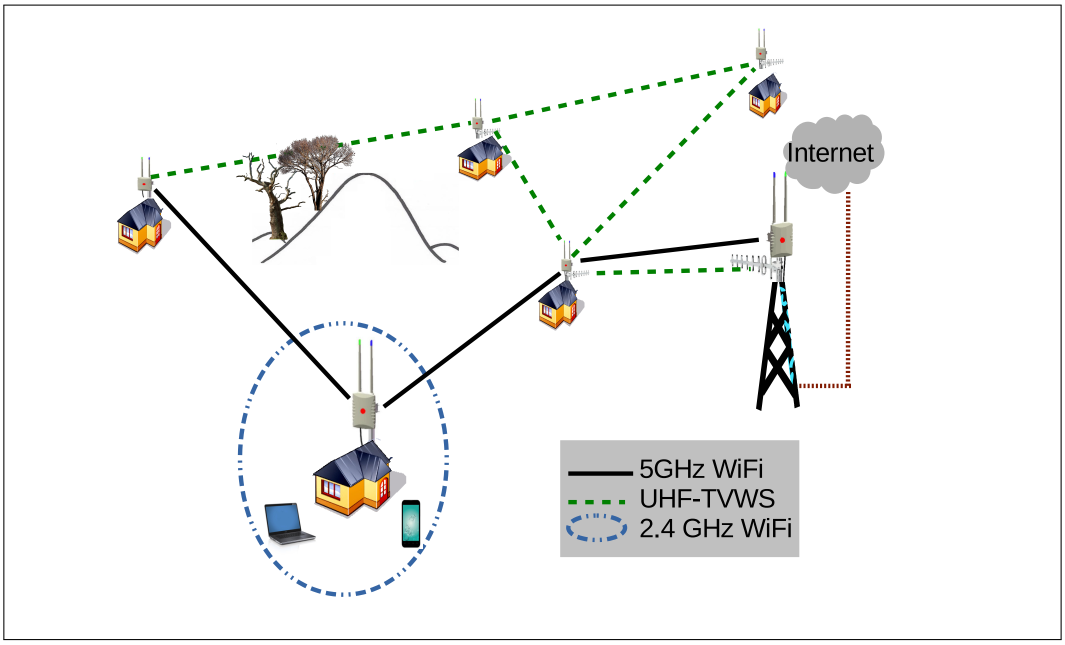
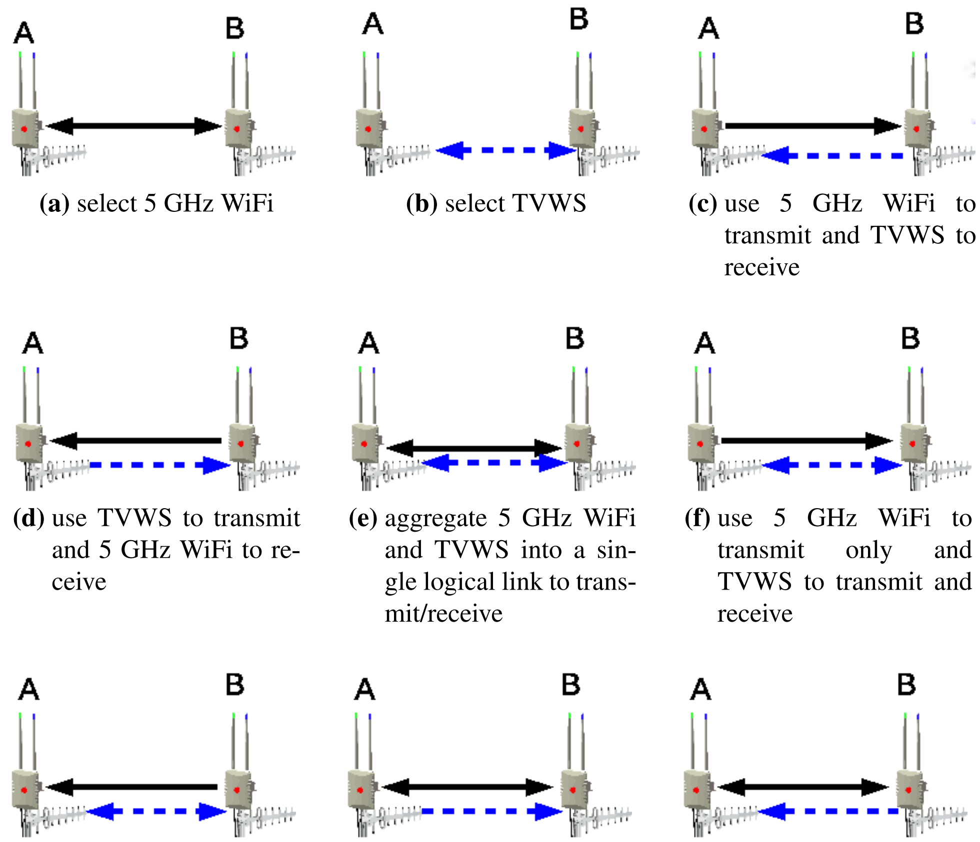


Figure 6.3: Envisaged application scenario using a combination of high frequency radios and low frequency radios such as 5 GHz WiFi and UHF-TVWS to extend broadband connectivity.

6.2 Problem description and formalisation

Given the required combination of radios described in the previous passage, this section describes the problem of link selection and the opportunities for multi-band-multi-radio enabled WMN routers. Granted node pairs with WiFi and UHF-TVWS radios, there are nine possible link configurations as the Alice & Bob topology in Figure 6.4 illustrates.



(a) select 5 GHz WiFi

(b) select TVWS

(c) use 5 GHz WiFi to transmit and TVWS to receive

(d) use TVWS to transmit and 5 GHz WiFi to receive

(e) aggregate 5 GHz WiFi and TVWS into a single logical link to transmit/receive

(f) use 5 GHz WiFi to transmit only and TVWS to transmit and receive

(g) use 5 GHz WiFi to receive only and TVWS to transmit and receive

(h) use 5 GHz WiFi to transmit and receive, TVWS to transmit only

(i) use 5 GHz WiFi to transmit and receive, TVWS to receive only

Figure 6.4: Possible link options when using hybrid links. The black solid line and blue dashed line respectively represent 5GHz WiFi and UHF-TVW radios.

To generalise, we first consider two wireless devices, node A and node B. Each of these devices has a number of wireless interfaces, which can form connections between the two devices in a variety of configurations and permutations. A wireless interface is one wireless radio card using a specific technology, spectrum band and channel (e.g. 2.4 GHz WiFi, 600 MHz TVWS, LTE etc.) and antenna on board the device (say A) that can transmit or receive on one logical path to another like interface on another radio device (say device B). Successful transmission is only possible between two interfaces that are alike in centre frequency, bandwidth, and MAC technology. We model this situation as a bipartite graph $G = (A, B, E)$, where A and B are interfaces on the radio device. There are several ways that devices A and B can form connections. Consider the different options of technology and band that can be used, and possible combinations of these links with parallel links and link aggregation as shown in Figure 6.4. Each individual interface-to-interface link is modelled as a directed edge E in the graph model. An edge can be in one of a number of states, for example we may define the possible states as incident or transmitted. The set of possible edges on one device must be combined with the set of possible edge states on the second device. It is clear that as the number of interfaces on a device increases the number of possible link configurations grows rapidly. If we assume the wireless devices have a uniform number of radio interfaces, the total number of possible link configurations n is given by

$$n = (p^r - 1)^k \quad \text{for } p, r, k \in \mathbb{N} \tag{6.1}$$

where p is the number of possible edge states, k is the number of nodes and r is the number of wireless interfaces. The "-1" term is to remove the empty set, which is not a valid link configuration.

The system aims to find the set of link configurations:

$$\begin{gathered} S = \{S_j\} := \{y_{ji}\} \mapsto \min_i z_{ji}(x) \\ \text{where } j = 1, 2, \ldots, N-1 \text{ and } i = 1, 2\ldots, n \text{ for } j \neq i \end{gathered} \tag{6.2}$$

where x = amount of data to be served, y = link, z = transmission time, which depends on interference, congestion, etc. and is handled by the MAC protocol, and n = number of possible links, which is dependant on the number of radios per node.

6.2.1 Single point-to-point

Suppose there are two nodes A and B, which is the simplest case scenario, the solution to the link selection problem at any given moment is going to be one of the options presented in Figure 6.4. It is very easy to determine the optimal link in one of extreme deployment scenarios where only one radio is operational for one reason or the other. For example, in an area where there is no TVWS available, 5 GHz WiFi becomes the only option. Another example is when the node spacing is beyond WiFi's transmission distance, in which case TVWS becomes the viable option because UHF-TVWS attenuates less compared to WiFi as explained by Friis' path-loss model [148]:

$$L_{fs} = 20\log_{10}(f) + 20\log_{10}(d) + 32.45 \tag{6.3}$$

where L_{fs} is the path loss in dBm relative to mW, f is the operating frequency in MHz and d is the distance in km. The focus of this dissertation is on a typical scenario where both WiFi and TVWS are operable with performance subject to prevailing spatial/temporal spectral and environmental conditions.

For a one-hop scenario i.e. two wireless radio devices communicating only with each other (local optima), the link selection scheme chooses a link configuration y_i from the set of possible link configurations of size n to transmit a data package of size x in the minimum possible time. The time taken for that package transmission on that specific link configuration is $z_i(x)$.

$$y_i \mapsto \min_i z_i(x) : \quad i \in 1, 2, ..., n$$

In the case of multi-hop system (global optima) of N identical radio devices, the link selection method chooses a link configuration for each hop S_j, $j \in \{1, 2, ..., N-1\}$ such that the total transmission time is minimised. Disregarding buffer size constraints and the potential impact of multi-path interference, the total link selection set can be denoted as

$$S = \{S_1, S_2, ..., S_{N-1}\}$$
$$S_j \in S := y_{ji} \mapsto \min_i z_{ji}(x) \ : \ j,i \in \mathbb{N}$$

The results discussed in section 6.5 show that performance of these links depends highly on the combination of parameter settings such as channel, transmission power (txpower), channel width, modulation and coding scheme (MCS), and environmental factors.

6.2.2 Point-to-multi-point

Suppose there are three nodes A, B and C connected as shown in Figure 6.5. When node A has a queue of data destined for node B and another queue for node C, it can aggregate the links, send to node B in one timeslot and send to node C in another timeslot. Alternatively, node A can send to node B on one interface and send to node C on the other interface. For point-to-multi-point, we aim to choose the set of links $\{S_j\}$, where in this case, $j = 1, 2, ..., N-1$ for N-1 nodes connected to a single node.

$$S_j := y_j \mapsto \min_i z_{ji} + \tau \tag{6.4}$$

where τ = delay associated with media contention.

There are two requirements: (i) a routing protocol capable of exploiting available link options and (ii) a suitable routing metric to aid the protocol in determining the optimal option.

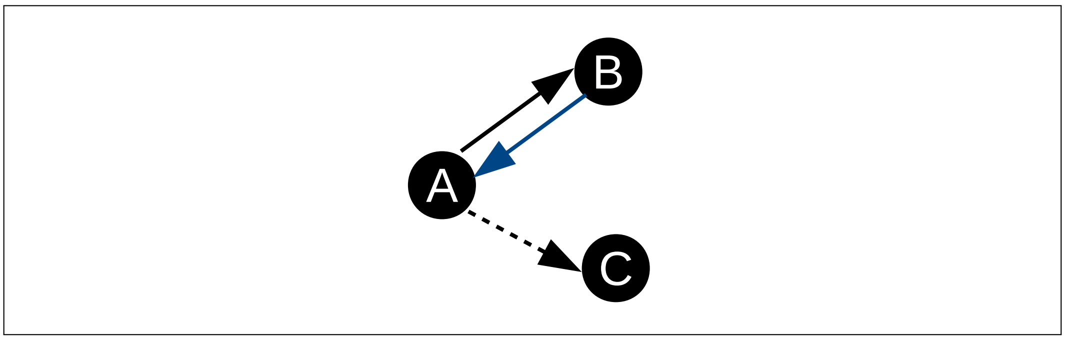


Figure 6.5: Transmission options for a basic point-to-multi-point link.

6.2.3 Multi-point-to-multi-point

The term *multi-point-to-multi-point* is used in this context to describe a generalised scenario arising from mesh network formation in which nodes connect in ad-hoc fashion. The routing task of selecting an optimal link in this scenario is to a significant extent partly a scheduling problem and therefore the solution may be described as “best effort”.

6.3 Hybrid-link utilisation model

Figure 6.6 shows the proposed three-tired multi-link utilisation framework along with an implementation example. This section discusses the three layers and sub-components, and highlights optimisation approaches at each layer.

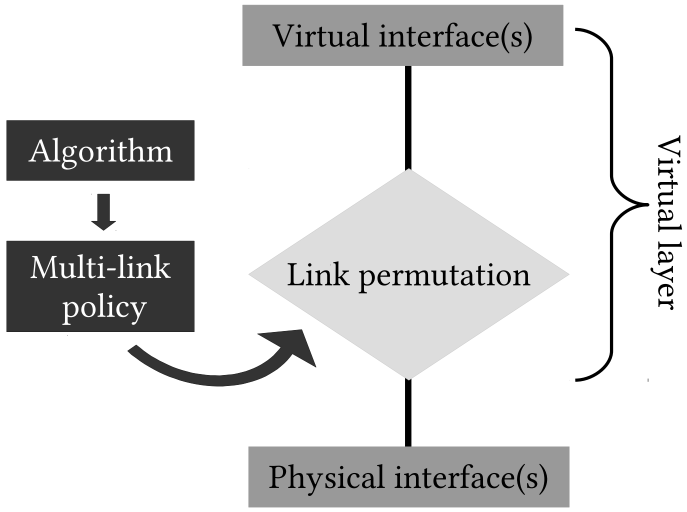
6.3.1 Virtual interface

Virtual interface is the logical connection point to the wireless mesh network. This is the interface that is “visible” to the higher layers of the network protocol stack. By virtualising the interface used by the mesh routing protocol, multiple virtual interfaces can be created thereby allowing a single node with possibly a single radio to join and participate in multiple mesh networks if desired.

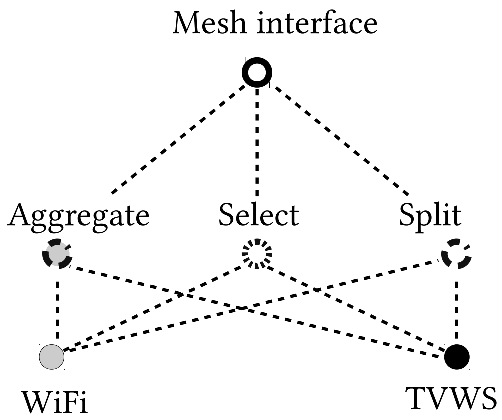
6.3.2 Link permutation

Link permutation defines the possible link options described in section 6.2, which depends on the number and type of radios. The routing protocol elects the link option from among possible permutations in a way that is similar to how the next-best-hop is selected. Link performance is influenced by factors *internal* and *external* to the network. As such, quality assessment of individual radio links is required to rank the link options. Owing to the unpredictable nature of wireless links, this dissertation proposes dynamic selection of the optimal link option from among the possible permutations. The immediate challenge is to develop routing algorithms capable of determining not just the locally optimal link option, but a link option that is optimal end-to-end.

In section 6.2, equation 6.1 was derived that expresses the number of possible



(a) Proposed framework



(b) Implementation example involving WiFi and TVWS hybrid links.

Figure 6.6: Multi-link utilisation framework.

link permutations in terms of *k* the number of nodes and *r* the number of radios on each node. As the values of *k* and *r* increase, the number of possible link options and information about the options increases aggressively as shown in Figure 6.7. For examples, as little as ten nodes yield 59049, 282475249, and 576650390625 possible link options for two, three and four radios respectively. This could be beneficial on one hand, for example if resilience and fault tolerance are the ultimate goals.

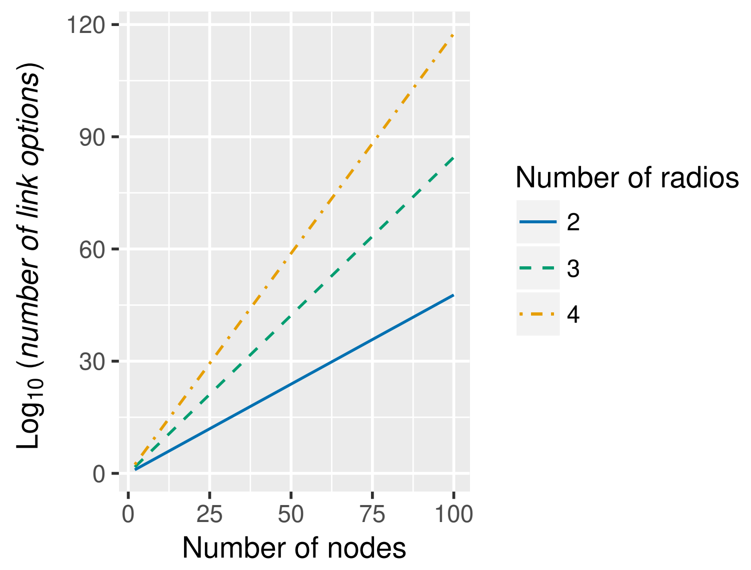


Figure 6.7: Link permutation analysis.

But on the other hand, findings from other fields of research such as *marketing research* regarding short-listing of candidate options show that it gets increasingly difficult to find the right candidate as the number of options and the information about the options increase [149]. The larger evaluation costs associated with the increase in choices and criteria results in a smaller consideration set [150]. Applying this reasoning from a human perspective to the mesh routing context lends way to a prediction that an increase in the number of link options may not necessarily translate into improved performance. As a matter of fact, the ensuing complexity could make it infeasible to pre-compute the quality of each and every option. For that reason, this dissertation identifies and focusses on three main link options, namely *single-I/O, split* and *aggregate*. The term single-I/O is being used to refer to a link consisting of a single-radio transceiver. On the other hand, a split link refers to a configuration where a node dedicates one radio to sending packets and the other for receiving. An aggregate link is when two or more radios are combined to form a single logical link for purposes of increasing throughput. These three are the key hybrid-link configuration approaches. The rest of the options identified in section 6.2 can be considered as shadows of these three principal options.

In related works, the split link concept is typically applied as a way of load-balancing. This dissertation extends this view and presents link splitting as a link asymmetry mitigation technique. A *splitting opportunity* exists when the high and low throughput of individual radios is in opposite directions as illustrated in Figures 6.8a and 6.8b. The splitting opportunity may result from RF interference, hardware

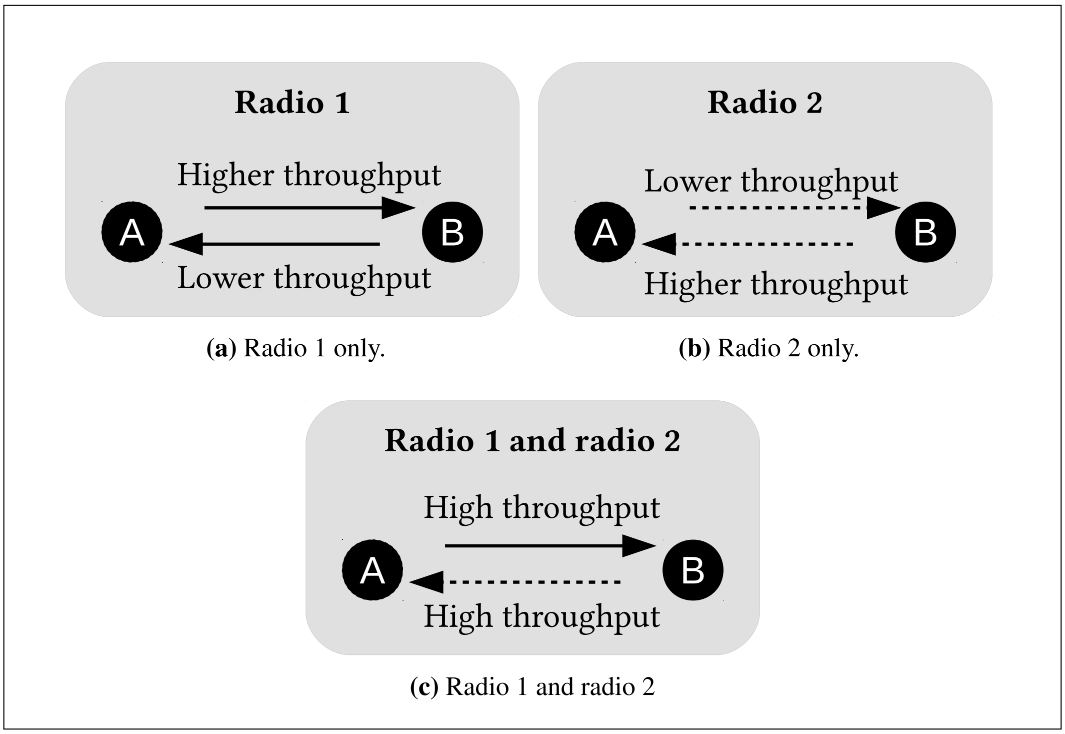


Figure 6.8: Radio link splitting opportunity.

imperfections and other causes. To illustrate, consider Figure 6.9: *node B* strategically placed at a high site and close to heavy duty television broadcast transmitter towers experiences a significant amount of RF noise in the UHF band. On the other hand, *node A*, located at a lower site somewhere in a residential area farther away from TV transmitters experiences a nominal amount of interference in the UHF band, but the 5 GHz WiFi radio gets affected by other WiFi devices nearby. The term 'close' is being used in this context to refer to the combined effect of geographical as well as spectral proximity to the source of interference [1].

[1]When a TVWS device operates on channel x and there are other strong TV transmitters using channel $x+1$ within interference range, the TVWS device is said to be spectrally close to the TV transmitter. Previous investigation[151] has shown the adverse effect that close spectral proximity of TV transmitters has on the throughput of TVWS nodes.

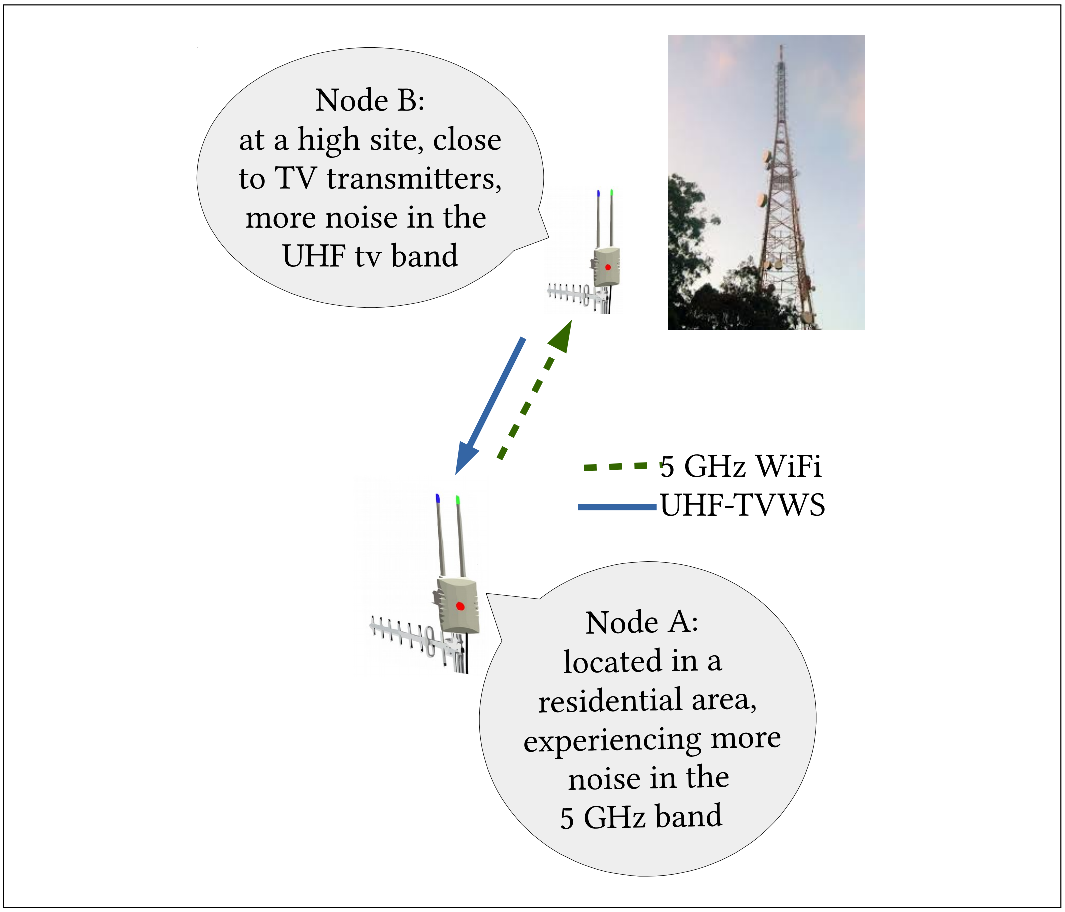


Figure 6.9: Link asymmetry caused by primary transmitters and other sources of strong RF signals interfering with wireless mesh routers. Faulty circuitry or misconfiguration can also result in link imbalances.

Under these conditions, when *node A* sends data to *node B* using the UHF link, there is a significant amount of packet loss at reception. Similarly, when *node B* sends data to *node A* via the 5 GHz interface, high packet loss is expected. Thus the splitting opportunity could be a permanent state of a link or an intermittent occurrence, hence the need for a dynamic selection mechanism. Regardless of the underlying cause, the key consideration when splitting radios comes down to the choice of uplink and downlink interfaces as illustrated in Figure 6.8. For example, with respect to node *A* in Figure 6.8, by splitting the link such that each node has the "best foot put forward" i.e. radio 1 serves the uplink while radio 2 serves the downlink, higher throughput can be achieved in both directions of communication between node *A* and node *B* as reflected in Figure 6.8c.

6.3.3 Multi-link policy and algorithms

The multi-link policy sets out the over-arching performance objective, which might be achieving fault tolerance, maximising throughput, load balancing and so forth. A network may adopt one or more policies depending on performance requirements. Algorithms in turn specify the policy implementation detail. Some example policies and algorithms that can be applied on an aggregated link are hereby discussed below.

1. **Round-robin**. Packets are transmitted across all the aggregated interfaces sequentially starting from the first available interface to the last. This approach provides fault tolerance and load balancing. The drawback of round-robin in its basic form is that if the radios have different transmission rates, the low data-rate interface creates a bottleneck. Thus effective throughput gets determined by the radio link with the least capacity.

2. **Broadcast**. Each packet to be sent is duplicated and transmitted on all available interfaces for redundancy. Typically, this policy is not applied as a direct throughput enhancement approach. Instead, it is aimed at achieving fault tolerance as sending out multiple copies of packets maximises the chances of delivery.

3. **Active-backup**. This is a multi-link usage policy where one radio is designated as the "primary" transceiver. The second available radio gets activated only when the active radio fails. This could be applicable in scenarios where there are costs associated with using a particular alternative radio. In such cases, instead of using multiple radios in parallel to increase capacity, it makes sense to use the costly fallback link on a as-needed-basis.

4. **Network coding**. The basic principle of network coding is to combine multiple packets into a single transmission as opposed to having multiple transmissions. This approach aims to improve performance by reducing the number of transmissions thereby minimising contention/media access delays. Since the introduction of the idea [152], several network coding and decoding schemes

have been developed [153], [154], [155], [156]. Just as is the case with aggregation and splitting, an opportunity for network coding has to first be identified. A network coding opportunity exists if node A and node B are both able to overhear the relay node. Once the opportunity is identified, the relay node buffers packets meant for node A and node B, but instead of transmitting to node A and then to node B, the relay node codes the packets and sends at once. Node A and node B in turn decode the packet and they each get the packet addressed to them.

While multi-link policies are chosen based on the desired performance objective, the achievable performance gains remain dependent on availability of the opportunity such as a network coding opportunity described above or the radio splitting opportunity described in section 6.3.2. This dissertation recommends *optimisation with loose coupling* design approach to ease the interchange and combination of policies and algorithms with the different link permutations e.g. combining link aggregation with network coding.

6.3.4 Physical interface

Physical interface refers to the underlying physical wireless network cards. There is substantial motivation for using multiple radios. This includes the need for both high and low operating frequencies to meet technical or regulatory requirements as explained in the chapter introduction or simply as a way to increase network capacity.

6.4 Experimental evaluation

The objective of the study was to investigate the performance of the different 5 GHz WiFi and UHF-TVWS radio settings, namely channel, channel-width, and transmission power (txpower) under different environmental conditions such as trees/vegetation, building structures and landscape that tend to affect line-of-sight. The physical setup comprised a specially designed multi-radio mesh router with 5 GHz and UHF-TVWS antennas, and a portable power source for powering the device as shown in Figure 6.10. Table 6.1 lists the specifications of the equipment used in the experiment. The experimental performance measurement exercise started off with an indoor setup to benchmark performance and calibrate the equipment prior to setting up the experiment outdoors. The indoor setup comprised nodes set up inside the research lab[2] such that node A and node B were 21 m apart, and 1 m, 0.9 m and 4.5 m away from the wall sides while the TVWS antenna stood at 0.36 m below the ceiling as shown in Figure 6.11. This was followed by outdoor experiments setup to measured performance of 5 GHz WiFi and UHF-TVWS in three scenarios, namely clear line of sight, near line of sight obstructed by trees, and near line of sight obstructed by building structures as shown in Figures 6.15 and 6.17. Figure 6.13 shows the aerial view of the measurement site.

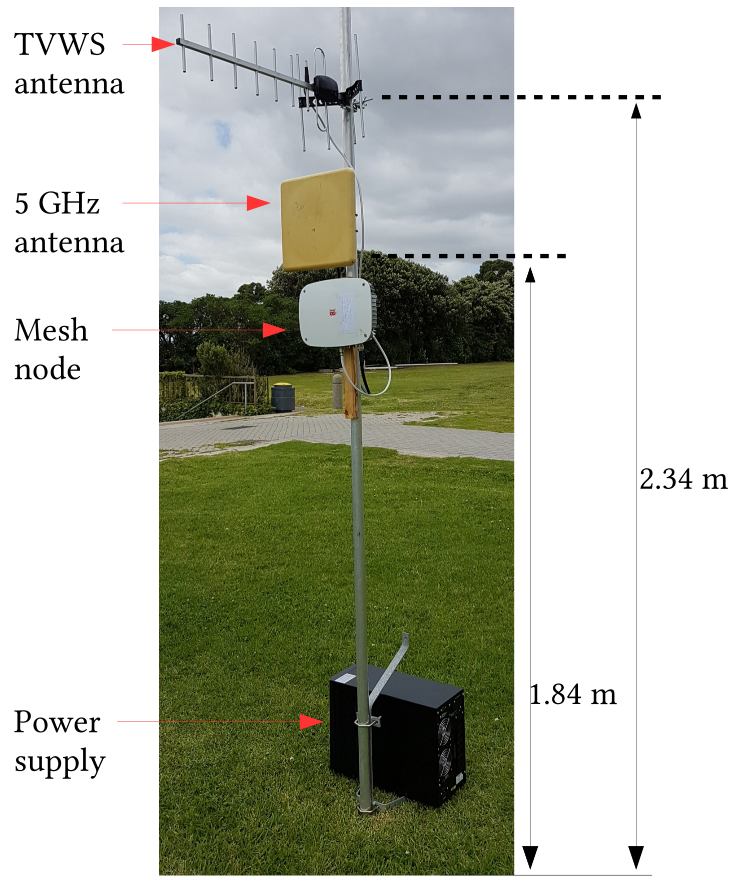


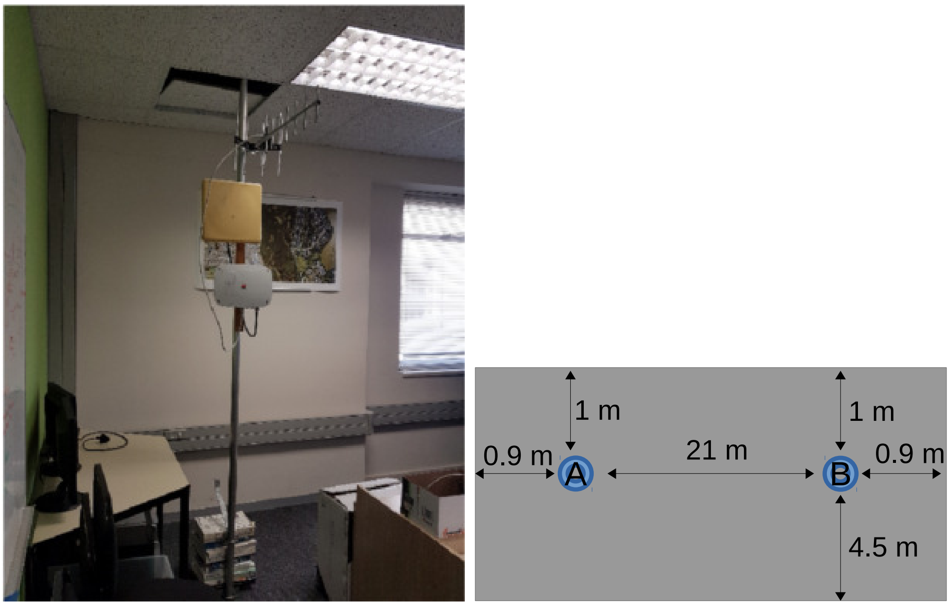
Figure 6.10: Outdoor setup

[2]Centre in Information and Communication Technologies for Development (ICT4D) lab, Computer Science building at the University of Cape Town.

The measurement process involved mounting the setup on two ends of a site to capture the environmental variable of concern. Performance was measured using *iperf* and *ping* tools for different combinations of channel, txpower and channel width settings. The process was controlled from a laptop (not visible in the picture) connected to the node over a dedicated 2.4 GHz WiFi access connection. A custom measurement script was developed for this purpose that executed control commands between node pairs over a dedicated control link established using 3G modems. Techniques such as *ssh port forwarding* were used to circumvent the 3G service provider's Network Address Translation (NAT) server or firewall by establishing a *reverse ssh tunnel*. In addition to facilitating remote control of the setup, the dedicated control link ensured that the data collection process had minimal impact on the experiments conducted on the 5 GHz WiFi and UHF-TVWS links.

Table 6.1: Node specifications.

WiFi	**TVWS**
i) System board: Mikrotik RB433 ii) Operating system: OpenWRT iii) WNIC: Atheros-based 802.11 a/b/g mini PCI adapters. iv) Antenna: • Brand: made/distributed by scoop (www.scoop.co.za) • Model: ANT-P523 • Gain: 23 dBi • Frequency: 5150 - 5850 MHz • Cable type and length: coax, 1 m	i) System board: Mikrotik RB433 ii) Operating system: OpenWRT iii) WNIC: Doodle labs DL509-78 Broadband Radio Transceiver for the 470-784 MHz TV band. iv) Antenna: • Brand/Model: Maxview, MXR0053 TV Aerial -10 element • Forward Gain: 8 dB • Front to back ratio: 10-20 dB • Acceptance angle: 25 • Frequency range: 470-860 MHz; channel 21-69 • Cable type and length: coax, 1.55 m



(a) Node setup. **(b)** Node spacing.

Figure 6.11: Indoor setup.

6.5 Results and discussion

6.5.1 Indoor performance

Figure 6.12 shows the relationship between throughput and transmit power observed from the indoor setup. For the 5 GHz WiFi radio, throughput slightly increases with transmit power. A more marked increase in throughput would be expect in an outdoor real-world setup owing to the anticipated increase in SNR. The suspicion is that the reduced distance between the nodes reduces the possible range of throughput values. Very surprisingly and counter-intuitively, once the transmit power surpasses 10 dBm for TVWS, the throughput in fact decreases rapidly, which completely contradicts Shannon's Law. This is because of the input signal level at the receiver being well above its recommended range, thereby causing saturation of the electronics and distortion of the signal. The DL509-78 transceiver is quoted to have a recommended input signal strength range of -40 to -80 dBm, while on the TVWS interface the input signal levels were measured to reach above -30 dBm, even climbing to +9 dBm in one measurement and above -20 dBm for a transmit power of 20 dBm in several measurements. Such high input power values cause the signal responses of the RF receiver front-end electronics to become distorted. The operational amplifiers cannot output a voltage above their supply voltage in response to a higher input power - i.e. they saturate at such high input signal levels - so they are unable to reflect the variations in the received signal accurately, causing signal distortion and inability of the system to decode the signal correctly. On the other hand, for the same transmit power values, the receiver-side 5 GHz WiFi card showed lower input signal strength measurements, all falling below -40dBm, so saturation and the resulting decreased throughput was not observed in the experiments on the 5 GHz radio under the same conditions. This observation underscores the point that considering signal strength alone can be misleading when assessing link quality or determining optimal operating parameters as it clearly fails to reflect possible link failure/deterioration due to phenomena such as power saturation. Furthermore, it becomes important in these types of studies to isolate or distinguish platform related characteristics from the properties attributed to the operating radio frequency.

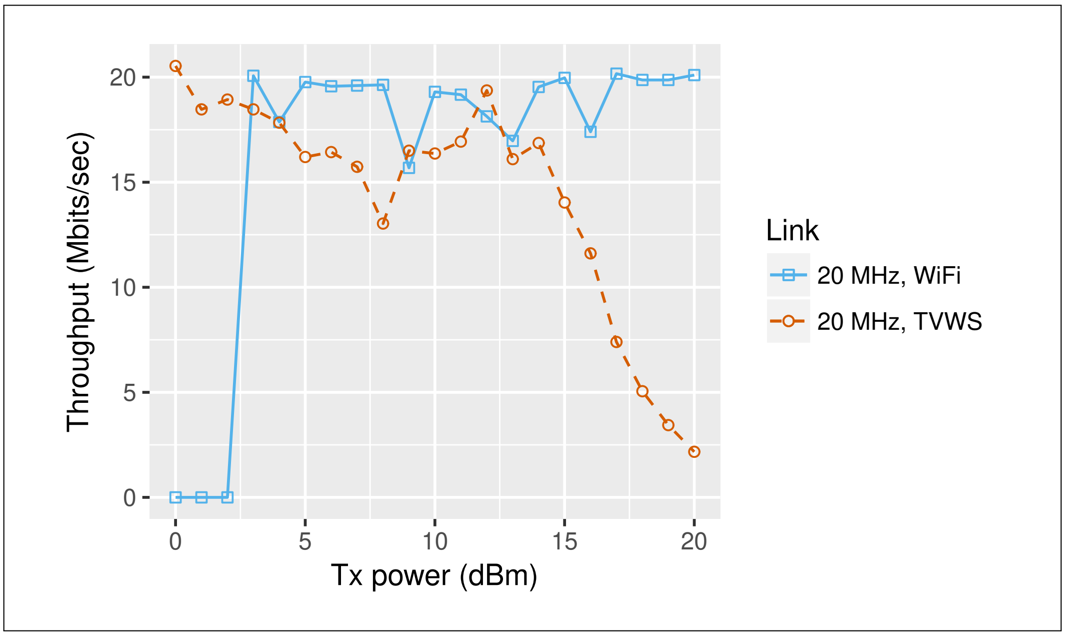


Figure 6.12: Throughput vs txpower at a short distance on a 20 MHz channel. A similar trend was observed for 10 MHz and 5 MHz channels.

6.5.2 Outdoor performance: clear line-of-sight

This round of experiments were conducted at the University of Cape Town (UCT) rugby field shown in Figure 6.13, where clear-line-of-sight (marked by the solid yellow line) was established. The distance between the two endpoints was approximately 0.65 km. Figure 6.14 gives a synopsis of performance for radio links with unobstructed line-of-sight. Overall performance in terms of throughput ranged from zero to just under 15 Mbits/sec depending on the choice of operating channel, txpower and channel-width settings as shown in the figure. For example, the throughput slot for 5 GHz WiFi channel 48, 20 dBm txpower and 20 MHz channel-width is empty because there was no throughput for that combination of settings. The horizontal line across the bar marks the throughput in the opposite direction while the vertical lines indicate the standard error in the forward direction throughput measurement. The results shown are only for 5 GHz WiFi and UHF-TVWS operating on channel 48 and 11 respectively, however a similar pattern was observed on alternative operating channels. The other observation is that at that distance, it can generally be said that the 5 GHz WiFi link outperforms UHF-TVWS. Furthermore, there was a marked difference in performance between busier and cleaner TVWS channels. The results presented in this section were included in a paper [157].

Figure 6.13: Aerial view of outdoor measurement sites.

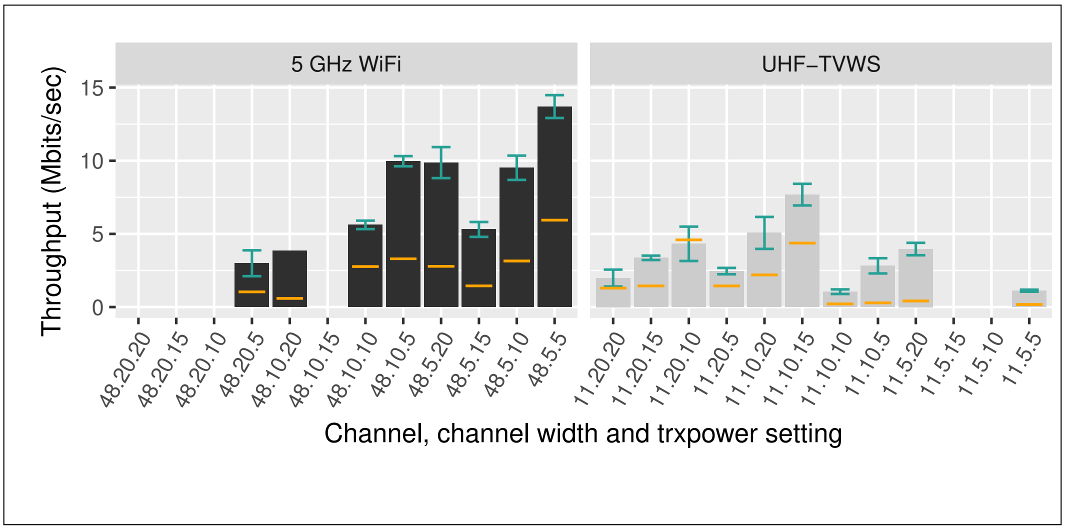


Figure 6.14: Performance of 5 GHz WiFi and UHF-TVWS links for different txpower and channel width combinations. The bars are labelled x.y.z where x, y and z correspond to the operating channel, channel width (MHz) and txpower (dBm) respectively.

6.5.3 Outdoor performance: near line-of-sight

Obstructed by trees

The set of experiments to evaluate performance of a near-line-of-sight link obstructed by trees were done in the wooded area around UCT tennis courts shown in Figure 6.13 on the previous page, marked by the dashed yellow line. The measurement exercise proceeded as follows: one node was fixed on one end while the second node was positioned such that a tree obstructed the line-of-sight as shown in Figure 6.15, and throughput measured. The second node would then be repositioned such that there was an incremental number of trees in between and performance measured on each increment. The site had pine trees whose trunk circumference measured approximately 2 m on average. The space between the trees from the first to the last was as follows: 20 m, 28 m, 7 m, 9 m, 5 m, 18 m, 25 m. The spacing is irregular because these are trees growing freely in nature.

Multiple data samples were collected for different combinations of settings. The combination of channel, channel-width and txpower that gave the best results at the highest tree count was then considered at all the other tree counts. For the TWVS radio this turned out to be channel 7, 5 MHz channel-width, 5 dBm txpower, whereas for the 5 GHz it was channel 44, 20 MHz channel-width and 20 dBm txpower. The rationale behind this is that it is better to have a low-throughput link that works end-to-end than a high-throughput link that breaks mid-way along the path. Figure 6.16 shows the average forward and reverse throughput. From these results, it is evident that a 5 GHz WiFi link breaks completely as soon as the link is obstructed by more than two trees. On the other hand, a TVWS link is operable with as many as eight trees obstructing the line-of-sight. Based on this observation, the expectation is that the TVWS will still be operation if the extent of obstruction and distance increase. The study was carried out in the middle of a wooded area, but the analysis only considers the number of trees that would be covered if a straight line was drawn between the two endpoints. Considering the effects of multi-path fading, several other trees scattered about undoubtedly affected performance.

Figure 6.15: Setup of near line-of-sight link obstructed by tree.

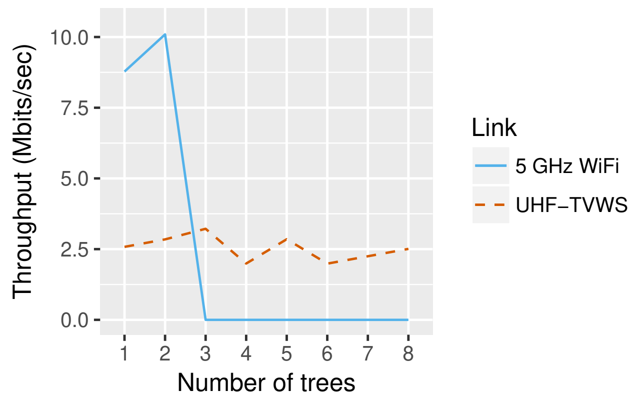


Figure 6.16: Throughput of UHF-TVWS and 5 GHz WiFi over a link obstructed by trees.

Obstructed by concrete building structures

Figure 6.17 shows one end of the setup mounted at UCT traffic Department area to measure performance of a near-line-of-sight link obstructed by a concrete building structure. Figure 6.18 shows the performance of the UHF-TVWS link for this setup. Notice the absence of 5 GHz performance results for this setup. This is because the 5 GHz radio could not establish a link between the two endpoints. The throughput of the 5 GHz radio remained zero for all possible combinations of operating parameter. It was possible to adjust the degree of obstruction so to speak, by shifting the setup ever so slightly either to the extreme left or extreme right of the building structure. However, even with a reduced degree of concrete structure obstruction, the 5 GHz link failed to work.

The experimental results confirm the theoretical expectation that high operating frequencies such as the 5 GHz band are suitable for short to medium distances with clear line-of-sight. On the other hand, lower operating frequencies such as the UHF-TVWS band perform better for long distance and obstructed line-of-sight. The results also show that when a 5 GHz radio link is obstructed it breaks completely, whereas a TVWS link still works albeit with degraded throughput depending on the degree and extent of obstruction. There exists an interesting interplay among the channel quality and channel width, and transmission power settings. Further investigation is needed to gain more clarity on what constitutes optimal settings.

Figure 6.17: Link obstructed by a building structure. The other node (not visible) was positioned behind the building structure and at a much lower position due to the undulation of the ground.

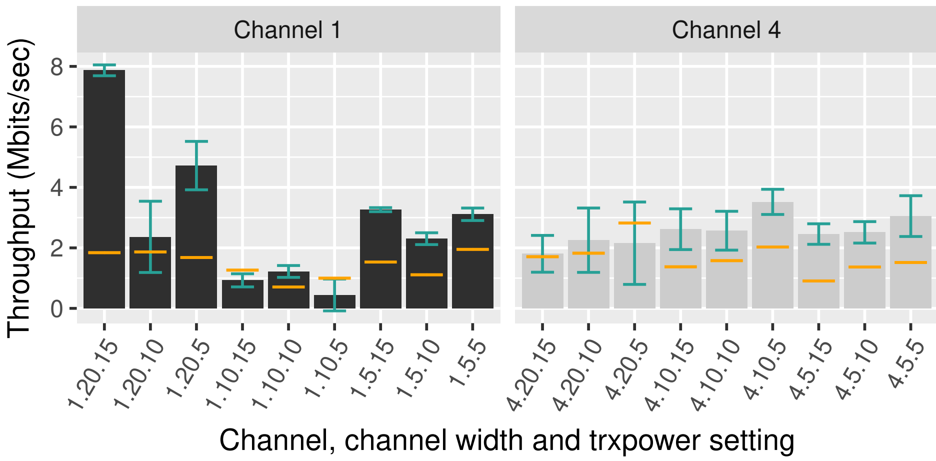


Figure 6.18: Throughput of UHF-TVWS over a link obstructed by a building structure. The blueish vertical lines indicate the standard error calculated as $(standard\ deviation) \div \sqrt{(sample\ size)}$, while the orange horizontal lines mark the link's throughput in the reverse direction.

6.5.4 Vertical vs horizontal polarization

There were performance variations observed between vertical and horizontal polarization, which may be attributed to differences in channel quality subject to polarization. For example, a channel may be vertically occupied, but horizontally vacant or vice-versa. Other than the channel quality, there is no statistical evidence to suggest a difference in obstacle penetration/circumvention capability between vertical and horizontally polarised radio antennas of either 5 GHz or UHF-TVWS radios.

6.5.5 Contextualizing performance results

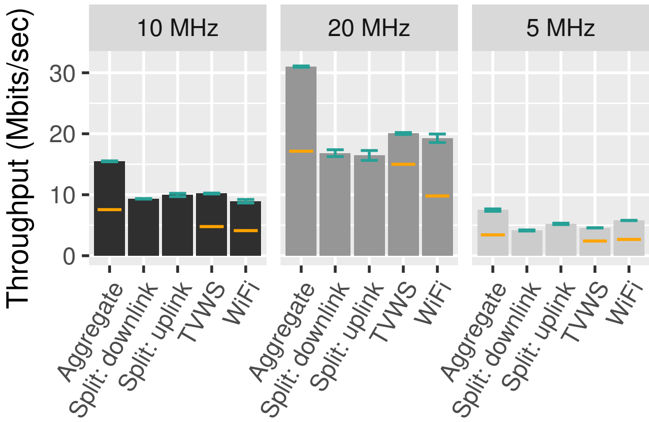
To put the achieved throughput into perspective, consider Internet provisioning in Macha, a rural village in Southern Zambia. The village was initially connected to the Internet via a 256 kbps downlink and a 64 kbps uplink satellite connection with a running cost of 1 200 USD per month. They later upgraded to a 2 Mbps microwave terrestrial connection that costed 3 600 USD per month [9]. For rural communities where the estimated average income is no more than $1 per person per day, the setup costs plus these monthly recurring charges is grossly expensive. We were able to achieve throughput above 2 Mbps using TVWS despite obstructions across the link. Although this comparison does not take distance of communication into consideration, TVWS can nonetheless be considered as a viable cost-effective solution for connectivity extension to rural and under-served communities.

6.5.6 Multi-link performance

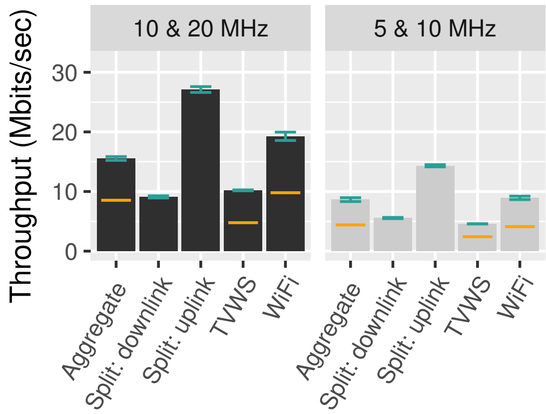
Figure 6.19 shows the performance when the 5 GHz WiFi and UHF-TVWS links are used jointly. Link aggregation was realised by distributing outbound frames over the WiFi and TVWS interfaces, while link splitting was implemented by alternating frame sending and receiving tasks between the two radios using Batman-advanced mesh protocol [158]. Batman-advanced was used because of its inherent support for optimised multi-radio utilisation. The data-rate was set by varying the channel width from the set of supported values, which are 20 MHz, 10 MHz, and 5 MHz.

The results show that when the radios' data-rates are approximately equal, aggregating provides the best performance in terms of throughput and round trip time

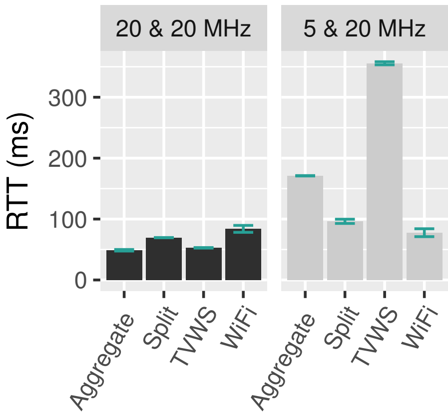
(RTT) as observed in Figures 6.19a and 6.19c. The increases in throughput of an aggregated link relative to a single-I/O link ranges from 44.5 % to 61.8 %.



(a) Uniform data-rate.



(b) Non-uniform data-rate



(c) Average round trip time (RTT).

Figure 6.19: Performance of individual radios, aggregate and split link from the indoor setup. The orange horizontal lines in (a) and (b) mark the link's reverse direction or downlink throughput. To determine RTT, 500 packets were sent with a wait interval of one second and a packet size of 65507 bytes, which was sufficiently large to force fragmentation. The maximum transmission unit (MTU) on each interface was 1532 bytes.

The benefit of splitting the send and receive functionalities between the two radios compared to selecting either radio is not obvious unless one considers throughput in the forward as well as reverse direction. Splitting achieves optimal throughput consistently in either direction, whereas a single-I/O link may achieve high throughput in one direction and significantly lower throughput in the other as shown in Figure 6.19a.

For links with unequal data-rates, the resultant throughput when WiFi and TVWS links are aggregated is higher than the throughput of the link with a lower data-rate, but less than that of the single-I/O link with a higher data-rate as shown in Figure 6.19b. Therefore, layer-2 link aggregation is only beneficial when the radios have uniform data-rates. For radios with unequal data-rates, link splitting provides better performance as observed from the RTT in Figure 6.19c. The poor performance of aggregation involving non-uniform data-rates is due to an increase in the number of frames arriving out of order, which exacerbates delays in fragment reassembly at the receiving end. On the other hand, when the uplink and downlink are split between the two radios, there is a significant improvement in throughput relative to single radio performance as shown in Figure 6.19b. The improved performance of a split link, sometimes even exceeding theoretical expectation as observed in Figure 6.19b, can be attributed to the minimised contention delay and subsequent efficiency in the store and forward mechanism, and the sending/receiving of acknowledgement packets. Thus link splitting is potentially an effective approach towards mitigating link asymmetry.

Aggregation has potential to increase overall throughput. However, the current implementation uses *basic round-robin* (BRR) represented in Algorithm 4, which is most beneficial when the links aggregated have approximately uniform data-rates. With BRR, when the radios have unequal data-rates, the radio with the least data-rate bottle-necks the resulting aggregate link.

To improve performance of the aggregate link amid unequal data-rates, this dissertation proposes *adaptive round-robin* (ARR) presented in Algorithm 5. The basic idea behind ARR is to transmit data units on each radio proportionate with the radio's bandwidth instead of transmitting evenly and sequentially over the radios.

Figure 6.20 shows the performance of ARR-based aggregation algorithm compared with BRR. In the analysis, the data-rate of radio 1 is kept at a constant 20

Algorithm 4 : Basic round-robin (BRR).

While (data queue != empty)
    for $i = 1$ to n
        send next unit on $radio[i]$

Algorithm 5 : Adaptive round-robin (ARR).

For $i = 1$ to n
    Probe bandwidth of $radio[i]$
Compute x_i the radio bandwidth ratios
While (data queue != empty)
    for $i = 1$ to n
        send next x_i units on $radio[i]$

Mbits/sec while the data-rate of the second radio varies from 1 to 20 Mbits/sec. The numerical analysis results show that ARR yields better throughput when the aggregated radios have unequal data-rates. The gains in throughput of using ARR increase as the difference between the individual data-rates of aggregated radios widens. Whereas, the overall throughput of aggregating using BRR diminishes as the difference in data-rates increase.

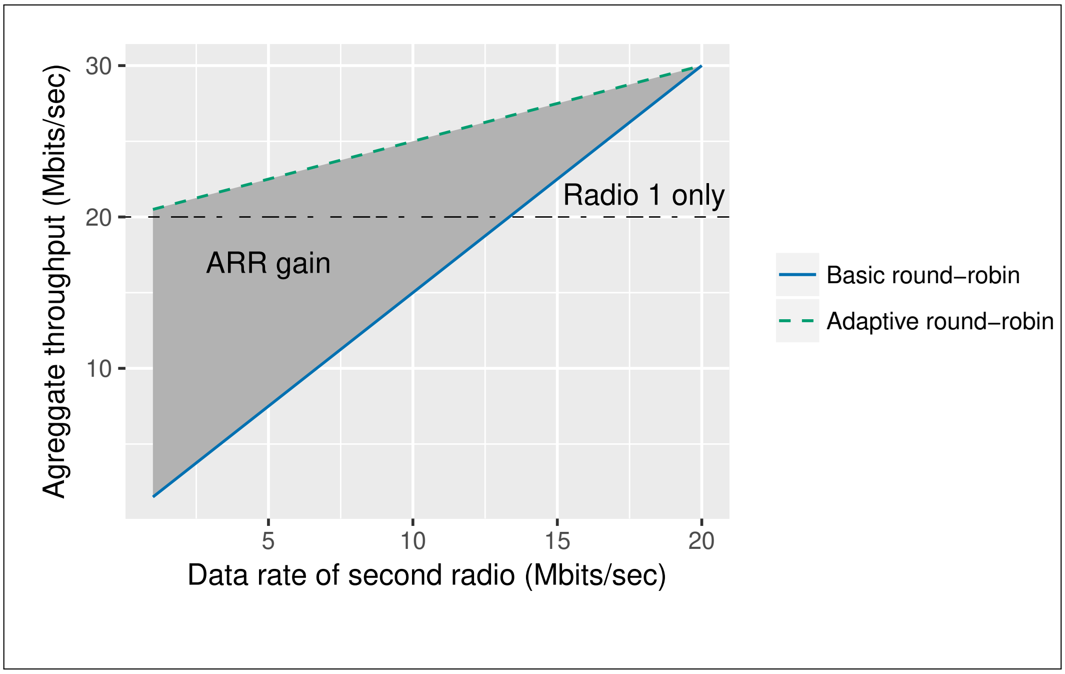


Figure 6.20: Basic round-robin vs adaptive round-robin. The data-rate for the first radio is kept constant at 20 Mbits/sec. **Note:** the illustration disregards the potential impact of out of sequence packet losses.

6.6 Towards a mechanism/scheme for auto-selection

Using the experience gained from experimenting with 5 GHz and UHF-TVWS hybrid-links, this section discusses work towards a mechanism for auto-selection of optimal link option for ad-hoc mesh nodes. The optimal solution can be determined by solving a global optimisation problem formulated as a network utility maximisation (NUM). There are several NUM formulations to cater for representation of different scenarios. The basic model is

$$\max \sum_{r \in R} U_r(c_r) \tag{6.5}$$

where R is the set of options, c_r is the rate associated with option r and U is the utility [159]. The utility U is not known a priori, but can be interpreted in terms of the network's performance objective(s) such as minimisation of transmission time or maximising the overall amount of data served depending on the application scenario. From this formulation, it is easy to see that once this utility is specified from a user and/or operator angle, it will have an influence on what is perceived to be the optimal hybrid-link option.

For example, BRR-based aggregation is primarily aimed at achieving load-balancing rather than maximise throughput. as observed from Figure 6.20 in the previous section. With the BRR-based approach, aggregation only starts to exhibit throughput gains in comparison with the single-I/O option (radio 1 only) when the second radio's data-rate exceeds 13.3 Mbits/sec. In other words, given a radio with a capacity of 20 Mbits/sec, aggregation does not yield any improvement if the capacity of the second radio is less than 13.3 Mbit/sec. In such instances, using the 20 Mbit/sec radio alone provides higher throughput compared to the aggregated link.

Table 6.2 presents the rule-based selection criteria that has been developed based on the experimental results of this research. The table shows generalised conditions under which each of the hybrid-link options thrive. In keeping with the WMN operational characteristics of ad-hoc connectivity, self-configuration and self-healing, the mesh protocol can now harness these guidelines to determine when to aggregate, when to split the radio link and when to select the single-I/O option.

Table 6.2: Rule-based link option selection criteria for multi-radio enabled nodes. The criteria spells out the conditions under which each of the options performs optimally in throughput terms. **Note:** the order of options in this table is a deliberate indication of the view that generally speaking, multi-link utilisation offers better performance in comparison with the single-I/O option. The table includes criteria for single radio selection, but from a programming perspective, this could be viewed as the option of last resort i.e. the default option when all the other conditions are not met.

Option	**Criteria/condition**	**General comment**
Aggregate	When $\|d\| < \frac{r_i}{n} = TRUE$, where d = the difference between the highest and the lowest data-rate of the radios and $r_i \neq 0$ is the least data-rate of the radios involved and n = number of radios. **Note** that this is judged based on BRR efficiency.	As the gap in the data-rates of the radios widens, overall performance reduces because the radio with the least achievable data-rate bottle-necks the resulting aggregated link.
Split	When $\overrightarrow{r_i} > \overrightarrow{r_j}$ AND $\overleftarrow{r_j} > \overleftarrow{r_i}$ where $\overrightarrow{r_i}$, $\overleftarrow{r_i}$, $\overrightarrow{r_j}$, $\overleftarrow{r_j}$ is the forward and reverse throughput for radio i and radio j respectively.	Outperforms aggregation, depending on combined effect of the extent of link asymmetry and choice choice of uplink and downlink radio.
Single-I/O	For $n = 2$: Select R_j when $\|d\| < \frac{r_i}{n} = FALSE$, where R_j is the higher data-rate radio. For $n > 2$: Select $R_j \in S$ where the set of operable radio links $S = \{R_j\}$ is singleton.	Opting to use single radio outperforms the hybrid alternatives only when the other radio is unable to establish a link.

Therefore, to solve the problem in formulation 6.5, the major step is to determine the forward and reverse throughput of each radio. Considering data packets between a single source p and a single destination q: if q is a single-hop neighbour, communication takes place along the link $(p,q) \in E$. If not, p reaches q along a multi-hop path comprising a link (p,i) and a path $[i,q]$, where i is a single-hop neighbour and $[i,q]$ is the path through a subnet $S = (N - \{p\}, E - \{(p,i) : i \in (\textit{1-hop neghbours})\})$. Based on the criteria derived in Table 6.2, the optimal link option between node pairs can be determined as follows:

$$r = \begin{cases} \text{aggregate} & \text{if } |d| < \frac{r_i}{n} \\ \text{split} & \text{if } \overrightarrow{r_i} > \overrightarrow{r_j} \wedge \overleftarrow{r_j} > \overleftarrow{r_i} \\ \text{single-I/O} & \text{otherwise} \end{cases} \tag{6.6}$$

Under the following scheduling constraints:

$$\sum_{i=1}^{f} \delta_i \leq 1, \qquad 0 \leq \delta_i \leq 1 \qquad \text{(i)}$$

$$o_{ij} \leq \sum_{l_{ij} \in I_i} \delta_i c_{r_{ij}} \qquad \text{(ii)}$$

where f is the total number of maximal *independent sets* denoted as I_1, I_2, ..., I_f in the associated *conflict graph*. A conflict graph refers to a model of the effect of inter-link interference on link activity. An independent set in this context is a set of links that can be active at the same time and δ_i is the fraction of time allotted to the independent set I_i such that $\delta_1 + \delta_2 + ... + \delta_f$ equals one time unit. The quantity of data flowing through link l_{ij} is denoted by o_{ij} while $c_{r_{ij}}$ denotes the throughput of the link. The constraint (i) comes about because at any given time, only elements of the independent set may be active simultaneously, and (ii) holds because a link can be a member of multiple independent sets, hence the collective intervals of activity of the independent sets limits the maximum amount of time a link may be active.

Thus while the choice of ideal link option r at the node level can be decided quite easily, determining the global optimum requires global knowledge of data-rates together with scheduling and routing decisions. In WMNs such kind of centralised control is not available. Fortunately, a number of mesh routing protocols such as BATMAN [160], where nodes do not maintain a full path, but instead only maintain information about the next hop towards the destination, have exhibited superior performance compared to protocols that maintain end-to-end information. For that reason, the link option selection criteria formulated in equation 6.6 is expected to yield performance enhancement regardless of the number of active sender/receiver pairs. A detailed analysis of how the conflict graph influences the choice of the optimal solution is provided in appendix C.

6.6.1 Discussion on what constitutes an optimal configuration

Transmission time and amount of data served are two similar, but different performance objective constructs from a practical standpoint. Considering transmission time is more user centric and more likely to lead to optimal QoS. On the other hand, depending on network traffic patterns, a service provider with a "per Mega-byte" billing model may consider the amount of data served on the network to be a desirable measure of performance. To explain the difference, consider a user with 1000 MB of data to download and 1000 MB of data to upload. Assume further that the link is split such that the uplink is 1 Mbit/sec and the downlink is 20 Mbit/sec. In this particular example, overall the split link is only as strong as the weakest radio in that the time required to complete both downloading and uploading will be determined by the 1 Mbit/sec radio. In this case, aggregating yields better performance in terms of transmission time for this particular user. However, if the network has a constant flow of upward and downward traffic instantiated by multiple users, splitting the link maximises the network utility function in terms of data served.

To conclude, there exists scenarios where a given link option might maximise overall network throughput for example, but provide degraded performance to a set of users located elsewhere on the network. Thus the scheme of auto-selecting a suitable configuration should address the concern about fairness among different users distributed arbitrarily across the network. Moreover, the term "elastic traffic" commonly appears in literature to refer to traffic generated by applications that are capable of adapting their data transfer rate in accordance with bandwidth availability. This brings about an additional challenge of handling multiple elastic traffic flows competing for network bandwidth.

6.7 Chapter summary and future work

This chapter reported on the performance of 5 GHz and UHF-TVWS links in different environmental conditions and provided motivation for 5 GHz and UHF-TVWS hybrid links. The study also shed light on different ways of utilising hybrid links and developed a rule-based criteria for determining the optimal link option.

Future work will include further test-bed based investigation to understand effective throughput of hybrid link options as the number of hops and flows increase. The findings from this exploration will go towards refining the rule-based selection criteria for multi-hop environments and applied to build mechanisms for auto-configuration of hybrid links. Furthermore, the study will be extended to other radio frequency bands and focus on the effect that other environmental factors such as weather conditions (e.g rainfall) and type of ground surface have on link performance. For example, performance measurements were conducted at the UCT rugby field, which provided clear line of sight over a short-grass surface. However, the effect that signal propagation over a concrete or water surface would have on link performance is still only vaguely understood.

Chapter 7

Other deployment considerations

Throughput optimisation is usually among the main performance objectives of all communication network networks. Literature is replete with work on efforts aimed at improving throughput [161], [162], [163], [164].

TABLE 7.1 gives a high level overview of the various throughput optimisation approaches commonly applied at the different layers of the *OSI* protocol stack. Judging by the studies surveyed, there is a higher concentration of effort at the upper layers. Higher-layer protocol level optimisation is essential in order to exploit the network's physical layer capabilities, however in reality the extent or impact of such optimisations is bound by the limitations of the underlying physical connectivity. Therefore, optimisation at the physical layer is of paramount importance. The scope of this research covers the first three lower layers.

This study was motivated by the ever increasing relevance of wireless communication and the particular interest in TVWS based communication. The implementation of a TVWS network may vary from application to application and from region to region, however the general requirement is for the device to determine the allowed TVWS channels as well as the transmission power that is safe to use. To meet this requirement, the device can either scan its spectral environment to determine free channels or query a GLSD, which serves the query with a list of channels that the device can use at its location and height. Each of these approaches for protection of primary transmitters and coexistence with other secondary users raises a number of questions. For example, at what height should the scanning be done

Table 7.1: Throughput optimisation techniques commonly applied at different layers of the OSI reference model.

Application	Application layer routing techniques
Presentation	
Session	
Transport	Congestion control techniques.
Network	Multi-path routing where data packets are forwarded on multiple paths at the same time.
Data link	Link scheduling techniques that try to mitigate interference by assigning a set of time slots to each link in which it can transmit. Link adaptation techniques where transmitter aims to reduce packet error rate by switching to a higher or lower transmission rate in response to changes in link quality.
Physical	Reconfigurable antennas, Multiple input multiple output (MIMO) antennas each having an independent data flow.

and what is the implication of increasing/decreasing the antenna height? When the GLSD provides a list of free channels, are the channels really free? These and other questions prompted additional investigation to assert DSA based network deployment requirements. Subsequently, experiments were conducted with the following four joint objectives:

(i) investigate the correlation between RSSI and receiver antenna height in the UHF band and establish the relationship among the height, RSSI, and throughput;

(ii) investigate the performance of the current GLSD implementation;

(iii) investigate the accuracy of existing propagation models for estimating white space and interference analysis in the UHF band;

(iv) ascertain TVWS channel availability in the area.

7.1 Experimental setup

The study was conducted in the Southern Cape peninsula of South Africa, a region endowed with mountains and other geographically difficult topological elements.

In the absence of additional equipment and to avoid the need for a spectrum license, an actively transmitting channel of the local television broadcasting was used as a source of the reference signals. The receiving hardware setup included a R&S FSH4 spectrum analyser, a 2.1 dBi R&S omnidirectional antenna and short cables, all mounted on a boom lifter as shown in Figure 7.1. The spectrum analyser was connected to a wireless router placed on the boom lifter. The setup was controlled from a laptop in the vehicle and wireless router over a WiFi network.

The spectrum analyser (not visible) was placed below the antenna to minimise cable length.

Figure 7.1: Setup of antenna covered with a low permittivity radome mounted on boom lifter used to perform measurements.

The measurement procedure involved lifting the measurement setup on the arms of the boom lifter, measuring the actual height above ground using a laser range finder, and performing a frequency scan (set and triggered from within the vehicle, over the wireless network). The results of a scan were saved into a data file. This was repeated several times for each value of height. Thus the transmitter height remained constant while the receiver height was varied.

Each frequency scan was done from 451.25 MHz until 1,081.25 MHz with resolution bandwidth of 1 MHz and video bandwidth of 3 MHz. The choice of frequency and resolution bandwidth was dictated by two factors: (i) the need to capture the video carriers of analogue television transmissions (which are located around 1.25 MHz from the left edge of an 8 MHz wide television channel), and by the limitations on the number of point in a single sweep that can be used by the spectrum analyser, i.e. fixed to 631 points.

The measured values, in dBm, reflect the power at the input of the spectrum analyser. These can be translated into the field strength E incident onto the antenna by taking into account the losses in the cables and connectors (about L_c=1dB) and applying the antenna factor AF for the selected antenna (which is a function of this antennas gain G_A and wavelength $\lambda = 3 \times 10^8/f$, where f is the frequency in Hertz (Hz)). The antenna factor AF is defined as the ratio of electric field $E(V/m)$ to voltage at the antenna terminals V (Volts), i.e.

$$AF = \frac{E}{V}, \tag{7.1}$$

where AF = antenna factor (m^{-1}), E = electric field (V/m) and V = voltage at antenna terminals [165]. When AF and the signal level at the antenna are given in decibels and decibel-microvolts ($dB\mu V$) respectively, E is calculated by adding the signal level at the antenna and the antenna factor as shown in equation (7.2).

$$E_{[dB(\mu V/m)]} = V_{[dB(\mu V)]} + AF_{[dB(m^{-1})]}, \tag{7.2}$$

The voltage induced at the antenna terminals V, may be related to the power sent from the antenna into the cable, P, as $V = \sqrt{50\Omega \times P}$. AF may be expressed in terms of wavelength and gain in a 50-ohm system as follows:

$$AF = \frac{9.73}{\lambda\sqrt{G_A}}[m^{-1}], \tag{7.3}$$

In dB, it may be written as

$$AF_{[dB(m^{-1}]} = 19.8 - 20.log_{10}(\lambda) - 20.log(G_A), \tag{7.4}$$

where G_A is the antenna gain, which is 2.1 dBi for the equipment used in this study. The conversion of the signal level measured in dBm to $dB\mu V$ for a 50Ω system is done as follows:

$$dB\mu V = dBm + 90 + 20 \times log(\sqrt{z}), \tag{7.5}$$

where z is the system impedance, which was 50Ω for the setup used in this study.

7.1.1 Selecting reference transmitter

To identify a reference transmitter station out of dozen transmissions visible in the spectrum, a table was constructed and populated with key transmitter details, namely operating frequency, height, ERP, GPS coordinates and receiver details such as height, and GPS coordinates. The details are based on combined information sourced from SENTECH [166], who are the national distributors of licensed broadcast signal in South Africa, and Meraka white space database [167], which is the only publicly available GLSD in the region known to us. The transmission distance was computed from the GPS coordinates of the transmitter and receiver. Path loss was then calculated using FSPL. The expected incident power level at the receiver was then calculated as $EIRP(dBm) - PathLoss(dB)$. The transmitter giving the highest signal level at the receiver and the channel/frequency of interest was selected as the reference transmitter.

7.1.2 Calculating RSSI on a channel

The *START* and *STOP* frequencies of television channel
$N \in [21, 69]$ can be determined as

$$\begin{aligned} START &= 470 + W(N-21)\ [MHz] \\ STOP &= 478 + W(N-21)\ [MHz], \end{aligned} \tag{7.6}$$

where W = 8 MHz is the channel width. In this paper the RSSI on a channel is computed by (i) converting the received signal in dBm to power in Watts, (ii) summing the elements within W MHz channel, and (iii) converting the sum back to dBm. In each channel, the channel power thus computed as integral power within $START$ and $STOP$ at the channel.

7.2 Findings and discussion

The results presented in this chapter were presented in the following publications [18], [19]. [168].

7.2.1 Height influence

Owing to the wider frequency range that DSA based networks are envisaged to operate on, there is need for a thorough exploration to understand the unique outdoor propagation qualities of the different spectrum bands. Such an enquiry is necessary towards optimising the wireless network deployment. For this reason, we carried out experiments to learn about the characteristics of operating channels in the UHF band. More specifically, the study firstly investigated the relationship between the antenna height and Received Signal Strength Indicator (RSSI), and then analysed the throughput corresponding to RSSI thresholds.

WiFi radios for example, regulate the modulation rate depending on the RSSI level and the MCS employed. These adjustments are triggered by specific ideal threshold values. Figure 7.2 shows the data-rate corresponding to RSSI thresholds. The values shown are for Doodle lab DL587-78 wireless cards [130].

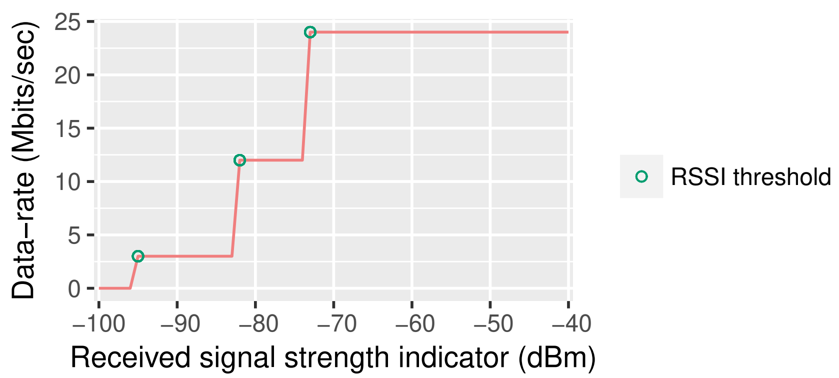


Figure 7.2: RSSI thresholds for 802.11g radio data rates.

Figure 7.3 shows the RSSI measured at different receiver antenna heights above ground. The results show RSSI increasing by approximately 2.5 dBm for every 1 meter increase in receiver height from 2 m to 8.5 m, which could be due to improved obstacle clearance such as the height of houses in the area. The gain in RSSI can also be attributed to improved Fresnel zone clearance. Above 8.5 m the gain in RSSI plateaued and become less consistent as the graph shows. The observed correlation between RSSI and height presents two related opportunities. Firstly, the gain in RSSI imply that the transmission range of UHF-based radio links can be boosted by raising the antenna height. Secondly, for static nodes, the RSSI achievement can be translated into throughput as shown by the "*theoretical data rate* curve. The theoretical data-rate curve was derived by applying a model to the measured RSSI. The model down-scaled the measured UHF signal power by 30 dB to model a TVWS transmitter signal. The resulting TVWS RSSI value was then translated into the theoretical data-rate using the curve shown in Figure 7.2.

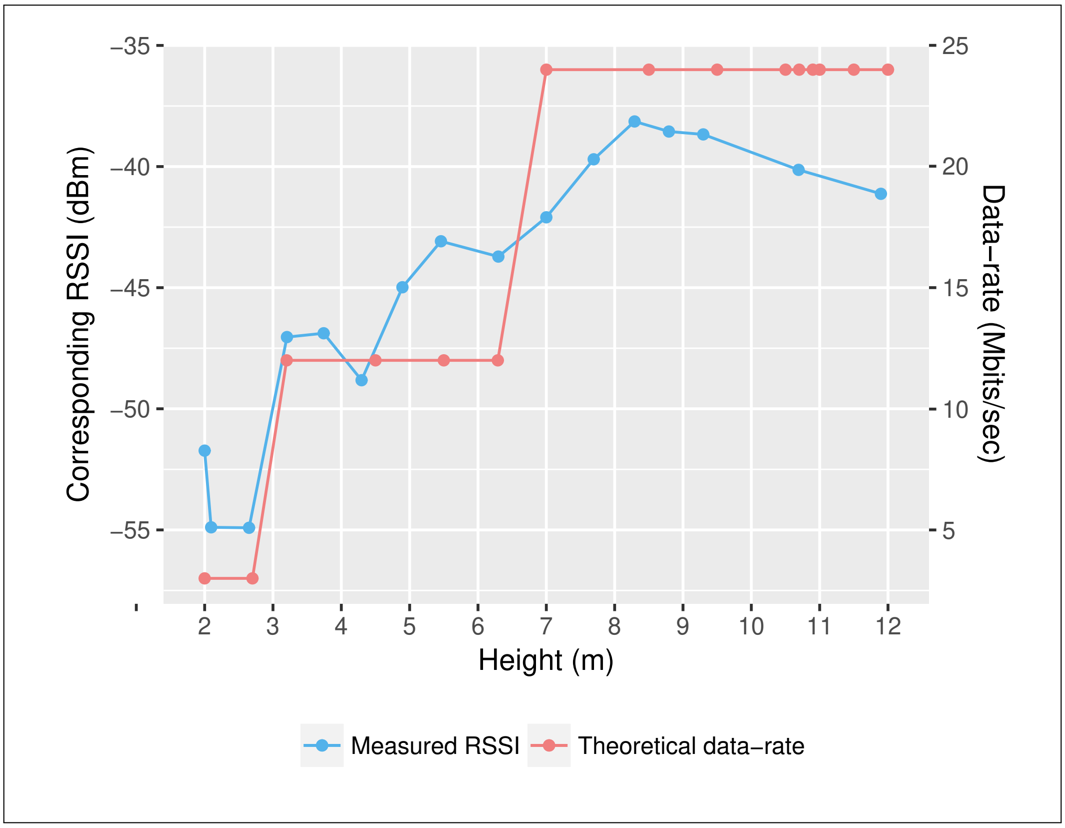


Figure 7.3: RSSI dependency on height and achievable throughput (Mbps) for a range of RSSI thresholds.

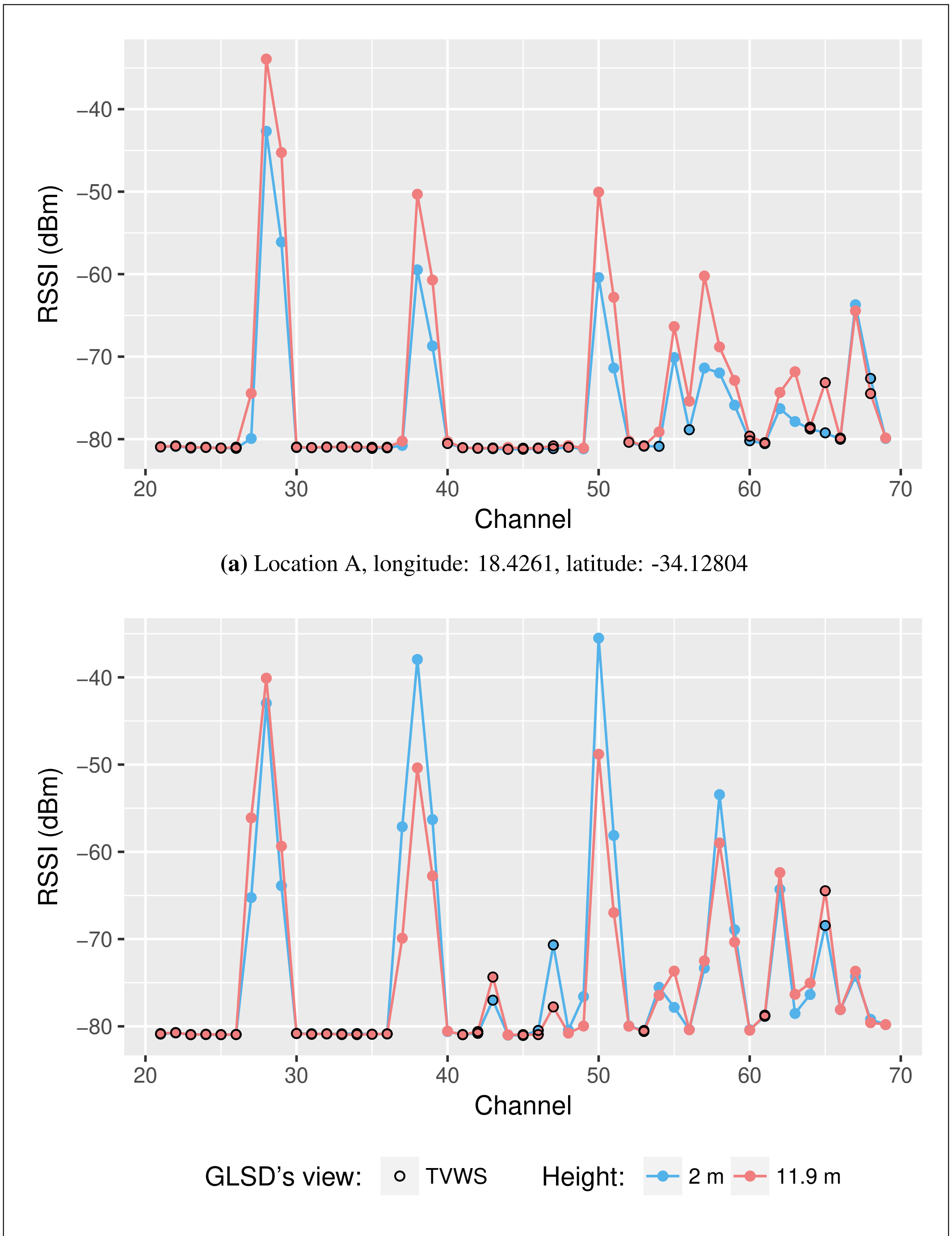
The data-rate associated with the RSSI threshold displayed in Figures 7.2 and 7.3 assumes a negligible (e.g. -100 dBm) and unchanging noise floor and interference. In practice, positioning a node higher up not only increases the RSSI, but also tends to inflate the noise floor in comparison with nodes at lower positions. This is because interfering signals from a far distance are equally unobstructed, which escalates the severity of RF signal interposition. Interference is a complex phenomenon in that, one transmitter's well intended signal is perceived as obstruction by other neighbouring networks. However, the RSSI is expected to rise quicker than the noise floor such that the benefits of raising the antenna height will out-weight the impact of increase in the noise floor.

Since this enquiry only covered the UHF band, there is an opportunity for future work to extend the study to other spectrum bands.

7.2.2 GLSD limitations

ICASA's TVWS regulation demands that a WSD queries a GLSD for access to TVWS. For this reason, an investigation into the performance of the GLSD was conducted. The study was aimed at determining the accuracy of the current GLSD implementation. To that end, radio frequency spectrum scans were carried out at selected locations using the procedure detailed in section 7.1. The research carried out encompassed a comparative analysis of the GLSD's view of white space in the television band with the ground truth. Based on the spectrum scans, a signal presence was observed on some of the channels labelled free by the GLSD as Figures 7.4a and 7.4b show. Figure 7.4 shows results at two locations only, however a similar trend was observed from spectrum scans conducted at other locations within the Cape Peninsula region. These results reveal inadequacies of the GLSD as currently deployed. This evidence goes to suggest that the GLSD approach should be complemented by spectrum scanning to determine clear channels for wireless connectivity.

There are two mutually possible explanations for the GLDS's imperfect performance. Firstly, it is a model-driven GLSD (see section 2.3.3), and therefore the *false negatives* may be due to inaccuracies in the underlying propagation modelling. Secondly, the scope of a model-driven GLSD is limited to registered transmitters. Thus a GLSD is agnostic to unregistered transmitters, which means that the GLSD considers channels vacant though they might be occupied by unregistered users.



(a) Location A, longitude: 18.4261, latitude: -34.12804

(b) Location B, longitude: 18.42398, latitude:-34.1398

Figure 7.4: Possible options when using 5 GHz WiFi and UHF-TVWS hybrid links.

'Unregistered user/transmitter' should not be confused with unauthorised spectrum access because, when new transmitters are legitimately commissioned, old ones de-commissioned or undergo changes affecting transmission parameters such as orientation and alike, that counts as unregistered until the GLSD is updated accordingly.

7.2.3 Tuning the model

Given the considerable rate of false positives and false negatives exhibited by the model-driven GLSD, further analysis was carried out to investigate the accuracy of existing propagation models. The study compared the incident power measured at the receiver with the value predicted by prominent propagation models, namely ITU-R P1546-5, which is based on Hata, and Longley-Rice Irregular Terrain Model. The focus was on these models because these are the models the current GLSD implementation uses for interference analysis and estimating available white space. For reference purposes, the analysis included the Free Space Path Loss (FSPL) model as well.

Accuracy of modelling can be determined by considering the difference between the model output and the actual measured values. The margin of error is quantified and commonly expressed in terms of the Root Mean Square Error (RMSE), which is given by

$$RMSE = \sqrt{\frac{\sum_{i=1}^{n}(X_i - X_i^{"})^2}{n}} \tag{7.7}$$

where X_i is the observed value, $X_i^{"}$ is the modelled valued and n is the number of data points [169].

	ITU-R P.1546	Longley-Rice	FSPL	Hata-fine-tuned
RMSE	11.91	19.32	25.96	0.66

Table 7.2: RMSE of propagation modelling.

Considering the RMSE values obtained in Table 7.2, it is evident that the existing propagation models may not always be inadequate for accurate path-loss prediction in the area. The high degree of error in the modelled path-loss estimation partly explains the GLSD's poor performance. Therefore, there is need to tune the models for improved accuracy. The ITU-R P.1546 yielded a lower RMSE compared to FSPL and Longley-Rice models as can be seen from Table 7.2 and that was the first reason ITU-R P.1546 became the model of choice to fine-tune. The second reason for choosing the ITU-R P.1546 is that, it has several parameters that can be tuned, which provides more room for tuning in comparison with the other models. The fine-tuned model was achieved by adding the average RMSE obtained in equation 7.7 to the Hata model. The resulting modified Hata model is shown in equation 7.8.

$$E = 81.73 - 6.16\log f + 13.82\log H_1 + a(H_2) - (44.9 - 6.55\log H_1)(\log d)^b \quad (7.8)$$

where

E: electric field strength $(dB(\mu V/m))$ for 1 kW e.r.p.

f: frequency in Megahertz.

H_1: transmitter antenna height in meters above ground, valid for 30 m to 200 m.

H_2: receiver antenna height above ground in meters, valid for 1 to 10 m

d: distance in kilometres

$a(H_2)$= $(1.1 \log f - 0.7)H_2 - (1.56\log f - 0.8)$

b= 1 for $d \leq 20$ km.

b= $1 + (0.14 + 0.000187f + 0.00107H_1^{'})(\log[0.05d])^{0.8}$ for $d > 20$ km where $H_1^{'} = H_1\sqrt{1 + 0.000007\ H_1^2}$

Figure 7.5 compares the measured Electric field strength values with the values predicted by the models under consideration. The tuned model that was derived as described above had a RMSE of 0.66 for 1-5 m above ground. Thus the results not only reveal the limitations of existing models, but also show that radio frequency spectrum scan be used to tune existing propagation models to improve the accuracy.

At this stage it is not clear from the data collected if the trend in the measured signal strength observed from 5-12 m is due to permanent topographical elements or was caused by some transient phenomena. However, there is compelling evidence

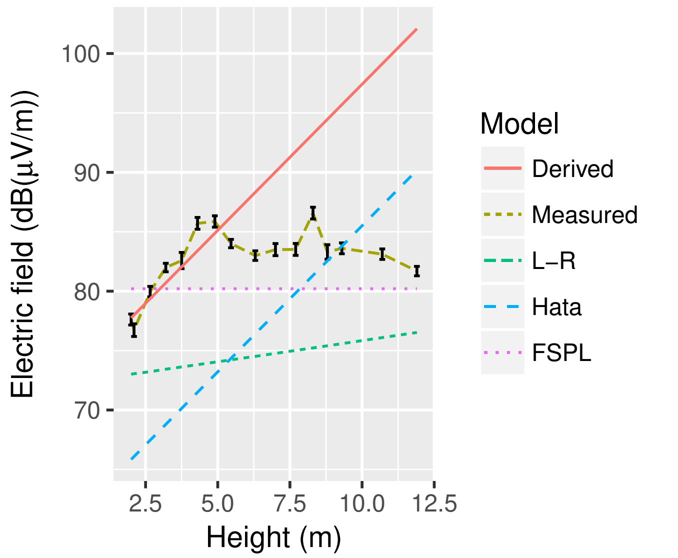


Figure 7.5: Comparing the predicted signal strength with the measured value. The black vertical bars along the measured curve shows the standard error of measurement.

indicating that the tuned model is location dependent, which makes extending studies of this nature to other areas indispensable. In addition, further investigation is needed to properly model propagation for receiver antennas that are 6 m or more above ground.

7.2.4 Other field experiences

This section highlights some additional lessons drawn from work towards the planning and implementation of a TVWS trial network.

To start with, though high gain antennas can be used with higher operating frequencies for longer distance, TVWS antennas are easier to align. A 5 GHz antenna for example, requires stricter alignment, which can be challenging at longer distances without additional specialised equipment.

Secondly, the wireless router firmware reports both signal strength and noise values. Therefore, in the absence of a dedicated spectrum analyser, the wireless network card itself can be used to gauge channel quality. The noise value reported when the antenna is disconnected measures the noise caused by leakages into the card's internal electronics. When the antenna is connected, but without any transmissions, the measured noise gives a good indication of interference from the environment.

Furthermore, there may be a trade-off between the RSSI and interference received resulting from antenna orientation. When a node is mounted to connect to some remote node, the convention is to orient the antenna such that the highest RSSI is obtained. However, there exists situations where the antenna alignment that maximises RSSI also increases the noise or the strength of unwanted signals. In such instances, pointing the antenna slightly away from the target to minimise the amount of interference albeit with reduced RSSI, may counter-intuitively yield better radio link performance.

7.3 Chapter summary and future work

This chapter has shown the correlation of UHF RSSI dependency on antenna height and established the theoretical relationship between RSSI and throughput. This presents an opportunity to optimise throughput through improved RSSI by adjusting the antenna height. The chapter also showed the discrepancies observed between the GLSD's view of TVWS and the ground truth. These findings hint at the drawbacks of a model-driven GLSD-only approach to white space detection. The GLSD inadequacy may be explained by inaccuracies inherent in existing propagation models for the region.

Future work will include an exploration of RSSI dependency on antenna height in other spectrum bands and further measurement of the height and RSSI benefits over the expected rise in the noise floor, and compare with theoretical expectations. In addition, there is need for more investigation to properly model UHF-TVWS propagation in the region for receiver antenna height from 6 m and higher.

Chapter 8

Conclusion

The 2018 ITU statistics[1] showed that the population that would still be offline in developing countries by the end of the year stood at 54.7 % . *Offline* can be defined in terms of coverage absence and/or inadequate affordable access. Affordability of access renders the startling ITU figure highly conservative as it is based largely on the former interpretation of connectivity. This calls for a relentless pursuit of research and development of solutions in areas that promise to improve the current connectivity landscape. This research was motivated by the potential benefits that mesh networking with DSA holds, which includes the following:

- *Performance enhancement and efficiency* in spectrum utilisation. Besides the potential to utilise suitable frequencies in bands that provide better coverage and penetration, DSA is envisaged to bring about network performance enhancement by alleviating channel congestion due to the over-utilised ISM band that is currently being used especially in urban areas.

- *Cost reduction and coverage extension* to rural communities that lag behind in connectivity despite abounding in TVWS. DSA allows for the use of frequencies that have superior propagation characteristics, which fosters the extension of connectivity to underserved communities. In comparison with the current 2.4/5 GHz WiFi deployments, using UHF-TVWS minimises the number of radios required to cover an area. That in turn reduces the roll-out cost, which is helpful especially for low-income sparsely populated regions. To

[1]SOURCE: https://news.itu.int/itu-statistics-leaving-no-one-offline/

add on, reducing the number of radios lessens the drop in overall end-to-end throughput that occurs as the number of hops increases.

These benefits help adhere to the targets of developing countries' such as South Africa's National Development plan, which identifies the need for improvement in broadband Internet capacity and access among the key actions required in establishing a strategic economic infrastructure. The other driving factor of this work was the ever present need for improved link and network throughput. WMNs are prone to drastic reductions in throughput for a range of reasons, which makes throughput enhancement an important aspect.

8.1 Recapitulation of the research questions

Using the regulatory authority's position on the framework for dynamic and opportunistic spectrum management, and arguments from other stakeholders as basis, this research developed and applied the principle of *comply-first-then-optimise*. The ordering of the research questions in the next subsections is reflective of the "comply-first-then-optimise" guiding principle. Assuming device-type approval is checked already, the compliance aspect in the context of this study refers not only to agree, but also to ensure that the device operates only on the channel(s) allowed at the device's particular location. Once a regulation compliant network is realised, there are various arms of performance optimisation that could be undertaken.

8.1.1 How should a self-configuring TVWS network stay compliant in a multi-hop environment?

There are two interrelated conditions that a WMN with DSA must meet. Firstly, connectivity among nodes must be established and maintained i.e. each node must be able to communicate with every other node. Secondly, every node must operate on channels that are allowed at the nodes' particular location as determined by the spectrum access method such as a GLSD. To that end, a MAC procedure was developed to ensure DSA regulation compliance. The solution caters for two critical WMN properties, namely multi-hopping and distributed network coordination.

Evaluation was conducted in a simulation environment using NS-3. The overall spectrum map was modelled based on the coordinates of the planned regional TVWS trial network and the actual information on spectrum availability in the regions. The details on spectrum status were based on combined information sourced from SENTECH[2], who are the national distributors of licensed broadcast signal in South Africa, and the CSIR Meraka whitespace database[3], which at present is the only publicly accessible GLSD that is available for the region the study is situated in. The dissertation showed how the proposed solutions meets the aforementioned requirements without incurring significant time complexity increase. In an additional effort, the research envisaged a worst case scenario arising when the intersection set of allowed channels for the global set of nodes is empty. The study considered radio virtualisation to obviate the risk of an otherwise disjoint network ensuing due to lack of network-wide contiguous common channels. This solution is reliant on the assertion that while there may be a shortage of network-wide common channels, single-hop neighbours more often than not, have several channels in common.

8.1.2 What characteristics of a DSA channel should be factored into a link metric for optimal route selection in WMN with DSA?

Link performance was examined to identify key factors influencing throughput. The preliminary investigation involved nodes with radios networked via RF cables and connectors to isolate external environmental influence. Baseline measurements of throughput and latency were then conducted. The aim was to identify raw data that could be obtained by interrogating the WNIC and used to infer link quality. The following elements were found to relate to link performance: quality of operating channel, channel-width, txpower, signal level, noise level and MCS. These factors can be placed in two generic categories depending on whether or not the effect on performance is negative or positive. The terms *reward* and *penalty* parameters were

[2]Website: http://www.sentech.co.za/
[3]Website: http://whitespaces.meraka.csir.co.za/

used to respectively refer to elements with a direct and inverse proportion relation to link throughput. The research had hypothesised that interrogating the WNIC and factoring in raw data into the protocol's link metric would improve the protocols ability to rank links and improve performance. Accordingly, one critical issue that had to be resolved was determining how much to reward or penalise a link based on the parameter values since the impact ratio may not be 1-to-1. To resolve that, the study introduced the concept of *scaling constants*. Scaling constants serve two purposes: (i) normalise raw data, which may be firmware-dependent; and (ii) scale the degree of reward or severity of penalty on a link.

8.1.3 On what basis should the WMN nodes select single-I/O operating radio, aggregate or split links?

Assuming nodes equipped with two radios operating on a high and low frequency such as 5 GHz WiFi and UHF-TVWS, the experimental results uncovered three main possible cases. The first case is where only the UHF-TVWS radio is operable, which can result from several factors such as coverage distance extending beyond 5 GHz radio's attenuation, presence of permanent or transient obstructions that the 5 GHz radios fails to penetrate and other causes. The results showed that when the line of sight is obstructed, 5 GHz WiFi completely fails to establish a link, whereas, a UHF-TVWS link continues to work even when obstructed as shown in section 6.5.3. The second possible case is where only the 5 GHz radio is usable, for example due to lack of clean channels, unavailability of UHF-TVWS altogether in the area at a particular point in time or saturation of the UHF-TVWS radio's front-end when the communicating nodes are too close to each other and the transmission power is set too high for the distance. Given the results in section 6.5.2, if the UHF-TVWS operating channel is not carefully selected and/or other operating parameters set improperly, deterioration in channel quality could severely reduce throughput down to zero. The third possible case is where both 5 GHz and UHF-TVWS radios are able to establish links, albeit with varying throughput and latency offerings.

The first two scenarios described above indicate extreme cases where the link is realisable with one radio and fails with the other. In these instances the decision process is simplified in that the choice of which radio to use and when, is confined to the one radio that establishes a link. A typical deployment is most likely to fall in the third category thereby providing an opportunity to establish hybrid links for high performance. In view of the different ways of defining hybrid links, this research adopted metaphors for describing hybrid link permutations. The theoretical number of possible options gets unwieldy quite rapidly as the number of radios and nodes increase. Therefore, for practical considerations, the focus was narrowed down to three principal options. The terms used in this dissertation to describe these options succinctly are *single-I/O*, *split* and *aggregate* [4]. Given these hybrid links, when the radios have approximately uniform data-rates, aggregation yields the best performance in terms of throughput and latency. When the data-rates are significantly different, splitting produces better performance.

8.2 What made this study different?

Previous work on link metrics for multi-radio WMNs considers radios operating in the same frequency band such as 802.11g or 802.11a with uniform free-space loss. On the contrary, this research conducted an exploration into the performance of 5 GHz and UHF-TVWS hybrid links that are characterised by a wider frequency range and non-uniform free-space loss. Furthermore, prior work on spectrum aware routing assume symmetric links i.e. the link quality in one direction is assumed to be equal to the link quality in the reverse direction, which might have been for purposes of simplifying the experiments. However, findings from the experimental performance measurements show that the symmetric link assumption does not hold typically for medium to long-range links in outdoor deployments. In addition, the methods of network selection studied previously are limited to mechanisms required for clients in *infrastructure mode* to select between cellular and WLAN, but this research considered hybrid links in a mesh context with ad-hoc connectivity. Infrastructure-type connectivity differs from this work fundamentally in that an

[4] Single-I/O refers to a link where a single-radio is used for both sending and receiving. A split link on the other hand is a configuration where a node uses one radio for sending packets and the other for receiving. An aggregate link refers to two or more radios combined to form a single logical link.

infrastructure-based network has a centralised point of control such as a base station or access point to which a client connects/disconnects quite straightforwardly. Whereas, connectivity among mesh nodes in ad-hoc mode is significantly different and more challenging in that decisions have to be synchronised on multiple ends because of the interdependence among the links, and yet there is no central controller.

8.3 Summary of results and contributions

To recapitulate, this research revisited the routing problem in WMNs with a view of leveraging DSA to overcome some of the challenges currently faced in WMNs and improve performance. The study attempted to address the routing requirements for a WMNs with DSA and made knowledge contributions in three areas of IP-based wireless networking. The first area relates to network formation and compliance in WMNs with DSA, focusing particularly on UHF-TVWS. The second dimension pertains to the adaptation of link metrics for routing in DSA based WMNs. This is comparable to the overhaul in link metrics' history necessitated by the progression of routing solutions from wired to wireless network environments. The third direction applies to multi-radio utilisation.

8.3.1 Regulation compliant TVWS mesh network formation

The problem of WMN formation with DSA had not been addressed hitherto. The multi-hop characteristic of WMNs coupled with the ad-hoc nature of mesh nodes poses two major challenges: (i) determining allowed channels at each of the nodes' location firstly, and then finding the globally optimal channel(s); and (ii) instantiating and coordinating channel switching. There is also a third challenge or constraint that has to do with maintaining connectivity and avoiding splitting the WMN when there is a shortage of common DSA channels. For a network deployed over a large topological area, a dense presence of primary and other secondary transmitters in one part or parts of the network may significantly reduce the set of channels common to all nodes. In response to the three aforementioned challenges, this research developed a distributed network formation and channel unification algorithm that ensures network converges on a common optimal channel. In the event that there is no channel common to all nodes, the proposed solution virtualises the radio of the node(s) at the fringe of an imminent network split.

8.3.2 Link metric

The research affirmed the hypothesis that augmenting existing link metric to factor in DSA channel characteristics would lead to improved performance. A framework was developed for augmentation, and scaling of reward and penalty parameters. For full-path based routing schemes, the problem of finding the optimal path end-to-end could be formulated as an optimisation problem and solved using the weighted exponential sum approach to calculate the end-to-end path cost. While prior related studies have looked at link metrics in WMNs, one key contribution of this work is the general metric reinforcement framework that has been given to improve performance.

In addition, the idea that there is no one size fits all when it comes to routing metric is a common thread evident in several publications. But strangely, the development of routing protocol for apparent general use cases, has ironically continued with static metric computation functions. This thesis made the first step to postulate the DLMeS concept, which is a novel approach to routing protocol design that attempts to consolidate and unify the years worth of contributions on routing metrics from prior studies.

8.3.3 Multi-radio utilisation

Literature abounds with publications on various DSA related topics, but there is a dearth of experimental and thorough investigative work around the performance of the different radio frequency operating bands. This research reported on the investigation into the performance of WiFi operating in 5 GHz and UHF-TVWS. The comparatively analysis indicated that there is no outright winner, the performance of wireless radio links operating in different spectrum band depends on the application scenario. Building on the existing catalogue of motivation for multi-radios in WMNs, this research added multi-radios operating in different spectrum bands as a means of (i) meeting spectrum requirements for deployments in different scenarios; (ii) realising robust WMN back-haul links; and (iii) mitigating interference, and link asymmetry.

The research further brought out a fresh perspective on the logical configuration of multi-radio enabled nodes and highlighted the different link options. To that end, a multi-link utilisation framework was developed for effective and efficient utilisation of the newly introduced hybrid links. The three-tier framework includes a link permutation layer, which encapsulates the possible send/receive options (i.e. either single-I/O, split or aggregate) as detailed in chapter 6 section 6.6. Based on the insight gained through experimentation, this study provides guidelines for link option selection and details specifying scenarios where each link type might be the best choice, which is a step towards the implementation of auto-selection mechanisms. In an additional effort, link splitting was discovered and contributed in section 6.3.2 as a potentially effective interference mitigation approach. The multi-link utilisation framework is an important construct because it encapsulates link permutations and supports the routing module in utilising hybrid links synergistically. Using these hybrid link utilisation approaches, experimental results showed a 40 - 60 % improvement in throughput on links comprising radios with approximately uniform data-rates. For multi-links established with dissimilar data-rates, aggregation produced 40 - 60 % of the lowest data-rate involved, which can be considered as poor or inefficient performance proportionate with the difference between the lowest and the highest data-rates in question. In response to that, the study introduced ARR -a novel multi-link utilisation technique for multi-radios consisting of dissimilar data-rates. The numerical analysis carried out showed that ARR achieves 75 % overall increase in throughput.

8.4 Limitations of the research

To start with, the study was situated in the Southern Peninsula in the Western Cape Province of South Africa and that is where the radio frequency spectrum scans were conducted. The assumptions about spectrum availability used in subsequent simulations as well as the conclusions made about the performance of propagation models were based on this region's spectrum map and empirical data. The view in other regions may be different. Furthermore, the experiments focused on 5 GHz and UHF-TVWS operating bands, whereas white space can be found in any spectrum band. Nonetheless, given additional time and resources, an extended study is possible and that is part of future work.

Furthermore, the evaluation of Augmented link metric and regulation compliant mesh network formation were conducted in a simulation environment due to limitations in the current size of the out-door test-bed. The enormous complexity associated with modelling a wireless channel suggest that results obtained from a simulation environment only give an approximation of performance, but serve well as a guide nonetheless. More test-bed based evaluation is included in future work.

Borrowing from the field of *particle physics*, it has been shown that when the behaviour of entities in isolation or as a small collection is compared to a much larger collection, the collective properties can be totally different! Reasoning from this point of view, it is hard to predict with absolute certainty how the solutions presented in this dissertation would perform as the number of nodes gets larger and larger. However, the scope covered in this dissertation suffices for typical community WMN deployment scenarios. With that in mind, the next section lays down pointers to possible lines of further enquiry and exploration.

8.5 Opportunities for future work

8.5.1 Extension of the study to other spectrum bands

This research analysed the performance of 5 GHz and UHF-TVWS hybrid links. Significant variations in performance across different combinations of channels, transmission power and channel width values were observed. Clearly, the choice of spectrum could make or break a link. Further investigation is needed to understand the intricate interplay among the quality of the operating channel, transmission power level, channel width value and how the surrounding environment (physical and spectral) influences the choice of optimal operating parameter -especially in a mesh network environment where interdependencies between links is pronounced.

Future work could also extend the investigation and study the phenomena in other operating bands. While still on the comparative analysis of different operating bands, other aspects requiring further exploration include the (i) effect of weather conditions such as rainfall; and (ii) effect of ground surface type (e.g. concrete vs grass/foliage) on link performance. This set of experiments could also cover an investigation of performance over water surface. The rationale behind that is, there are deployment scenarios where islands have to be connected or connection points stretching across a lagoon for example. The expected radio performance in such scenarios is not well understood. Just to add on, if the radios used in the experiment are of different platform implementations, it is important for researchers to isolate "radio" the circuitry from "radio" the operating frequency band in the analysis. For example, this dissertation (see section 6.5.1) reported on a strange throughput/-transmission power relationship exhibited by the UHF-TVWS radio link that only after critical analysis, was attributed to the radio circuitry. Therefore, it is crucial to draw a clear distinction between aspects of performance emanating from the link's radio front-end and the frequency band related performance behaviour.

8.5.2 Extend coverage without incurring a decrease in effective throughput

As currently deployed, WMNs suffer a severe decrease in effective throughput as the degree of multi-hopping increases. The multi-radio approach aims to alleviated this problem by increasing the I/O channels. This research developed a multi-link utilisation framework aimed at exploiting the full potential of multi-band multi-radio node capabilities. Future work could focus on leveraging multi-radios to achieve synergistic benefits along the throughput dimension [5]. A possible starting point is further improvement in the efficiency of the aggregation technique to maximise throughput. For example, given a set of transmit/receive node pairs

[5]The mesh approach as a whole, extends coverage beyond the reach of any one node. It can be said that coverage extends direct proportionally with the number of nodes. What is needed is to begin to think about how this "team work" exhibited by mesh nodes can be leveraged to increase throughput and minimise latency. The question to consider is, can the end-to-end throughput be achievable commensurate with node/hop count?

with n radios and each radio providing T Mbit/s, more work is needed to progress the aggregate throughput towards $n * T$ Mbits/s. This research contributed ARR to improve efficiency in hybrid links involving dissimilar radios. Future work could explore parallelising the aggregation algorithm alongside MIMO techniques to achieve higher throughput. In addition, the conditions dictating whether or not to select single-I/O, split or aggregate the link may appear transiently or exist long-lastingly. Therefore, automating the decision mechanism is crucially needed.

8.5.3 Enhancing GLSD performance

The GLSD is the Regulators' preferred method of spectrum access for the TVWS paradigm because of its promised protection guarantees for the primary users. A preliminary investigation was conducted to assert white space availability. The study compared the GLSD's view of TVWS with the ground truth. The results revealed significant discrepancies between the white space estimated by the GLSD and the radio frequency spectrum scans conducted on the ground. The inaccuracies may partly be due to the GLSD's specific implementation detail, and to a larger extent result from the limitations in the propagation modelling. The propagation models are particularly inadequate in the region where this research was situated (i.e. Southern Peninsula, Western Cape Province of South Africa), which is endowed with mountains and other topographically difficult elements. Future work could consider enhancing PAWS functionality in such a way that GLSD clients are allowed to push spectrum scan results to the spectrum database for the GLSD to refine its subsequent results. Additional effort could also be directed towards fine-tuning current propagation models to improve accuracy. Propagation models tend to be location/region dependent. For that reason, one possible direction to consider is location based model-tuning based on radio frequency spectrum scans. In addition, the speed with which a GLSD transaction is completed is key towards mechanisms for corrective measures particularly in ad-hoc multi-hop environments. While this might be trivial for nodes with access to a high-speed Internet connection, the number and size of parameters specified in the GLSD query as well as the response have an impact on the response time. But considering the bandwidth required for messaging is relatively low, the lack of connectivity is a greater problem than low-speed connections are. The current GLSD implementation requires WSDs to have an Internet connection to access TVWS. There is need for more innovation in this area to cater for Internet-less entities needing to use TVWS connectivity for purposes such as community based intranets. Possible approaches to consider is the placement of *GLSD proxies* in regional local networks to deal with this.

8.5.4 Exploration of other spectrum opportunities

Recent years have witnessed an increase in wireless based communication, a trend exhibiting no signs of slowing down whatsoever. The current definition of white space (unused frequency at a particular location and time) limits the spectrum opportunity to three dimensions, namely frequency, time and space. The terms *white space, black space,* and *grey space* are some of the terms currently being used to refer to the known spectrum opportunities. Additional "space" exploration is necessary to meet the ever increasing spectrum demand -especially in urban and peri-urban locations. Against this background, some general research directions to complement and extend this work are hereby listed below:

- The experimental study conducted revealed the correlation between antenna height and RSSI in UHF and showed the theoretical throughput achievable for different RSSI thresholds (*see* section 7.2.1). What remains to be done is investigate the antenna height, RSSI and SNR interdependency and establish the trade-off for the RSSI gain. Extending this part of the work may encompass field measurements of throughput for different PHY modes at different receiver heights and comparing it with theoretical expectations.

- Analyse spectrum scans over a longer period of time to gain more insight into the time-dependant spectrum dynamics.

- The current TVWS detection techniques is entirely based on the transmitter location. The current state-of-the-art is incapable of detecting television broadcast signal receiver because of the passivity of television sets. As DSA technology matures, future work could explore ways of detecting the presence or absence of television receivers.

- The results of spectrum scans showed that depending on the polarisation of primary and other transmitters, a channel could be vertically occupied, but horizontally vacant and vice versa. For that reason, there is an opportunity to design and implement nodes with inbuilt mechanism for dynamic antenna polarisation along with spectrum sensing to determine clean/optimal channels.

- Generally speaking, there has been a continued perfection of virtualisation techniques in the computer science fraternity as a way of improving capacity and value of computing resources. Spectrum is commonly referred to as a scarce finite resource, and rightly so. Based on that view, another strand of thought to consider for future work is, can the spectrum resource be virtualised for improved capacity and value?[6]

- ITU lays down guidelines, but leaves it up to individual countries to define their spectrum regulation. Individual Southern African countries for example, have been drafting while some have already passed DSA regulation valid within the country's jurisdiction. However RF signals are not respecters of geographical boundaries, which raises concerns about the need for a unified local and regional regulatory framework.

8.6 Concluding remarks

WMNs have long been thought to offer the most hope in extending connectivity to unconnected communities. DSA potentially allows the mesh nodes to utilise spectrum such as UHF-TVWS that has superior propagation qualities. By so doing, DSA helps to achieve *first-mile* connectivity. The unconnected represent a greater fraction of the population and on that account, one might argue that the term 'last-mile' conventionally used by network operators and the networking community as

[6]There is a separate hidden question of what value really is. For instance, spectrum licence fee related costs incurred by service providers inevitably gets passed on to end users. That now begs the question of which one is more valuable: the revenue the regulator gets through licence issuance or the income end users would serve if the service provider charged less?

a whole to refer to the unconnected sector, ironically carries with it a diminished sense of urgency, insignificance and a low priority connotation. Against this backdrop, this dissertation uses the term ‘first-mile’ in conclusion to refer to the stretch from the remotest user to the closest POP to underscore the much needed shift in perspective. DSA offers an opportunity for first-mile and rural connectivity, however suitable MAC and routing algorithms are required to support WMNs using DSA.

All in all, contributions have been made, however more remains to be done in extending connectivity to reduce the offline population in low-income and developing communities. In addition, continued effort is needed to maintain the solution curve ahead of QoS requirements. It is my expectation that the work presented in this dissertation will stimulate further research and quicken the on-going work on standardizing DSA protocols that use WMNs.

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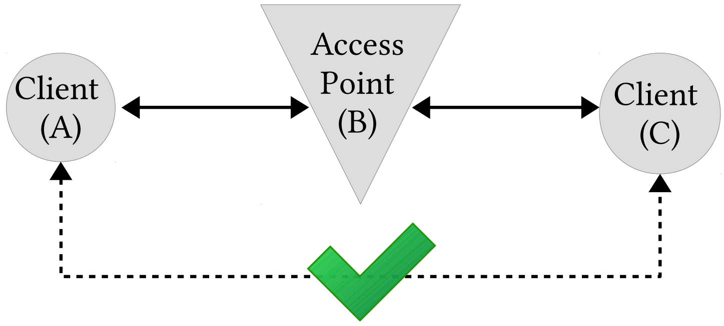
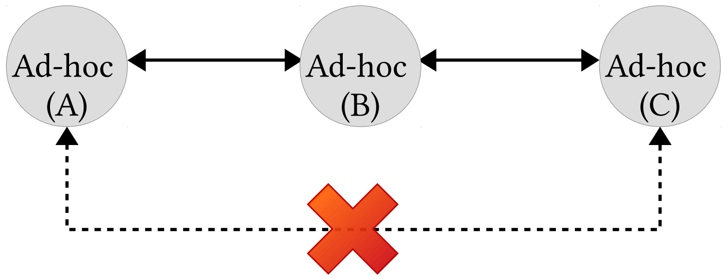
Appendix A

802.11s key features -an overview

For an 802.11 based multipoint-to-multipoint WMN, all the mesh routers have to operate in ad-hoc mode in order to facilitate direct communication between any sender/receiver pairs. The principle of WMNs is that every node relays packets on behalf of other nodes thereby expanding coverage. However, as mentioned in chapter 2 section 2.1.2 of this dissertation, by default ad-hoc mode does not support multi-hopping as illustrated in Figure A.1. Multi-hopping is achieved by applying layer 2 or layer 3 routing. Routing can be realised by either statically creating routing tables for all nodes (which gets less practical as the number of nodes increase and link status varies) or using a routing protocol that automatically creates and maintains the nodes routing tables. Aside from the open-source community, several proprietary solutions for building 802.11 based WMNs have been developed by companies. The IEEE 802.11s standard [26], [27], which defines MAC procedures that are required to achieve wireless multi-hopping was established to address interoperability issues among solutions for 802.11 based mesh networks. The 802.11s standard describes wireless mesh networks that perform routing at layer-2 (link layer). This appendix details key 802.11s MAC features relevant to the simulation carried out in chapter 4 of this dissertation. More specifically, the next sections describe the neighbour discovery and topology formation process, the beaconing and synchronisation maintenance procedure aimed at avoiding beacon collisions, and the channel switch features that can be harnessed to realise the solution proposed in chapter 4 of this dissertation.



(a) Node A is able to communicate with node C via node B.



(b) Node A and node C are able to communicate with node B, but there is no communication between node A and node C.

Figure A.1: In infrastructure (master-client) mode, clients are able to communicate directly as packets get relayed by the access point as shown in **(a)**. Whereas in ad-hoc mode, by default there is no communication between node A and node C because node B does not relay data packets as illustrated in **(b)**.

A.1 Neighbour discovery and topology formation

When a WMN router boots up, it may use passive or active scanning to either discover and join an existing mesh network or initiate the establishment of a new mesh. Passive scanning describes the observation of beacon frames across a given spectrum band, whereas active scanning refers to the transmission and scanning of probe frames. The scan mode is determined by the *ScanMode* parameter value of the *MLME-SCAN.request* primitive. Among the information encoded in the beacon and probe frames is the *Profile*, which refers to a set of parameters that specify the mesh network attributes. Appropriate fields in the frame are used to specify the mesh attributes, namely mesh ID, path selection protocol, path selection metric, congestion control mode, synchronisation method and an authentication protocol. A mesh node is configured with a profile and if two nodes have matching profiles [1], they start to associate. Thus a node becomes a member of an existing network if its activated profile is the same as the profile of the discovered node or establishes a new network if the activated profile differs from the profiles received. After joining the network, the node proceeds to establish peer links with its neighbours [2].

Figure A.2 shows the flowchart to explain the mesh peering management protocol (MPM) framework protocol interaction. As shown in the flowchart, MPM is used to control peering instances when *dot11MeshSecurityActivated* is false. If dot11MeshSecurityActivated is true, the *authenticated mesh peering exchange* (AMPE) protocol is used instead. The study conducted in this dissertation is focussed on the workings of MPM, which uses *Mesh Peering Open frames, Mesh Peering Confirm, and Mesh Peering Close frames* for establishing, managing and ceasing the peering. A peering instance is successfully established when both nodes have sent and received (and correctly processed) both a Mesh Peering Open frame and a corresponding Mesh Peering Confirm frame for this particular connection. Once a node receives and accepts a Mesh Peering frame, it assigns a unique *AID* to the transmitter. The AID value is a 16-bit identity of a neighbouring node and is used to encode the *traffic indication map* (TIM) element in the beacon frame. When traffic is buffered, the TIM element is used to identify the neighbouring node for which traffic is pending. A node further maintains an enumerated state variable for each neighbouring node. The value of the state variable determines the frame type that may be exchanged between the node pairs. Prior to establishing a peer link, the type of frames transmitted is limited to the ones used for peer discovery, MPM and *simultaneous authentication of equals*(SAE). Nodes do not transmit other frames until a peer link has been established.

[1] There are other conditions specified in the standard that must be met to consider the discovered node as a peer candidate.

[2] Peering takes place after the nodes involved signal that they are able to establish mesh peering by setting the *accept additional mesh peering* subfield to 1. The node can toggle this element to 0 to indicate when it is unable to establish additional peer links. Internal policies can be applied to limit the number of mesh peering for example based on the node's internal resources. Actual internal policy specifics are outside the scope of the standard.

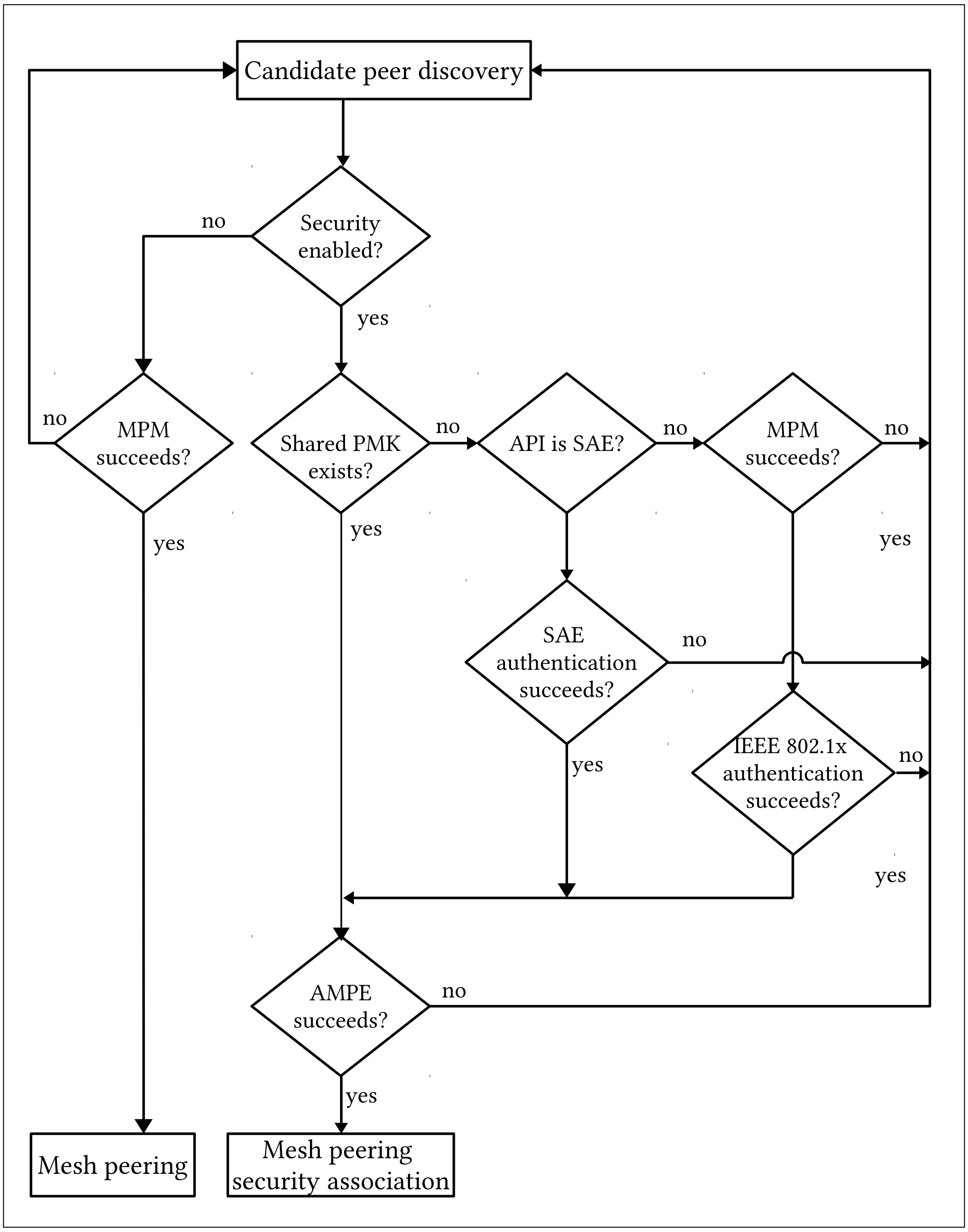


Figure A.2: Protocol interaction in the MPM framework. Once neighbouring nodes have verified matching mesh profiles via the scanning procedure, the MPM protocol uses three frame types, namely Mesh Peering Open, Mesh Peering Confirm, and Mesh Peering Close for creating and managing a peer link. MPM success happens when both nodes exchange and correctly process the Mesh Peering Open and Mesh Peering Confirm frames.

A.2 Mesh Peering Management finite state machine

Figure A.3 shows the finite state machine of the MPM protocol. This section describes the states, actions and events associated with the state machine.

States used by the MPM finite state machine:

- IDLE - the node either listens for incoming Mesh Peering Open frames (i.e. passive scanning) or initiates mesh peering (i.e. active scanning).
- OPN_SNT - the node has sent a Mesh Peering Open frame and is waiting for a Mesh Peering Open frame and Mesh Peering Confirm frame from the neighbouring node.
- CNF_RCVD - this state is when the node has not received a Mesh Peering Open frame, but has received a Mesh Peering Confirm frame. Therefore, in this state the node is yet to send a corresponding Mesh Peering Confirm.
- OPN_RCVD - this state follows receipt of the Mesh Peering Open frame. In this state, the node has not yet received the Mesh Peering Confirm, but the node has sent a Mesh Peering Confirm Confirm frame corresponding to the Mesh Peering Open frame received.
- ESTAB - in this state, a node has received both the Mesh Peering Open and Mesh Peering Confirm frames, and thus a peer link is established with a neighbouring node.
- HOLDING - the HOLDING state is when the node is closing the peering instance that had been initiated or established already.

Actions and events pertaining to state machine transitions:

- CNCL(localLinkID, peerMAC, ReasonCode) cancels the peering instance identified by *localLinkID*.
- ACTOPN(peerMAC, localLinkID) is used by the SME to create a new peering instance.

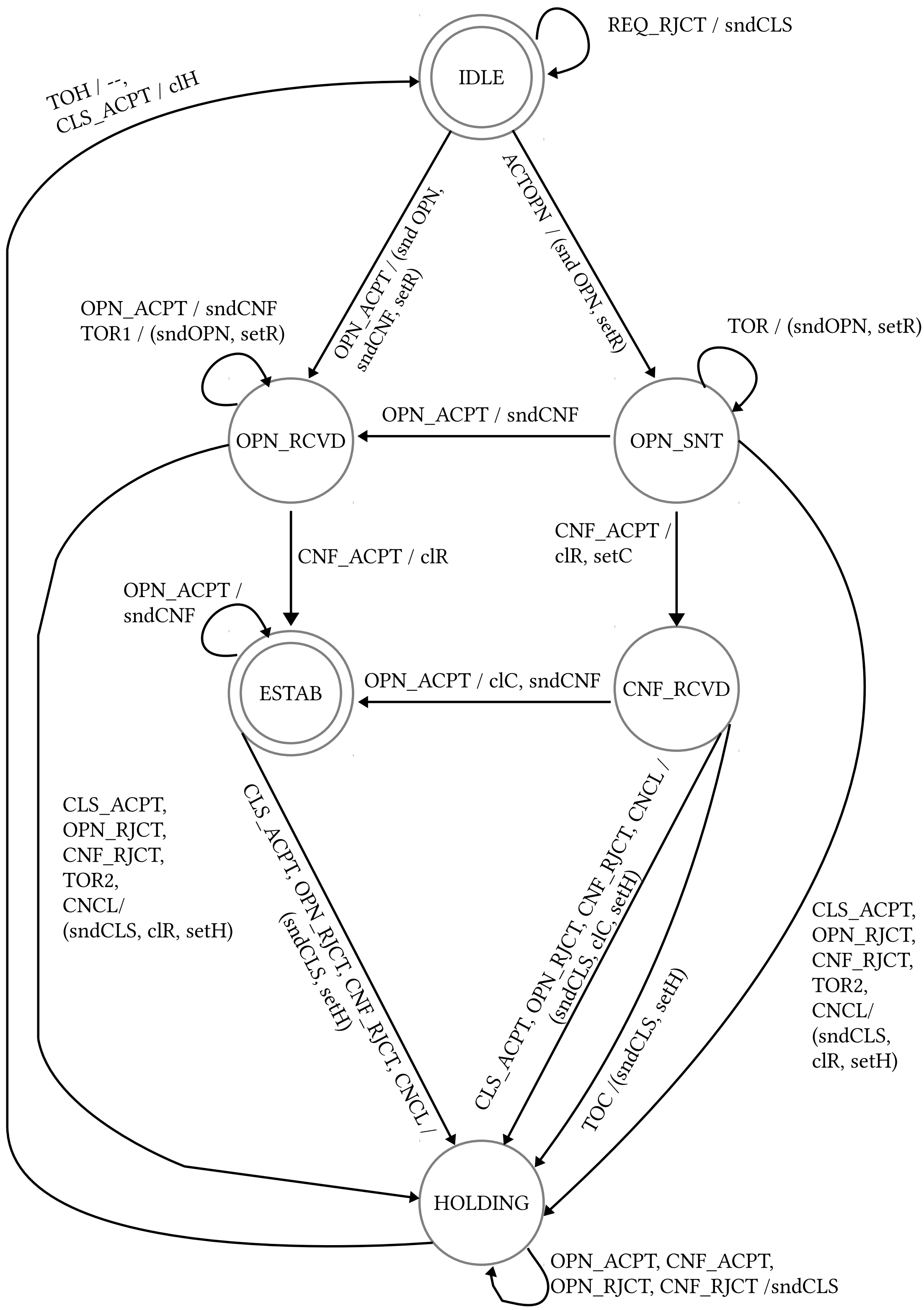


Figure A.3: Finite state machine of the mesh peering management protocol.

Events generated by frame processing:

- OPN_ACPT -PeeringOpen_Accept(peerMAC, peerLinkID) event occurs when a Mesh Peering Open frame that meets the peering criteria has been received.

- OPN_RJCT -PeeringOpen_Reject(peerMAC, peerLinkID, Configuration, reasonCode) means that a Mesh Peering Open frame has been rejected.

- CNF_ACPT -PeeringConfirm_Accept(peerMAC, localLinkID, peerLinkID) implies that a Mesh Peering Confirm frame for the *localLinkID* peering instance has been received.

- CNF_RJCT -PeeringConfirm_Reject(peerMAC, localLinkID, peerLinkID, reasonCode) happens when a Mesh Peering Confirm frame is rejected.

- CLS_ACPT -PeeringClose_Accept(peerMAC, localLinkID, peerLinkID, reasonCode) is an indication that a Mesh Peering Close frame has been received.

- REQ_RJCT -PeeringRequest_Reject(peerMAC, peerLinkID, reasonCode) occurs in the special event that a node rejects an incoming Mesh Peering Open frame to initiate peer link establishment.

Actions are triggered by either events or *timers*. Some of the actions related to MPM frames are:

- sndOPN -sendOpen(peerMAC, localLinkID, Configuration) is done by the node to send a Mesh Peering Open frame to its neighbour.

- sndCNF -sendConfirm(peerMAC, localLinkID, peerLinkID, Configuration) sends a Mesh Peering Confirm frame.

- sndCLS -sendClose(peerMAC, localLinkID, peerLinkID, reasonCode) sends a Mesh Peering Close frame.

The timers are here by described below:

- *retryTimer* invokes a resend of the Mesh Peering Open frame when a matching Mesh Peering Confirm has not been received.
- *confirmTimer* is triggered when a Mesh Peering Confirm is not received, which is an indication to abort the link establishment.
- *holdingTimer* indicates that a link may be closed and triggers a graceful shutdown.

A.3 Beaconing and synchronisation

All mesh nodes periodically transmit Beacon frames, which assists in mesh discovery. By default, the neighbour offset synchronization method is used for synchronisation. A method [mesh beacon collision avoidance (MBCA)] for mitigating Beacon frame collisions among hidden nodes is also defined. ¡neighbour offset synchronization primer¿ The timing offset value is calculated as follows:

$$time_{offset} = t_s - t_r \tag{A.1}$$

where time t_s is the value in the timestamp field i.e. the time the frame was sent, t_r is the time the frame was received. Each node keeps the $time_{offset}$ value calculated from the most recent Beacon or probe response frame received from the nodes neighbours.

A.4 Channel switching

Channel switching may be necessitated by the need to comply with regulation, avoid interference, and maintain connectivity. The 802.11s standard specifies informational elements such as *supported channel, supported regulatory classes* that nodes can make use of in selecting a channel. However, at present the standard does not specify any algorithm necessary to determine the channel to use.

Before switching to a new channel, a node uses the *Channel Switch Announcement* along with *Mesh Channel Switch Parameters* elements in the beacon/probe response/channel switch announcement frames to inform its neighbours that it is moving to a new channel. Appropriate fields in the Mesh Channel Switch Parameters are used to specify the new channel and the time the node sending the channel switch announcement intends to switch to the new channel. Additionally, the node initiating the channel switch can toggle the *Transmit Restrict* Flags subfield to 1 to force the other nodes to suspend transmission frames on the current channel other than frames relating to the channel switch announcement until the channel switch occurs. The announcement is repeated and propagated through the network until the intended switch time with the aim of ensuring that all the nodes in the network are able to hear the channel switch announcement at least once.

When a node receives a Channel Switch Announcement, it may accept the advertised channel switch or take alternative courses of action such as joining a different network where applicable. If the channel switch is accepted, the node schedules the channel switch in tandem with the information received and continues to send Channel Switch Announcement frames with Channel Switch Parameters element values matching the values in the received Channel Switch Announcement except for the TTL, which is decremented by 1 on each hop. In the event that the channel switch announcement lacks the Mesh Channel Switch Parameters elements or the TTL is expired or there is already another channel switch in the process with greater or matching precedence[3], the Channel Switch Announcement is rejected and not processed further.

[3]The precedence value, which is specified in the Mesh Channel Switch Parameters element accompanying the channel switch announcement is randomly selected from a uniform distribution ranging 0 to 65535.

Appendix B

Scalability analysis using USL

In this section we show how to model a routing metric's scalability using the Universal Scalability Law (USL) [170]. Scalability is analysed in terms of network *convergence*, which we define as the time taken from start-up for each of the routers to build a complete routing table. The method can be adapted to analyse scalability in terms of other performance objectives such as memory/processor utilisation, etc. USL is given by the expression:

$$C(N) = \frac{N}{1 + \delta(N-1) + kN(N-1)} \tag{B.1}$$

To model metric scalability using USL, let:

C = convergence in seconds.

N = number of nodes.

δ = queuing delay due to the serial nature of metric computation.

k = delay resulting from inter-process communication.

B.0.0.1 Determining δ and k

Equation (B.1) can be rearranged as shown in equation (B.2).

$$\begin{aligned} \frac{N}{C(N)} - 1 &= \delta(N-1) + kN(N-1) \\ &= k(N-1)(N-1+1) + \delta(N-1) \end{aligned} \tag{B.2}$$

Table B.1: Network convergence

(N)	Convergence: Airtime	Convergence: augmented Airtime
2	1.001	1.001
3x3	1.208	1.208
4x4	1.0046	1.0046
5x5	1.009	1.008
6x6	1.011	1.011
7x7	1.011	1.011
8x8	1.013	1.013
9x9	1.016	1.015
10x10	1.019	1.017

To determine the scalability parameters δ and k, the denominator in equation (B.1) is transformed into a second order polynomial of the form $y = ax^2 + bx + 0$. Let

$$x = N - 1, \qquad y = \frac{N}{C(N)} - 1 \tag{B.3}$$

Rewriting equation (B.2) using substitutions from equation (B.3):

$$y = kx^2 + (\delta + k)x \tag{B.4}$$

Relating equation (B.4) to the second order polynomial of the form $y = ax^2 + bx + 0$ implies that:

$$a = k, \quad b = \delta + k = \delta + a, \quad \delta = b - a \tag{B.5}$$

Table B.2 shows the calculations required to model the non-linearity relative to N = 2, which for our specific case (convergence) is the lowest meaningful value of N. Using least squares polynomial regression, for Airtime metric: a = -0.0002714, b = 1.01448, R^2 = 0.9998. For augmented Airtime metric: a = -0.0002322, b = 1.0121767, R^2 = 0.9998.

From Figure B.1 showing the observed convergence when either Airtime or Augmented Airtime metric is used and the predicted convergence of Airtime metric,

Table B.2: Modelling non-linearity

Airtime metric: (N)	C	N-1	$\left(N \times \frac{C(2)}{C}\right) - 1$
2	1.001	1	1
3x3	1.208	8	6.458
4x4	1.0046	15	14.943
5x5	1.009	24	23.802
6x6	1.011	35	34.644
7x7	1.011	48	47.515
8x8	1.013	63	62.242
9x9	1.016	80	78.804
10x10	1.019	99	97.234
Augmented Airtime metric: (N)	C	N - 1	$\left(N \times \frac{C(2)}{C}\right) - 1$
2	1.001	1	1
3x3	1.208	8	6.458
4x4	1.0046	15	14.943
5x5	1.008	24	23.826
6x6	1.011	35	34.644
7x7	1.011	48	47.515
8x8	1.013	63	62.242
9x9	1.015	80	78.883
10x10	1.017	99	97.427

Table B.3: USL computed parameters

a	b	δ	k	R^2
Airtime: -2.714^{-4}	1.01448	1.01475	-2.714^{-4}	0.99
Augmented: -2.322^{-4}	1.01218	1.01241	-2.322^{-4}	0.99

two observations can be made:

- A link metric can be augmented to improve performance without significantly affecting scalability.
- Metric scalability can be analysed using the USL.

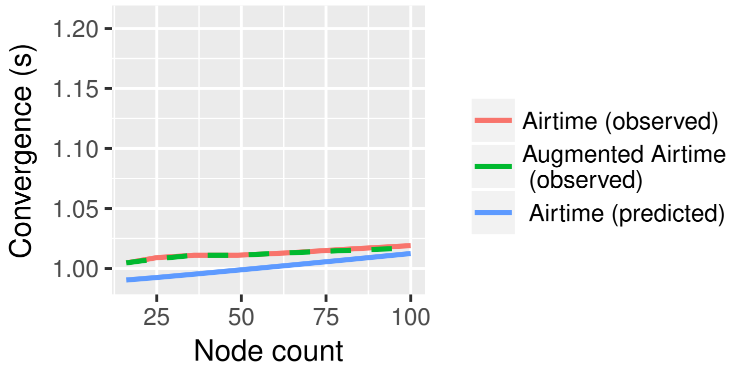


Figure B.1: Scalability analysis in terms of convergence.

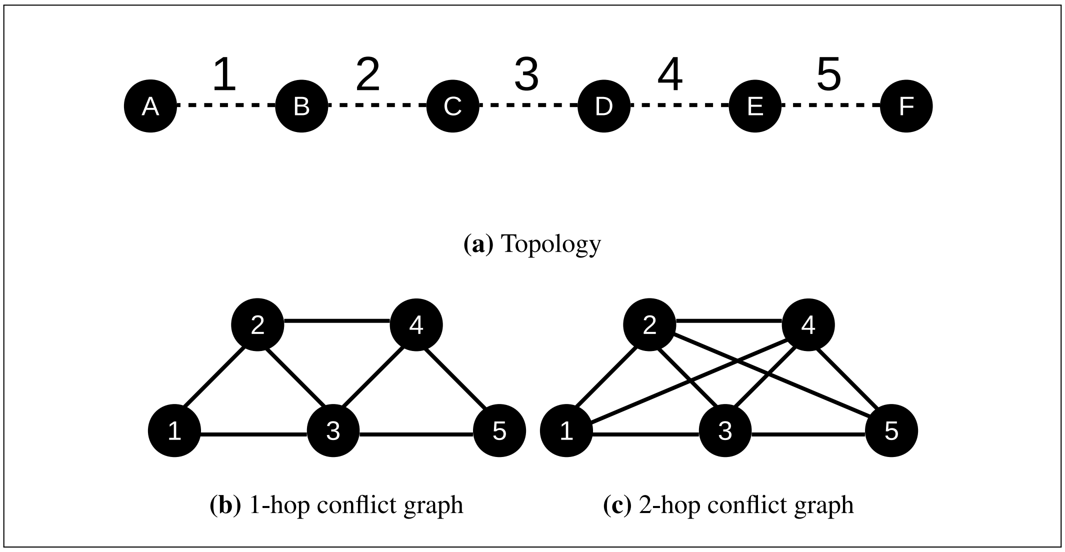
Appendix C

Link conflict graph

C.1 Overview

A *conflict graph* is useful in understanding the interference on a wireless link caused by simultaneous transmission on another link operating on the same frequency. The edges of a conflict graph indicate potential conflict among the nodes. In other words, the influence of each node on the network is represented by links of the conflict graph. To understand the construction of a conflict graph, consider the basic single radio single channel chain configuration depicted in Figure C.1a. In order to construct the conflict graph, each link is represented by a node and the edge represents a conflict between two associated links. For example, assuming uniform and omnidirectional transmission ranges, link 1 and link 2 conflict because node B cannot simultaneously transmit/receive to/from node A and node C. Link 3 conflicts with link 1 because while node C is transmitting, the reception at node B is affected. Figure C.2 on the other hand shows a disconnected single-hop conflict graph because multi-radio enabled nodes operating on different channels can have multiple active transmission/reception simultaneously.

Considering the topologies illustrated in Figures C.1a and C.2a, single-hop conflict graph implies that the interference model is such that the transmission/interference range does not extend beyond the adjacent node. When the interference range extends as far as the nodes' 2-hop neighbour, it can be referred to as a 2-hop conflict graph.

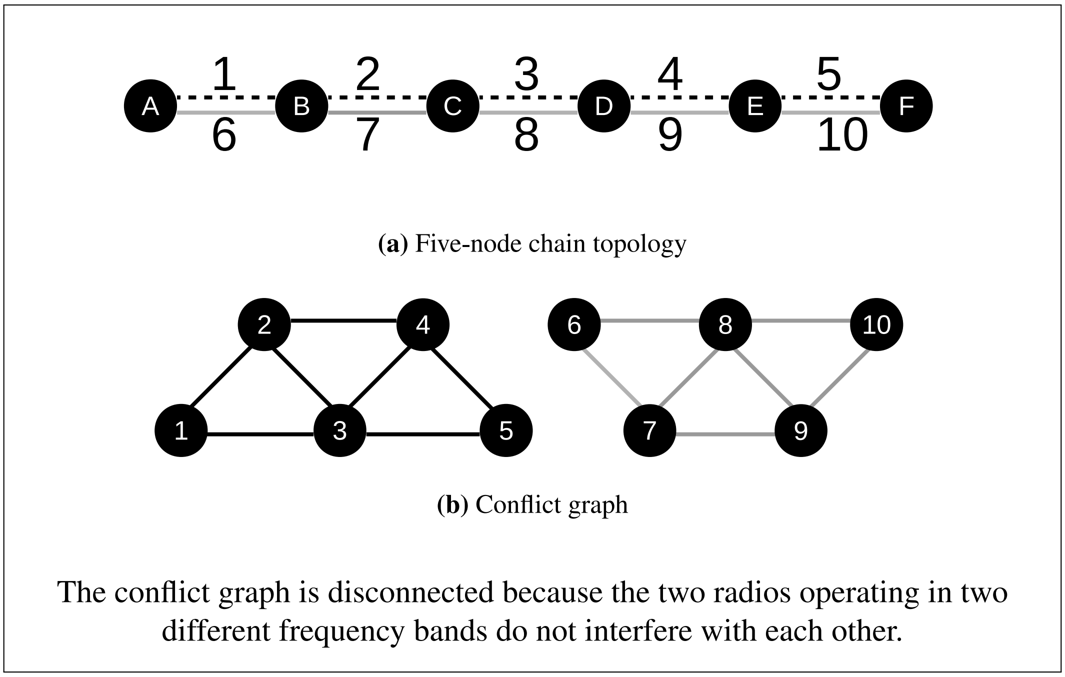


(a) Topology

(b) 1-hop conflict graph

(c) 2-hop conflict graph

Figure C.1: Single radio single channel five-node chain topology and its associated 1-hop and 2-hop conflict graphs.



(a) Five-node chain topology

(b) Conflict graph

Figure C.2: Two-radio two-channel five-node chain topology and its associated single-hop conflict graph.

To generalise let,

$$w_{ij} = pr_j(i) \div \left[\frac{pr_j(j)}{snr_j} - pn\right] \tag{C.1}$$

where w_{ij} is the interference on link j caused by link i, $pr_j(i)$ is the received power at link j caused by the transmission on link i, pn is the noise power, snr_j is the receiver sensitivity dependent signal to noise ratio needed for a successful transmission at link j. A transmission at j will be successful iff

$$\sum_{i \in S, i \neq j} w_{ij} < 1 \tag{C.2}$$

where S is the set of links and $j \in S$.

When condition (C.2) holds true for all $j \in S$, links can transmit at the same time successfully and such a set is referred to as an *independent set*. If a non-independent set results when one link is added to the independent set S, then S is referred to as a *maximum independent set* [171].

C.2 Modelling the effects of wireless interference

The conflict graph concept has been used in literature to estimate network throughput under the constraints of a given workload [82], [172]. The next section adapts the methods used in related work and applies them to estimate path capacity of hybrid back-haul links. When multiple nodes equipped with a single and identical radios are within interference range of each other, only one node can transmit at a time. The conflict graph models the effects of interference to indicate links that can transmit simultaneously. For a node with multi-radios tuned to different channels, links between node pairs on different channels do not conflict and can therefore have multiple simultaneous transmissions. The conflict graph model is used to compute throughput with the impact of interference among neighbouring nodes factored in. The interference modelling can take one of two forms depending on the media access protocol. The first kind asserts that interference occurs at the receiver as such the conflict graph requires only the receiver to not be interfered with. The second way of modelling applies the premise that interference occurs at both the receiver and transmitter, thus both need to be clear of interference for communication to be successful.

C.3 Estimating path capacity

Chapter 6 6.2 described the problem of link selection. Abstract and reductive solutions to the link selection problem for a point-to-multi-point as well as multi-point-to-multi-point were presented in subsections 6.2.2 and 6.2.3. Thinking back at the link options discussed in chapter 6 namely aggregate vs split vs single-I/O: how does the choice of what is optimal get affected as the number of flows increases in a multi-hop environment? In this appendix, the conflict graph model is applied to analyse network capacity comprising aggregate and split radio links. The analysis considers several traffic matrices and randomised communicating node pairs. The illustrative results show variation in path throughput for single-I/O, aggregate and split radio links subject to the pattern of communication. This perspective presents an opportunity to benefit from integrating the conflict graph derived constraints in the overall (aggregate vs split vs single-I/O) decision process.

The network is modelled as a graph $G(V,E)$ where the vertices V and edges E respectively represent the set of nodes and links in the network. The network nodes are denoted by n_i such that $1 \leq i \leq N$ where $N = |V|$ is the total number of nodes. The path P from source n_1 to destination n_d can be represented as the ordered set of nodes selected by the routing protocol i.e. $P = \{n_1, n_2, ..., n_d\}$. The link connecting node n_i and node n_{i+1} denoted by l_i while c_i represents the capacity of link l_i and $L = \{l_1, l_2, ..., l_{d-1}\}$ is the set of links used along the path.

Taking $G_x(E,X)$ to be the conflict graph of G, there exists an edge between two vertices if the two links interfere and unable to transmit at the same time. Let $G_x(P)$ be the sub-graph of G_x such that the vertices are the links L in P. Considering further the sets formed by vertices of $G_x(P)$ and its single-hop neighbours to correspond to $N_i(P)$, for $i = 1,2,...,d-1$, the time required by two links $l_i, l_j \in N_i(P)$ to transmit 1 bit on the link can be denoted as $\frac{1}{c_i}$ and $\frac{1}{c_j}$ respectively. This implies that the total time t required by a 1-bit datum to traverse link l_i and link l_j equals $\frac{1}{c_i} + \frac{1}{c_j}$ since each set $N_i(P)$ comprises links that need their transmissions to be scheduled in different time intervals. Thus the l_i, l_j path capacity may be represented by $\frac{1}{t}$. To generalise, the capacity of each sub-path consisting of links in $N_i(P)$ is given by

$$C_i(P) = \frac{1}{\sum l_j \in N_i(P) \frac{1}{x_j}}, \text{ for } i = 1, 2, ..., d-1 \tag{C.3}$$

Since the effective path capacity is dependent on the sub-graph with the least capacity, the theoretical capacity of a path, $C(P)$ is given by

$$C(P) = \frac{1}{b(P)} \tag{C.4}$$

where $b(P) = \max_i \sum_{l_j \in N_i(P)} \frac{1}{x_j}$, for $i = 1, 2, ..., d-1$

To calculate the conflict graph $G_x(P)$, the network graph G is first defined and the capacity of each link x_i is modelled based on the measured link throughput. The node links are then used as vertices and edges are added between interfering neighbour links to generate the conflict graph G_x. The assumption is that interference only happens between neighbour wireless radios using the same channel. In addition, successful communication requires both the sender and receive to have no incident interference, which is similar to the 802.11 protocol model. Considering randomised source/destination pairs, capacity was estimated by focusing on the path that would be selected by a shortest-path based routing protocol. The aim is to compare the path capacities of different hybrid link utilisation options under the same scheduling system.

C.3.1 Assumptions

To facilitate the analysis, it is assumed that (i) links have identical data-rates = r; (ii) all nodes have omnidirectional antennas; (iii) nodes are uniformly spaced and that the distance between node pairs is indicative of both the transmission range and interference range; (iv) the sending node has an unlimited amount of data; (v) receiving nodes have unlimited buffer size. It is further assumed that the same scheduling scheme is used throughout.

The next sections describe four node layouts considered in the estimation of path capacity using the highlighted hybrid link options. Each node is assumed to have only two radios. The layout considered is intentionally simple to facilitate an exhaustive analysis.

Setup 1: two-node topology

Let us start with a simple two-node setup shown in Figure C.3. Communication takes place only between node *A* and node *B*. It is assumed that both nodes have a limitless amount of data to transmit and boundless storage capabilities to buffer incoming data. The solid line represents one radio e.g. 5 GHz, while the dashed line indicates a wireless link established with another radio such as a UHF-TVWS radio. There is no interference between the two radios since they operate on different channels and in different radio frequency bands. But to simplify the analysis, they are assumed to have uniform data-rates. Table C.1 shows the matrix representation of the conflict graph. Individual links are labelled 0, 1, 2, 3 as shown in Figure C.3. Links that do not interfere are marked with a 0 while a 1 indicates conflicting links. For example, link 0 and link 1 cannot be both be active at the same time, hence in the conflict matrix $(0,1) \rightarrow 1$. On the other hand, link 1 and link 2 can be active in the same timeslot, hence $(1,2) \rightarrow 0$.

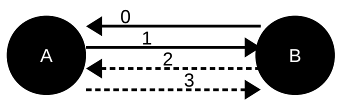


Figure C.3: Basic two-node setup.

Table C.1: Conflict matrix for setup 1.

Link: single-I/O	**0**	**1**
0	0	1
1	1	0

Note. For single-I/O, the conflict graph is the same for either radio, which means links 0 and 1 have the same conflict graph as links 2, 3.

Link: aggregate	**0, 2**	**1, 3**
0, 2	0	1
1, 3	1	0

Note. with aggregation, link pairs (0, 2) and (1, 3) behave as one logical links, hence the resulting conflict graph is identical to that of the single-I/O.

Link: split	**0**	**1**	**2**	**3**
0	0	1	0	0
1	1	0	0	0
2	0	0	0	1
3	0	0	1	0

Setup 2: three-node V-topology

The second setup consists of three nodes setup as shown in Figure C.4. In this setup, node *A* is able to communicate directly with node *B* and *C*, whereas communication between node *B* and *C* is via node *A*. The links are labelled 0, 1, ..., n from left to right and top to bottom as shown in the figure. The first scenarios considers communication between node *C* and node *B*. The second case considers a scenario where node *A* has data to send to node *B* and data to send to node *C*. In the case of the second scenario, Single-I/O can be interpreted as only one radio in use or it may be interpreted as one radio linked to one node and the second radio link to the other node both serving send/receive functions. Just to clear up some potential misconception, for the split link option, it does not mean node *A* sending to node *B* on say, link 1 and at the same time send to node *C* on link 6. While this scheduling appears to optimise capacity since link 1 and link 6 are not in conflict with each other and can thus transmit on these links in the same timeslot, such a configuration would be inconsistent with our definition of a split link. Based on how we have defined it, the split link option means node *A* will transmit to node *B* on, say link 1 and transmit to node *C* on link 4 because the radio marked by the solid line becomes the transmitting radio whereas the other radio (dotted line) gets used for receiving only in a given timeslot. Such operation fits our functional definition of a split radio link. Table C.2 shows the conflict matrix constructed for the setup shown in Figure C.4.

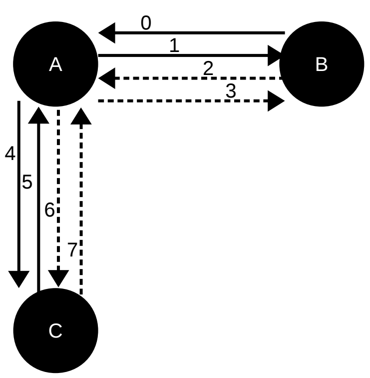


Figure C.4: Basic three-node V-topology setup.

Table C.2: Conflict matrix for setup 2.

Link: single-I/O	0	1	4	5
0	0	1	1	1
1	1	0	1	1
4	1	1	0	1
5	1	1	1	0
NB. For single-I/O, the conflict graph is the same for either radio i.e. links 0, 1, 4 and 5 have the same conflict graph as links 2, 3, 6 and 7.				

Link: split	0	1	2	3	4	5	6	7
0	0	1	0	0	1	1	0	0
1	1	0	0	0	1	1	0	0
2	0	0	0	0	0	0	1	1
3	0	0	1	0	0	0	1	1
4	1	1	0	0	0	1	0	0
5	1	1	0	0	1	0	0	0
6	0	0	1	1	0	0	0	1
7	0	1	1	1	0	0	1	0

Link: aggregate	0, 2	1, 3	4, 6	5, 7
0, 2	0	1	1	1
1, 3	1	0	1	1
4, 6	1	1	0	1
5, 7	1	1	1	0
NB. with aggregation, link pairs (0, 2), (1, 3), (4, 6) and (5, 7) behave as one logical links, hence the resulting conflict graph is identical to that of the single-I/O link shown above.				

Setup 3: six-node chain topology

The third setup considers a six-node chain topology illustrated in Figure C.5. It is assumed that the interference range does not extend beyond the node's one-hop neighbour as the figure shows. The source/destination node pair of interest is node A and F. The conflict matrix associated with Figure C.5 setup is shown in Table C.3.

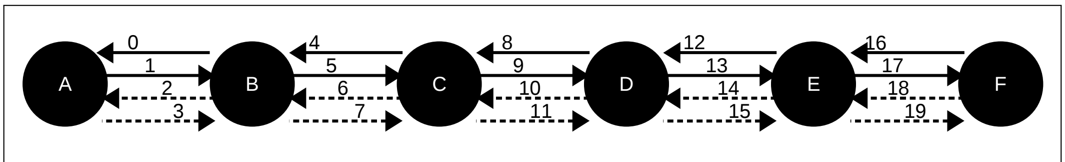


Figure C.5: Six-node chain topology.

Table C.3: Conflict matrix for setup 3.

Link: single-I/O	**0**	**1**	**4**	**5**	**8**	**9**	**12**	**13**	**16**	**17**
0	0	1	1	1	1	1	0	0	0	0
1	1	0	1	1	0	1	0	0	0	0
4	1	1	0	1	1	1	1	1	0	0
5	1	1	1	0	1	1	0	1	0	0
8	1	0	1	1	0	1	1	1	1	1
9	1	1	1	1	1	0	1	1	0	1
12	0	0	1	0	1	1	0	1	1	1
13	0	0	1	1	1	1	1	0	1	1
16	0	0	0	0	1	0	1	1	0	1
17	0	0	0	0	1	1	1	1	1	0

Note. the conflict graph for single-I/O is the same for either radio, hence only the solid line links are considered in this analysis. Just to reiterate, a bidirectional MAC model is assumed, which means that for communication to be successful, the transmitter and the receiver must both be interference-free. For example, links 0 and 9 are in conflict because node C's transmission are head by node B thereby interfering with node B's transmission/reception.

Link: aggre-gate	**0, 2**	**1, 3**	**4, 6**	**5, 7**	**8, 10**	**9, 11**	**12, 14**	**13, 15**	**16, 18**	**17, 19**
0, 2	0	1	1	1	1	1	0	0	0	0
1, 3	1	0	1	1	0	1	0	0	0	0
4, 6	1	1	0	1	1	1	1	1	0	0
5, 7	1	1	1	0	1	1	1	1	0	0
8, 10	1	0	1	1	0	1	1	1	1	1
9, 11	1	1	1	1	1	0	1	1	0	1
12, 14	0	0	1	1	1	1	0	1	1	1
13, 15	0	0	1	1	1	1	1	0	1	1
16, 18	0	0	0	0	1	0	1	1	0	1
17, 19	0	0	0	0	1	1	1	1	1	0

NB. link pairs (y, z) indicate link that would behave as one logical links when aggregated, hence the resulting conflict graph is identical to that of the corresponding single-I/O option shown above.

Link: split	**0**	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**
0	0	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0	0	0
1	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0	0	0
2	0	0	0	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0	0	0
3	0	0	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0	0	0
4	1	1	0	0	0	1	0	0	1	1	0	0	1	1	0	0	0	0	0	0
5	1	1	0	0	1	0	0	0	1	1	0	0	0	1	0	0	0	0	0	0
6	0	0	1	1	0	0	0	1	0	0	1	1	0	0	1	1	0	0	0	0
7	0	0	1	1	0	0	1	0	0	0	1	1	0	0	0	1	0	0	0	0
8	1	0	0	0	1	1	0	0	0	1	0	0	1	1	0	0	1	1	0	0
9	1	1	0	0	1	1	0	0	1	0	0	0	1	1	0	0	0	1	0	0
10	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	1	0	0	1	1
11	0	0	1	1	0	0	1	1	0	0	1	0	0	0	1	1	0	0	0	1
12	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	1	0	0
13	0	0	0	0	1	1	0	0	1	1	0	0	1	0	0	0	1	1	0	0
14	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0	1	1
15	0	0	0	0	0	0	1	1	0	0	1	1	0	0	1	0	0	0	1	1
16	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1	0	0
17	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	1	0	0	0
18	0	0	0	0	0	0	0	0	0	0	1	0	0	0	1	1	0	0	0	1
19	0	0	0	0	0	0	0	0	0	0	1	1	0	0	1	1	0	0	1	0

Setup 4: three by three grid layout

The fourth setup considers a three by three node setup shown in Figure C.6. With this grid layout, there are several sender/receiver node pairs that can be considered. For this analysis, the communication of interest is assumed to take place between node *A* and node *I*. As stated earlier, all communication takes place under the same scheduling scheme. When node *A* has data to send to node *I* it has the option of sending via node *B* or node *D*. As a matter of fact, node *A* can send via both node *B* and node *D*, and node *B* and node *D* can in turn forward to *E* as well as *C* and *G* respectively. However, to simplify the analysis, multi-path routing is disallowed.

Assumed path: $B- > E- > H$.

Single-I/O links along the path: 1, 12, 32, 45 or 3, 14, 34, 47.

Aggregate links along the path: [1, 3], [12,14], [32, 34], [45, 47].

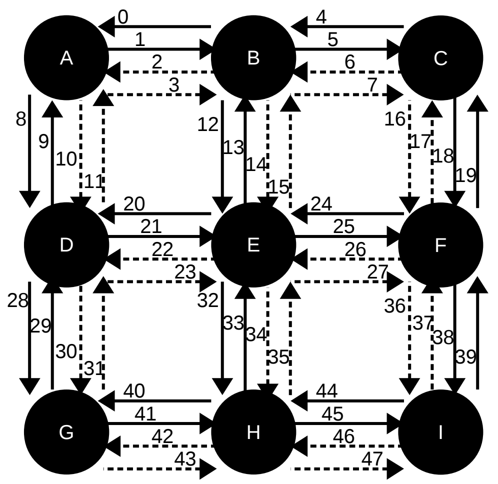


Figure C.6: Three by three grid layout.

As stated earlier, the assumed interference model requires both the sender and receiver to be clear of interference. The conflict graph constructed from the setup illustrated in Figure C.6 is represented in matrix form as shown in Tables C.4 and C.5. Chapter 6 introduced the concept of *multi-link utilisation* options with emphasis on three main ones, namely single-I/O, split and aggregate. With the different multi-link utilisation approaches, we obtain different conflict graphs. The performance metric of interest is path throughput yielded by the different link options under the constraint of the same scheduling method. The conflict matrix shows sets of links that can be active simultaneously and conflicting links that cannot be active simultaneously based on the interference model in place. In addition to knowing scenarios where each option offers the best performance, the purpose of this analysis is to explore the path throughput given by each of the link options in the light of the associated conflict graph. The analysis presented herein assumes omnidirectional antennas, however the method can be adapted quite easily to analyse path capacity in networks involving directional antennas only or a combination of omnidirectional and directional antennas.

Table C.4: Conflict matrix for setup 4 single-I/O link option.

Link: single-I/O	**0**	**1**	**4**	**5**	**8**	**9**	**12**	**13**	**18**	**19**	**20**	**21**	**24**	**25**	**28**	**29**	**32**	**33**	**38**	**39**	**40**	**41**	**44**	**45**
0	0	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	0
1	1	0	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	0	0	0	0	0	0	0
4	1	1	0	1	1	0	1	1	1	1	1	0	1	1	0	0	1	0	1	1	0	0	0	0
5	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	0	0	0
8	1	1	1	1	0	1	1	1	0	0	1	1	0	1	1	1	1	0	0	0	0	1	0	0
9	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	0	0	1	1	0	0
12	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	0	1	0	0	1
13	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
18	1	1	1	1	0	1	1	1	0	1	1	0	1	1	0	0	1	0	1	1	0	0	1	0
19	1	0	1	1	0	1	1	1	1	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1
20	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
21	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1	1	0	0
24	0	0	1	1	0	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	0	1	1
25	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
28	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	1	1	1	0	0	1	1	0	1
29	0	1	0	0	1	1	0	1	0	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
32	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
33	1	0	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
38	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	0	1	1
39	0	0	1	0	0	0	0	1	1	1	1	0	1	1	0	0	1	1	1	0	1	1	1	1
40	0	0	0	0	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1
41	0	0	0	0	1	1	0	1	0	0	1	1	0	1	1	1	1	1	0	1	1	0	1	1
44	0	0	0	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1
45	0	0	0	0	0	0	1	1	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	0

Note. the conflict matrix of the split link option for test 4 is not included due to space constraints, however it is easy to see that the pattern is similar to the split link conflict matrix shown in Table C.3.

Table C.5: Conflict matrix for setup 4 aggregate link option.

Link: aggregate	**0, 2**	**1, 3**	**4, 6**	**5, 7**	**8, 10**	**9, 11**	**12, 14**	**13, 15**	**16, 18**	**17, 19**	**20, 22**	**21, 23**	**24, 26**	**25, 27**	**28, 30**	**29, 31**	**32, 34**	**33, 35**	**36, 38**	**37, 39**	**40, 42**	**41, 43**	**44, 46**	**45, 47**
0, 2	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	0	0	0	0	0	0
1, 3	1	0	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	0	0	0	0	0	0	0
4, 6	1	1	0	1	1	0	1	1	1	1	1	0	1	1	0	0	1	0	1	1	0	0	0	0
5, 7	1	1	1	0	1	1	1	1	1	1	1	1	1	1	0	0	1	1	1	0	0	0	0	0
8, 10	1	1	1	1	0	1	1	1	0	0	1	1	0	1	1	1	1	0	0	0	0	1	0	0
9, 11	1	1	0	1	1	0	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	1	0	0
12, 14	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	0	1	0	0	1
13, 15	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1
16, 18	1	1	1	1	0	0	1	1	0	1	1	0	1	1	0	0	1	0	1	1	0	0	1	0
17, 19	1	0	1	1	0	0	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	0	1	1
20, 22	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1
21, 23	1	1	0	1	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1	1	0	1
24, 26	1	0	1	1	0	1	1	1	1	1	1	1	0	1	1	0	1	1	1	1	1	0	1	1
25, 27	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1	1	1	1
28, 30	1	1	0	0	1	1	1	1	0	0	1	1	1	1	0	1	1	1	0	0	1	1	0	1
29, 31	0	1	0	0	1	1	0	1	0	0	1	1	0	1	1	0	1	1	0	0	1	1	1	1
32, 34	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1	1
33, 35	1	0	0	1	0	1	1	1	0	1	1	1	1	1	1	1	1	0	1	1	1	1	1	1
36, 38	0	0	1	1	0	0	1	1	1	1	1	1	1	1	0	0	1	1	0	1	1	0	1	1
37, 39	0	0	1	0	0	0	0	1	1	1	1	0	1	1	0	0	1	1	1	0	1	1	1	1
40, 42	0	0	0	0	0	1	1	1	0	0	1	1	1	1	1	1	1	1	1	1	0	1	1	1
41, 43	0	0	0	0	1	1	0	1	0	0	1	1	0	1	1	1	1	1	0	1	1	0	1	1
44, 46	0	0	0	0	0	0	0	1	1	1	1	0	1	1	0	1	1	1	1	1	1	1	0	1
45, 47	0	0	0	0	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	1	1	1	1	0

C.3.2 Path throughput

To recap, the method for estimating path capacity proceeds in three steps as follows: (i) determine the nodes and links between the source and destination; (ii) establish individual link capacities; (iii) determine the conflicting links from the conflict graph matrix.

Building on the expression ($\frac{r}{\sqrt{n}}$) given in chapter 2 for best case path throughput between two end points, we can ascertain that the effective throughput is in the order of $\frac{r}{\sqrt{n-s}}$ where r is the link data rate, n is the total number of links along the path, and s is the number of links that can transmit simultaneously. The expression $n-s$ gives x, the number of conflicting links between the two end-points. The basis for this formulation is that the previous expression ($\frac{r}{\sqrt{n}}$) assumes greedy transmission i.e. each network node is assumed to be transmitting at the maximum rate.

By considering the number of conflicting links, the estimated path throughput factors in the resulting capacity contributed by the set of non-conflicting links that can transmit simultaneously. Table C.6 summarises the setups, set of links along the path and number of conflicting links based on the conflict graph constructed using the process described previously in section C.3.

Table C.6: Summary of conflicting links along the path associated with each option. The number of links $\boldsymbol{n}$ is determined from the path selected assuming a shorted-path routing protocol. The number of non-conflicting links $\boldsymbol{s}$ is derived from the conflict matrices presented in previous tables, whereas $\boldsymbol{x}$ calculated as $n - s$ is the number of conflicting links along the path.

Scenario	**Option**	**Path links**	**n**	**s**	**x**
Setup 1: A->B	Single-I/O	1 or 3	1	1	0
	Split	1 or 3	1	1	0
	Aggregate	[1,3]	1	1	0
Setup 2: C->B	Single-I/O	5, 1 or 7, 3	2	0	2
	Split	5, 3 or 7, 1	2	2	0
	Aggregate	[5,7], [1,3]	2	0	2
Setup 2: A->B and A->C	Single-I/O	1 or 3 and 6 or 4	2	2 or 0	0 or 2
	Split	1 and 4 or 3 and 6	2	0	2
	Aggregate	[1,3] and [4,6]	2	0	2
Setup 3: A->F	Single-I/O	1, 5, 9, 13, 17 or 3, 7, 11, 15, 19	5	2	3
	Split	1, 7, 9, 15, 17 or 3, 5, 11, 13, 19	5	4	1
	Aggregate	[1,3], [5,7], [9,11], [13,15], [17,19]	5	2	3
Setup 4: A->I	Single-I/O	1, 12, 32, 45 or 3, 14, 34, 47	4	2	2
	Split	1, 14, 32, 47 or 3, 12, 34, 45	4	2	2
	Aggregate	[1,3], [12,14], [32,34], [45,47]	4	2	2

Table C.7: Estimated order of link/path capacity for different hybrid link configurations.

Scenario	**Path capacity** (Mbits/sec)		
	Single-I/O	Split	Aggregate
Test 1: A->B	r	r	$1.5r$
Test 2: C->B	$\frac{r}{\sqrt{2}}$	r	$\frac{1.5r}{\sqrt{2}}$
Test 2: A->B and A->C	$\frac{r}{\sqrt{2}}$	$\frac{r}{\sqrt{2}}$	$\frac{1.5r}{\sqrt{2}}$
Test 3: A->F	$\frac{r}{\sqrt{3}}$	$\frac{r}{\sqrt{1}} = r$	$\frac{1.5r}{\sqrt{3}}$
Test 4: A->I	$\frac{r}{\sqrt{2}}$	$\frac{r}{\sqrt{2}}$	$\frac{1.5r}{\sqrt{2}}$
Note: aggregate capacity is estimated assuming a *basic round robin* based aggregation technique that achieves $\approx$ 50 % efficiency as explained in chapter 6 section 6.5.6.			

C.3.3 Illustrative results, implication and concluding remarks

Table C.7 summarises the path capacity of the setups described in previous sections. The illustrative results indicate that the single-I/O and aggregate link options always have similar conflict graphs. This is because when aggregated, two or more radios links behave as a single logical link. Optimal path throughput achievement is only guaranteed when optimal routing is accompanied by optimal scheduling. Empirical evidence in a related work [172], suggests that the benefit of optimal routing amid poor schedule surpasses the gains of optimal scheduling in the absence of optimal routing. Therefore, while optimal scheduling is essential, emphasis should be placed on optimising the routing strategy. Furthermore, the analysis output observed in Table C.7 hints at an opportunity there is to optimise path throughput by using a routing protocol that is aware of the underlying hybrid link configuration. For such routing to be effective, there is need for the routing link metric to capture the characteristics of hybrid links. For example, ETX of 1 on an aggregated link is not the same as ETX of 1 on a split link, which underscores the relevance of the work done on augmenting existing metrics as discussed in chapter 5 of this dissertation. Conversely, the analysis also points to the fact that additional path capacity optimisation can be achieved by employing upper layer multi-link utilisation awareness in the underlying scheduling approach. Thus overall, effective network throughput is dependent on routing, multi-link utilisation technique and scheduling functionalities whose interplay becomes increasing relevant as the number of simultaneous source-destination pairs rises.

Appendix D

Code snippets

The author may be contacted for further clarification and additional information on any part of this work. This chapter provides code snippets for anybody wishing to extend the work or simply drawing inspiration from it.

D.1 Auto-channel setting for ad-hoc mode

Auto-channel configuration is well defined for infrastructure mode. The master node dictates the channel to use. This section shows code snippet to enable auto-channel setting for nodes in ad-hoc mode running OpenWrt firmware.

```
#!/bin/sh
val=0; signal=0
#**************************************
# List of useful commands to work with
#**************************************
#cmd_set_channel="uci set
   wireless.@wifi-device[$index].channel="
#cmd_set_chanbw="uci set
   wireless.@wifi-device[$index].chanbw="
cmd_commit_wireless_setting="uci commit wireless"
cmd_apply_wireless_setting="wifi" #apply the change
#*************************
# Waiting time
# These values worked fine, but could be reduced on more
```

```
   powerful devices or may require increasing on slower
   devices
#*****************************************************************
delay_commit_change=5
delay_wait_for_signal=1
interfaces="zen wlan2 wlan3" #zen is used here just to test
   behaviour when listed interface is not physically
   present on the device
channel_width="5 10 20" #supported channel width values.
#*****************************************
# Listen on all the radios, one at a time
#*****************************************
for nic in $interfaces
do
#************************************************************
# Determine device or radio index for use with uci
   commands. The current approach is based on the reasoning
   that wlan0, wlan1', wlan2,..., wlanx are respectively
   indexed as 0, 1, 2, ... x. Of cource in future the
   detection of wireless interfaces can be automated e.g.
   selecting radios that are in ad-hoc mode to work with.
#***********************************************************
printf "\r\n======================="
printf "\r\nInterface: $nic"
printf "\r\n======================="
index=$(echo $nic |tail -c 2) #get the last character at
   end of interface name, which indicates the device index
   -useful when using uci commands to interact with device
#**********************************************************
#Customise the channel space to search for the repective
   radios
#**********************************************************
```

```
if [ $nic == "wlan0" ] #wlan0 is currently 2.4 GHz, ad-hoc
then
channel_space="1 2 3 4 5 6 7 8 9 10 11 12 13" #channel 14
   is also included if country setting=Japan
elif [ $nic == "wlan1" ] #wlan1 is currently not of concern
then
#channel_space=<specify channel list>
printf "\r\nChannel space currently undefined for $nic"
exit
elif [ $nic == "wlan2" ] #wlan2 is currently 5 GHz panel
   -this is where the focus is
then
channel_space="48 36 40 44 52" #considering a small subset
   of supported channels for testing purposes
elif [ $nic == "wlan3" ] #wlan3 currently corresponds to
   tvws radio
then
channel_space="1 2 3 4 5 6 7 8 9 10 11 12 13 14"
#Currently only expecting wlan0, wlan1, wlan2, wlan3
else
printf "\r\nChannel space unknown for $nic"
continue #continue with the next radio in the list
fi
set -- $channel_space #currently only useful to echo total
   number of channels, nothing else
printf "\r\nTotal number of channels: $#"
#****************************************************
# Ratchet through the whole list of probable channels
#*****************************************************
for channel in $channel_space
do
cmd_set_channel="uci set
```

```
    wireless.@wifi-device[$index].channel=" #This amounts to
    reseting the string on each iteration or else it
    concatenates to the previous string
cmd_set_channel=$cmd_set_channel$channel #concatenate
    channel value at end of command
printf "\r\nAction: set channel via cmd: $cmd_set_channel";
eval $cmd_set_channel #execute the command
#*******************************************************
# Ratchet through channel widths for each channel
#*******************************************************
for chanbw in $channel_width
do
cmd_set_chanbw="uci set
    wireless.@wifi-device[$index].chanbw="
cmd_set_chanbw=$cmd_set_chanbw$chanbw
printf "\r\nAction: set channel width via cmd:
    $cmd_set_chanbw";
eval $cmd_set_chanbw #set the chanbw
printf "\r\nAction: commit and apply changes via cmd:
    $cmd_commit_wireless_setting and
    $cmd_apply_wireless_setting";
eval $cmd_commit_wireless_setting #commit the changes
eval $cmd_apply_wireless_setting #apply settings
#********************************************************
#I tred to use 'wait' as alternative to sleep, which
    requires explicit specification of sleep time. I've
    found sleep to be better for this purpose because 'wait'
    only waits for command to complete, but it doesn't give
    the device enough time to wake up.
#********************************************************
printf "\r\nAction: attempt to detect signal";
sleep $delay_commit_change #This 5 sec delay is critical to
```

```
   allow kernal to reload new values. If there is no delay
   or delay is too small, "No such wireless device: wlanX"
   type of error occurs.
#*********************************


notUsedForAnything=$(iwinfo $nic scan | grep Signal | awk
   -F' ' '{print $2}') #Preceding the next command with
   this to wake wireless card up in case asleep due to
   inactivity
for i in `seq 1 1`; #started with 'seq 1 3' then changed it
   to '1 1' to see how far I can push it. Essentially this
   means detection is being done in 1 second
do
val=$(iwinfo $nic info | grep Signal | awk -F' ' '{print
   $2}')
signal=$((val)) #let's just get the last value sampled
sleep 1
done
#******************************************************
# Later I found "iwinfo <ifname> scan" to be more reliable.
   But there are two problems: i) its output may contain
   info from multiple cells; (ii) which may further vary
   the time to output thereby making suitable "sleep <time>
   hard to predict. On the positiv side, the grep version
   used here only considers the first occurence of "Signal"
   instance and I noticed that the node's configured BSSID
   is first in the ouput -at least in all my test cases.
#*********************************

#******************************************************
# If there is no signal, val == unknown. Whenever val is
```

```
   nonnumeric, signal stays at it's initial value, which is
   0 (zero)
#*******************************************************

#*******************************************************
# NOTE: "iwinfo <ifname> scan" often returns something,
   which may be a really low signal values such as -256,
   which is 0% signal strength. So, condition below may
   need to be adapted, e.g. assumption could be that if
   it's above -95dBm then it's the desired signal.
#*************************************************************
if [ $signal -lt 0 ]
then
printf "\r\n*******************************************";
printf "\r\nStatus: $signal dBm signal detected on channel
   $channel, chanbw $chanbw";
printf "\r\n*******************************************\r";
signal=0 #reset signal value for sanity with looping:)
break 2 #break out of the nested loop by two levels
else
printf
   "\r\n.....................................................";
printf "\r\nStatus: no signal detected on channel $channel,
   chanbw $chanbw";
printf
   "\r\n.....................................................\r";
fi
done #end for chanbw in channel_width
done #end for channel in channel_space
printf "\r\n" #return to the terminal on new line
done #end for nic in interfaces
```

D.1.1 Current limitations and possible future enhancements

Currently, the script starts off by changing the channel. If desired, it can be modified to start by attempting to detect signal on presence and only change the channel if there is no signal present on the current channel. In addition, the "network detection" is only based on signal presence, which poses two problems. Firstly, the detected signal could be caused by some random device in the spectral environment. This can be fixed easily by matching the node's profile with the source of the signal such as the essid for example. Secondly, I have noticed that when there is inactivity, the wireless NIC falls asleep. So the channels may match, but the signal remains equal to zero because there is no transmission/reception. This may be one of the driver-related issues to lookout for. My current workaround is to precede the signal detection with "notUsedForAnything=$(iwinfo $nic scan — grep Signal — awk -F' ' '{print $2}')" a variable that is used for nothing other than executing the "iwinfo <ifname> scan" command in an effort to wake the card. The "scan" command version also outputs signal, but I could not use because it outputs signal value from all visible cells. Whereas "iwinfo <ifname> info" only displays signal value of the node's associated cell as defined by the configured BSSID. Furthermore, the process executes one radio at a time. Future considerations could look at processing multiple radios in parallel.

D.2 NS-3 simulation

There is a wealth of documentation available online [140]. This section presents snippets of code used to implement key functionality. The work was done in ns-3.25.

D.2.1 Disable/enable passive/active scanning mode

```
//OPTION 1: set BeaconGeneration to false
  Config::Set
     ("/NodeList/*/DeviceList/*/$ns3::WifiNetDevice/Mac/$ns3::RegularWifiM
     BooleanValue (false));
```

```
//OPTION 2: set BeaconInterval higher than simulation time
    so it never occurs
  Config::Set
     ("/NodeList/*/DeviceList/*/$ns3::WifiNetDevice/Mac/$ns3::RegularWifiM
     TimeValue (Seconds (99999)));
//NOTE: the '*' can be customised to enable/disable
    beangeneration for specific nodes and radios
```

D.2.2 Set/check operating channel

```
  //To set the channel for radio 1 on node 4:
  Config::Set
     ("/NodeList/4/DeviceList/1/$ns3::WifiNetDevice/Phy/$ns3::
  YansWifiPhy/ChannelNumber", UintegerValue(36));

  //To check what channel the node is transmitting or
     receiving on. First create tracecallback functions
   void MonitorSniffRx (std::string context, Ptr<const
      Packet> packet, uint16_t channelFreqMhz, uint16_t
      channelNumber, WifiTxVector txVector, MpduInfo aMpdu,
      SignalNoiseDbm signalNoise)
   {
   std::cout <<"channel# = "<<channelNumber <<"channel
      FreqMhz = "<<channelFreqMhz <<std::endl;

   WifiMacHeader hdr;
   Ptr<Packet> m_currentPacket;
   m_currentPacket = packet->Copy();
   m_currentPacket->RemoveHeader (hdr);
   Mac48Address source = hdr.GetAddr2(); /*Look into
      hdr.GetAddr1(), hdr.GetAddr2(), hdr.GetAddr3(),
      hdr.GetAddr4() */
   Mac48Address dest = hdr.GetAddr1();
```

```
std::ofstream out (out_file_for_alll_nodes.c_str (),
   std::ios::app);
out<<context<<", "<<channelNumber<<",
   "<<Simulator::Now().GetSeconds()<<", "<<"0, "<<"1,
   "<<source<<", "<<dest<<", "<<
   packet->GetUid()<<std::endl;
out.close ();

void MonitorSniffTx (std::string context, Ptr<const
   Packet> packet, uint16_t channelFreqMhz, uint16_t
   channelNumber, WifiTxVector txVector, MpduInfo aMpdu)
{
/* Attempting to get source and destination address of
   transmitted packet */

/*OPTION 1:*/
WifiMacHeader hdr;
Ptr<Packet> m_currentPacket;
m_currentPacket = packet->Copy();
m_currentPacket->RemoveHeader (hdr);
Mac48Address source = hdr.GetAddr2();
Mac48Address dest = hdr.GetAddr1();
/*OPTION 2:*/
/*
packet->Copy()->RemoveHeader (hdr);
Mac48Address source = hdr.GetAddr2();
Mac48Address dest = hdr.GetAddr1();
*//*Option 2 works fine, but I think option 1 is more
   readable*/
std::cout<<"Source?: "<<source<<std::endl;
std::cout<<"Destination?: "<<dest<<std::endl;
```

```
    std::ofstream out (out_file_for_alll_nodes.c_str (),
       std::ios::app); //hardwired
    out <<context<<", "<<channelNumber<<",
       "<<Simulator::Now().GetSeconds()<<", "<<"1, "<<" 0,
       "<<source<<", "<<dest<<",
       "<<packet->GetUid()<<std::endl;
    out.close ();
    if (channelNumber == 0)
    {
    /* The correct way to switch channel is:
    * 1. Interface down, e.g. to stop packets from layer 3
    * 2. Wait before all output queues will be empty
    * 3. Switch PHY channel
    * 4. Interface up
    * In the absence of elegant solution, my current
       workaround is to schedule channel change to occur 1
       second from now.*/
    std::string nodeId=context.substr( 10,1 );
    std::string deviceId=context.substr( 23,1 );
    }
    }
//Make a racecall-back. This means MonitorSniffTx() and
    MonitorSniffRx() will fire up whenever any node
    transmits/receives anything. I used this mechanism to
    keep an eye on what node is sending/transmitting on what
    channel. The "*" can be customised so that the callback
    is only triggered by specific nodes of interest.
Config::Connect("/NodeList/*/DeviceList/*/Phy/MonitorSnifferTx",
    MakeCallback (&MeshTest::MonitorSniffTx, this));
Config::Connect("/NodeList/*/DeviceList/*/Phy/MonitorSnifferRx",
    MakeCallback (&MeshTest::MonitorSniffRx, this));
```

D.2.3 Encode/decode packets

While *Networking essentials* associate *frames* with layer 2 and *packets* with layer 3, in NS-S terms, there is no apparent distinction between a frame and a packet. These terms appear to be used interchangeably syntactically and semantically.

```
\\OPTION 1: modify the header
\\OPTION 2: modify payload
MeshTest::ReceivePacket (Ptr<Socket> socket)
{
 Ptr<Packet> packet; //original line
//By default, ns-3 will send "packetSize" of nothing. We
    can try to specify packet content.
Address senderAddress;
std::ostringstream msg;
while ((packet = socket->RecvFrom (senderAddress)))
{
InetSocketAddress addr = InetSocketAddress::ConvertFrom
    (senderAddress);
//loop over the node container and customise msg e.g. based
    on node id
if (addr.GetIpv4()==Ipv4Address("10.1.1.5"))
{
msg << "36, 40, 44, 48" << '\0';
bytesTotal += packet->GetSize ();
packetsReceived += 1;
NS_LOG_UNCOND (PrintReceivedPacket (socket, packet,
    senderAddress)); //Original position of line
/*Attempting to print packet contents: */
NS_LOG_UNCOND ("content of packet " << *packet); //this
    alone prints only the payload size
//Attempting to read the actual data sent/received, not
    just the payload size
```

```
uint8_t *buffer = new uint8_t[packet->GetSize ()];
packet->CopyData(buffer, packet->GetSize ());
std::string s = std::string((char*)buffer);
std::cout<<"Received: "<<s<< " from "<<addr.GetIpv4()
   <<std::endl;
}
}
```

Appendix E

Miscellaneous detail

This appendix contains miscellaneous details for completeness.

E.1 GLSD query and response messages

The Protocol to access White-Space (PAWS) Databases: use cases and requirements -RFC6953 [173], does not specify the data models for GLSD transaction, but instead provides guidelines on the parameters that the data model must support. Table E.1 show the mandatory and optional fields of a GLSD query. Table E.2 shows the GLSD response message.

Table E.1: GLSD query.

AVAIL_SPECTRUM_REQ	
deviceDesc:DeviceDescriptor	required
location:GeoLocation	required
owner:DeviceOwner	optional
antenna:AntennaCharacteristics	optional
capabilities:DeviceCapabilities	optional
masterDeviceDesc:DeviceDescriptor	optional
requestType:string	optional
any other	optional

Table E.2: GLSD response.

AVAIL_SPECTRUM_RES	
timestamp:string deviceDesc:DeviceDescriptor spectrumSpecs:list	required required required
any other	optional

↓

spectrumSpec	
rulesetInfo:RulesetInfo spectrumSchedules:list timeRange:EventTime frequencyRanges:list needsSpectrumReport:bool maxTotalBwHz:float maxContiguousBwHz:float	required required optional optional optional optional optional

↓

spectrumSchedule	
eventTime:EventTime spectra:list	required required

Table E.3: Parameter example size

Parameter	**Example**	**Size (bytes)**
deviceDesc	serial: 185C01FCA958, fccId: 2ABCB-RP132	12+11
location	19.661, 72.864	14
timestamp	start/stopTime: YYYY-MM-DDThh:mm:ssZ	20×2
spectrumSpecs	channels: 30,32,33	8

NB. depending on the GLSD implementation spectrum availability may be returned in terms of start/top frequency. Furthermore, if multiple spectrum portions have different availability durations, the GLSD will return an appropriate start/stop time stamp for each block, which will affect the size of the response message.

Appendix F

Reflection

I once heard a story of a millionaire who got asked the question, *"how much money is enough?"* His response was, *"just a little bit more."*

I liken network performance to money in that the demand for it only increases with the passage of time. A little bit more improvement in network performance is always a good idea. This chapter contains snippets of my raw thoughts hovered over my PhD journey. The tone is less academic, this is intentional.

F.1 Reasoning by analogy

I (like most people known to me) think in terms of images. I find it hard to think about a thing that I do not have a mental picture of. The research road on the other hand, is riddled with a lot of unknowns, otherwise it would not be called research. Therefore, to operate in the space of the unknown, I had to locate anchors from the world I know well to hook the unknown ideas. This parallel mapping of something unknown to what is known as a scheme of thinking about the unknown occurred to me quite naturally. It is only later on, further down in my research journey that I discovered that it is actually a formal method and is referred to as *reasoning by analogy* [1]. I am now able to look back and say that I applied reasoning by analogy.

Reasoning by analogy is the general principle of accessing knowledge from analogous fields i.e. drawing inspiration from an analogous field and applying the

[1] see the article at this url, "Avoiding Superficial" Analogies for the 4-step framework of reasoning by analogy. https://hbr.org/2005/04/how-strategists-really-think-tapping-the-power-of-analogy?referral=03759&cmvc=rritempage.bottom

solution to the target problem as illustrated in Figure F.1. This method of accessing knowledge from analogous fields has its origins in political science and has since been applied in business studies. In fact, it has been found that the more distant the field is from the context of the target problem, the more novel the solution [174]. For example, several top artificial intelligent algorithms have ironically been inspired by nature. Notable examples include ant-colony optimisation et al.

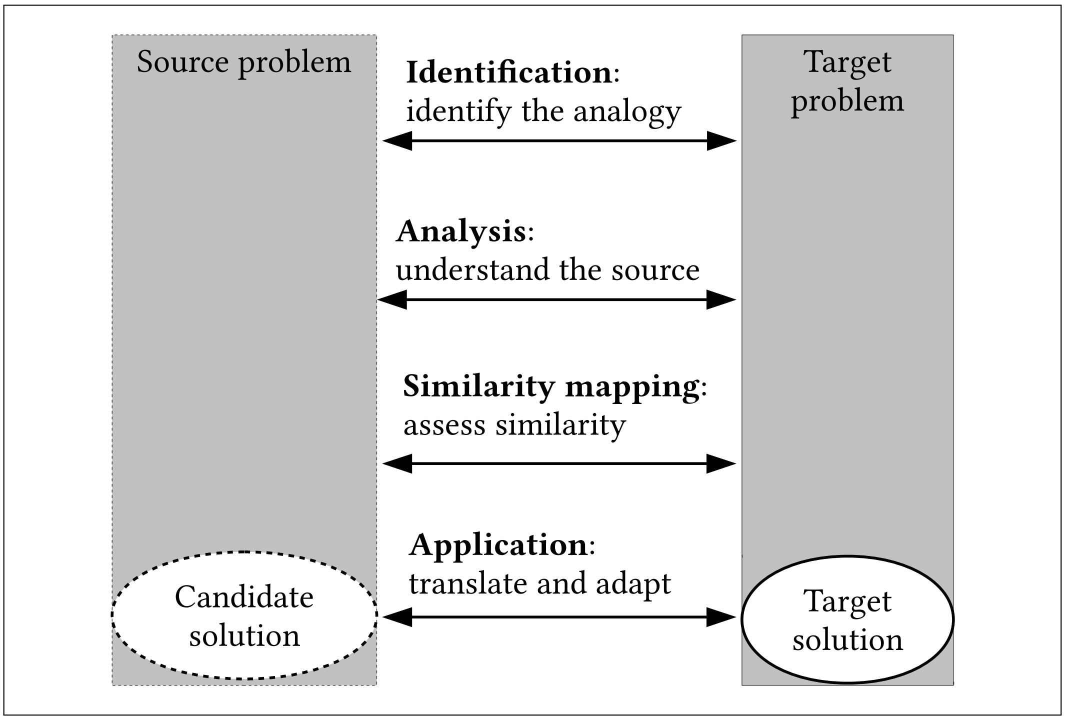


Figure F.1: Reasoning by analogy

F.1.1 The price tag

When two or more shops have the item I want, if the items are the same with a reasonable measure of comparison, the obvious thing I do is look at the price tag: the lowest price always takes the day. The routing metric is a lot like a price tag as the routing protocol uses it to determine the best path. My experience at the shopping mall helped me think about the role of the link metric in the routing process more clearly. Sticking with the price tag metaphor, it follows that if comparisons have to be made, they can only be made meaningfully if the the prices are quoted in the same currency. Comparing 13.17 ZAR vs 11.22 ZMK vs 0.82 Euro for instance, is daunting even for the numerically inclined, and nerve-racking when the price tag is missing altogether! Therefore, a uniform currency should be adopted or there should be a means of conversion from one currency to the other. As I grappled with the protocol's task of deciding between 5 GHz WiFi and UHF-TVWS links, a basic metric such as packet delivery ratio computed on the two links measures two different things. The challenge indicated struck me as a case of dealing with multiple currencies. This line of enquiry inspired me to devise the concept of *scaling constants* (introduced in chapter 5) that are an attempt at an abstract means of levelling dissimilar quantities.

F.1.2 The delivery guy: inspiration for routing

The "delivery guy" analogy is used in nearly all *network fundamentals* notes to illustrate protocol stack mechanics and the movement of data from one device to the other. As I thought about the routing problem, which is an intangible phenomena, I had to locate some readily perceivable analogy to tie it to, think with and learn from. There is obviously plenty analogies to draw from, but the immediate one for me was a road network, which in many respects is similar to a data communication network. Considering what a routing protocol does, the protocol and a motor vehicle driver clearly have similar objectives. I intently observed road traffic on by-ways and high-ways and the behaviour of road users. Imagining a delivery guy for a busy courier company on a typical day driving from one point to the other, I personified the routing protocol and situated it on the passenger's seat of a delivery van in a bid to draw lessons from the driver.

Everybody appreciates less or expediate smooth flowing traffic of any kind, be it road traffic, data traffic, you name it. In this section I try to draw parallels between the delivery guy and routing by highlighting a few examples out of a long list of the many ways in which the inner-workings of a routing protocol are similar to the experience and behaviour of an on-duty delivery driver. At the end of the day, the whole purpose of reasoning by analogy is to transfer lessons learnt from well understood processes or phenomena to the target problem area in question. Inspiration for innovative routing can be drawn from the analogies in the previous paragraph by posing the following metaphorical question: what can the protocol learn from the delivery guy?

1. **Wider/more lanes** are better because more cars can pass through at once. In the context of my work, this equates to spectrum: the wider the operating channel, the more bits we are able to push into the medium. This is the ultimate definition of *bandwidth*. Generally the wider the channel-width, the better in terms of data transfer. However, going beyond the analogy, there are several limitations when in reality. Firstly, as the channel-width increases, transmission distance reduces. Secondly, wider-channel widths are also more susceptible to noise unless of course there is sufficient investment in perfect filters.

2. **Speed limits, traffic lights, stop signs, time dependency** influences how quickly traffic reaches the destination. Yes the lane is open and oh, there are other lanes, so multiple vehicles can head-out, but how long it takes to reach the destination depends on what lies and what happens between the start and the intended destination. This is akin to *throughput*, a term that often times gets confused with bandwidth.

   Over time, a driver develops knowledge of the typical road situation based on time of day. He uses this to determine the best route to take. Spectrum and network usage are similarly time dependent. In addition to the real-time mechanism used by the protocol to determine the optimal route, historic data can be harnessed across two dimensions namely, spectrum usage and network usage to determine optimal path/channel at a given instance.

3. **Smooth road vs pot-hole riddled road** is a very good analogy for clear clean spectrum vs spectrum tainted with unwanted signals. Just as pot-holes force a good driver to slow down, modulation and coding schemes adjust the data-rates depending on the quality of spectrum. Generally, when the noise goes up, the modulation scheme scales down to a lower rate.

4. **Changing lanes** when and where available, doing it when necessary, and

without endangering other motorists is a common sight on the highways and byways. By observing how motorists utilise the road, I was able to get a grip on the essence of DSA. It sounds illogical to imagine a road network with a rule that says, “only this make and colour of vehicle is allowed to ever use a particular lane.” However, this is exactly what the fixed spectrum assignment principle has done. It makes sense by all standards for a driver to hop to an alternative lane when the one they are on gets jammed -and that is what DSA aims to achieve.

A good driver avoids changing lanes unnecessarily. The driver assess the situation to determine if the lane is going to be jammed for a significant period then only does he switch to an alternative lane. If not, he waits patiently for the lane to clear up again. In the same vein, DSA nodes require mechanisms to identify the “lanes” to hop into, judge when it is safe to do so and gauge the potential benefit or cost of switching to an alternative channel. In addition, there is need to quantify overhead associated with channel switching and determine key thresholds of when to switch channels.

5. **Prioritising** is another subroutine I bet the delivery person uses when there are multiple parcels to deliver and places to go to. I am confident he decides which one to start with and which one to end with before setting-out. Queuing packets as and when they arrive at the router and forwarding them based on first-in-first-out (FIFO) principle works fine and is easy to implement. But, is there a chance that we might get performance improvement if we build intelligence into the routers to prioritise traffic and forward accordingly? For example, routers can give higher priority to traffic generated by applications with higher real-time constraints such as VoIP traffic and lower priority to delay tolerant asynchronous data traffic.

6. **“No trucks allowed”** is a common sign found on byways leading to residential areas. It is typically there to alert drivers when trucks are not allowed on a particular road for reasons such as insufficient clearance or optimising traffic

flow. On this note, I leave it up to the creative reader to draw lessons from this and other metaphors and carry on, reasoning by analogy:)

F.2 Design first, model later vs model first, design later

Over the course of my PhD journey, I found myself engaging in interesting discussions around what the best approach is to this or that. The question was, should a system be modelled first and then designed or should it be designed first and modelled later?

One might argue that attempting to model what is vaguely understood could potentially stifle the subsequent design and therefore, we should design first and model later. However, proponents of the model first, design later approach favour the approach because the performance of resulting protocols (..and systems in general) can automatically be proved analytically. Cesana et al [97] remarked on the IEEE 802.11 MAC protocol as a case of "design first", which expectedly lacks an accurate model particularly for delay.

But what else adds to the confusion, is the disparity in views around what constitutes design particularly within the computer science and computer engineering fraternity. I head a story of a computer scientist working for a micro-processor manufacturing company. He described his job as "designing processors", but his colleagues with an engineering background corrected him saying, "no, you don't design, you draw up processor specifications."

After a protracted period of soul-searching, considering the arguments for and against, and analysing it all under the lens of personal experience, I've come to the conclusion that the truth lies somewhere mid-way between model first and design first. I think that aspects of a system that are well understood can be modelled; the design itself can add to clarity and conversely inform the modelling.

F.3 Progression of ideas

When I started working on this research, my initial set of experiments were conducted to compare the performance of WiFi operating in the 5 GHz and UHF-TVWS bands. The motive was to determine which one is suitable. However, as it turned out, there was no clear winner. TVWS performed superiorly in near line-of-sight whereas, 5 GHz WiFi out-performed TVWS in clear line-of-sight scenarios at short distances. It was clear at this point that WMN deployments will have to consist of hybrid links.

The initial idea was to select either 5 GHz or TVWS radio depending on the nature of the signal propagation path. This seemed like a great idea, however I noticed that throughput in the forward direction was not always equal to the throughput in the reverse direction. In some instances, the throughput in one direction was nearly double the throughput in the other direction, which is problematic when deciding which radio to use. After further experimentation, I observed a common scenario where one radio had good throughput in say, the forward direction while the other radio had better throughput in the reverse direction. This pattern begun provoking ideas about using the radios in concert as a way of mitigating link asymmetry whatever the cause might be. This line of enquiry eventually led to the second idea, which we now refer to as a split link i.e. split a single logical link into two physical streams e.g. use 5 GHz to transmit and TVWS to receive or vice versa depending on the nature the asymmetry. The idea is to always try and "put the best foot forward."

At this stage, the aspirations (if I could call it that) of determining and using the WINNING radio exclusively had dissipated. The exploration continued to identify synergies between multiple radios and eventually the idea of aggregating 5 GHz and TVWS came up i.e. combining 5 GHz and TVWS into a single logical link. This proved to be beneficial only when the aggregated radios has approximately uniform data-rates. Armed with General Systems Theory's assertion that the whole is greater than the sum of its part, I begun to think critically about how to possibly rip the benefits of aggregation amid non-uniform data-rates. That is how the *Adaptive Round Robin* algorithm detailed in Chapter 6 came about.

F.4 Two-ply vs single-ply toilet paper

I was in the campus bathroom one day [26 April 2018], it was a Friday and a holiday in South Africa. I got concerned about the amount of toilet paper that was there because it being a Friday, the cleaning staff would only replenish the following Monday. While at it, the thought of *two-ply vs one-ply* toilet paper came to mind. It then dawned on me that this is among the many humanity's unsettled issues as we continue to find both 2-ply and 1-ply toilet paper on the shelf. The manufacturers have left the matter up to the end-user to decide and rightly so.

In similar manner, if we regard the choice of whether or not to split/aggregate hybrid radio links as important as it should be, then I'm inclined to think that the decision should be made by the nodes. We need to get out of the way and just ensure the options have the "price tags" well-labelled for nodes to make informed decisions.

There are two schools of thought. The first one says, while in transit, a parcel remains the property of the sender. Therefore, the sender should dictate the route taken by the parcel. This line of thought leads to a conclusion that the split/aggregate decision should be made by the source node. But then again, if we consider the case of an online shopper, most online retailers let the user choose the shipping method in which case, the parcel is viewed as belonging more to the recipient than it does the entity dispatching it. Considering the conventional semantics of *source* and *destination* nodes, this second view leads us to a different conclusion, which is that the decision rests with the destination node. I consider both arguments to be valid and I'm of the view that an ideal solution lies somewhere mid-way and is subject to context.

F.5 Master key, or maybe not

While conducting the experimental tests, it was important to ensure that the nodes were operating on the same channel otherwise they would not form a connection. In between experiments the channel setting would sometimes change and it always took a moment to figure out why the link wasn't working. Out of this frustration, it is then that the idea of extending “self-configuring” capabilities to encompass channel settings came to mind. In the prototyped solution, the node is able to carry out an exhaustive search of the channel space, detect beacons and set the operating channel to the channel the beacon was detected on (*see* Appendix D section D.1).

The first limitation is that the detection might take longer as the channel space enlarges. The other limitation is that though the node is able to auto-configure its operating channel, its BSSID still has to be configured manually. The BSSID tells the node which network it belongs to. I thought about automating the BSSID setting as well, but did not do it. While it might be a desirable feature towards the realisation of a totally self-configuring network, I did not think it was a wise feature from a security standpoint. My thinking was, though I would pay both kidneys to own a key that is capable of opening any door, paradoxically I would fight tooth-and-nail to avoid having a door that can be opened by any key.

F.6 In the end, everything is virtual

In section 4.2.2 of chapter 4 I talked about virtualisation as a way for single-radio nodes to deal with a possible shortage in network-wide common channels. The idea is to use the one radio a node has and create virtual instances to allow the node to connect to multiple other nodes on different channels as if it had multiple radios. That is the only portion of my dissertation where I used the term “virtualisation”, because naturally that is how I understood it at the time.

In retrospect, my finding is that everything is virtual. In a way, virtualisation can be considered simply as a system of representing resources. With that said, the kind of virtualisation I presented is what might be termed as $1-to-n$ i.e. a single physical entity functionally mapped to multiple instances. I didn’t see it that way then, but looking back now, the multi-link utilisation approaches presented in chapter 6 can also be considered as virtualisation. For example, radio aggregation can be said to be virtualisation of the form $n-to-1$ i.e. multiple physical resources (radios) are mapped to a single resource (link) virtually. while other link permutations may fall in the $m-to-n$ or $n-to-m$ types of virtualisation depending on the number and nature of the mapping between the physical entity and the abstract instantiations. More detail on that philosophy can be found in Horsman's article on Abstract/Representation theory [175].

Now going back to the startling ITU statistics on the world's offline population presented in chapter 1 (Figure 1.1), which formed part of the underlying motivation and fuelled my passion about the research, my answer to the question of "how do we get the nearly 75% offline population online?", is one community based network at a time.